

HapTable: An Interactive Tabletop Providing Online Haptic Feedback for Surface Gestures

by

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**HapTable: An Interactive Tabletop Providing Online Haptic Feedback
for Surface Gestures**

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*To my grandparents and parents,
for their infinite love and support.*

*To my grandfather, A. Naip Tütüncüoğlu,
who still shines his light on my life.*

ABSTRACT

This dissertation aims to present a multitouch interaction surface to enable a more natural human-computer interaction. Within the last decade, touch screens largely replaced indirect input devices, and became widely integrated in our daily tasks. As user interactions moved from mechanical controls to touch controls, the performance and accuracy of users dropped due to the lack of tactile feedback. In mechanical controls, users continuously receive tactile information according to the stage of their interaction. Therefore, we suggest that adding haptic modality suitable for the interaction to current touch systems could potentially improve task performance. Touch screens currently only use visual modality to provide information to users. In this case, we suggest that haptic systems could be used to provide additional information to users, and help to relieve visual information overload.

We explored how we can augment current touchscreen based systems using haptic modality without compromising direct manipulation. For this purpose, we designed and manufactured HapTable -a large multimodal interactive tabletop. HapTable allows users to interact with digital content through natural touch gestures, and to receive visual and haptic feedback according to their interaction. HapTable first recognizes the gesture performed by the user. To provide suitable haptic feedback, it combines two different haptic technologies -piezoelectric actuator-based vibration in normal direction and electrostatic-based frictional vibration in tangential direction. We explored the first actuation technology to provide additional information on touch surfaces, such as a directional wind flow. Our findings indicate that users successfully recognized the direction of flow between two fingers, as well as under their palm. The latter actuation technology is used to provide tactility while turning a visual knob. Although the quantitative metrics did not show improvement in task performance

with haptic feedback, the qualitative metrics showed that users strongly preferred knobs with haptic feedback over the purely visual knob.



ÖZETÇE

Bu tez, insan-bilgisayar etkileşiminin daha doğal hâle getirebilecek geniş ve çok dokunuşlu bir etkileşim yüzeyi sunmayı hedeflemektedir. Son on yıl içinde dokunmatik arayüzler, klavye ve fare gibi dolaylı etkileşim araçlarının yerini almaya başlamış ve kişilerin günlük etkileşimlerinde yaygınca kullandığı bir teknoloji olmuştur. Fakat, fiziksel etkileşim araçlarından uzaklaşarak sadece dokunmatik araçlarla gerçekleştirdiğimiz insan-bilgisayar etkileşimleri, bu araçlarda dokunsal geri bildirim olmaması sebebiyle kişilerin görevi tamamlama başarılarının ciddi derecede düşmesine sebep olmuştur. Kişiler, fiziksel etkileşim araçlarını kullanırken, yaptıkları el hareketlerine ve etkileşim aracının o anki duruma göre sürekli olarak dokunsal geri bildirim alırlar ve gelecek hareketlerini bu bildireme göre ayarlarlar. Bu nedenle biz, dokunmatik ekranlara eklenilebilecek dokunsal geri bildirimlerle kişilerin görevi tamamlama başarılarının artabileceğini düşünüyoruz. Bunun yanı sıra şu anda, dokunmatik ekranlar sadece görsel kanaldan bilgi verebilmektedir. Bu sebeple eklenecek dokunsal sistem, kullanıcıya ek bilgi sunabilmek ve böylece görsel bilgi yüklenmesini hafifletmek için kullanılabilir.

Bu tezde, dokunsal yöntemler ile günümüzdeki dokunmatik ekranları nasıl geliştirebileceğimizi araştırdık. Bu sebeple, HapTable adını verdiğimiz geniş ve birden fazla duyuya hitap eden dokunmatik bir masa geliştirdik. HapTable, kullanıcıların doğal el hareketlerini kullanarak sanal içerik ile etkileşim haline girmesini sağlamakta, ve bu etkileşim sırasında uygun görsel ve dokunsal geri bildirimleri kullanıcıya sunmaktadır. HapTable, piezo elektrik motorlar ve elektrostatik-bazlı titreşim yöntemlerini birleştirerek hem normal yönde, hem de teğetsel yönde dokunsal geribildirim sağlamaktadır. Bu tez, ilk yöntemi kullanarak yüzeyde, rüzgârın yönü gibi ek bilgi sunmayı araştırmıştır. Araştırmalarımızın sonucunda, kişilerin hem iki parmak arasında, hem

de ellerinin altında bir akıntının yönünü başarıyla tanıdığını bulduk. İkinci dokunsal teknolojiyi ise görsel bir düğmeye dokunsal geribildirim eklemek için kullandık. Nicel sonuçlarda düğmenin çevrilmesindeki görev başarısı artmasa da, nitel sonuçlarda kullanıcıların, dokunsal bildirimi olan düğmeleri, dokunsal bildirimi olmayana göre daha fazla tercih ettiklerini gözlemledik.



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TABLE OF CONTENTS

List of Tables	xiv
List of Figures	xvi
Nomenclature	xxiii
Chapter 1: Introduction	1
1.1 Problem Definition and Approach	1
1.2 Applications	3
1.3 Contribution	5
1.4 Outline	6
Chapter 2: Related Work	7
2.1 Tabletops with haptic modality	7
2.2 Surface displays with haptic modality	7
Chapter 3: Design of HapTable	10
3.1 Design considerations for HapTable	10
3.2 Design of HapTable	13
Chapter 4: Gesture Selection and Recognition for HapTable	16
4.1 A taxonomy of hand motions on two-dimensional surfaces	16
4.2 Selection and Recognition of Hand Gestures on HapTable	19
Chapter 5: HapTable : Hybrid Haptic Actuation	25

5.1	Haptic Feedback via Electromechanical Actuation using Piezoelectric Bending Actuators	26
5.1.1	Creating vibration map for HapTable	26
5.1.2	Creating localized vibrotactile haptic feedback on HapTable	28
5.2	Haptic Feedback via Electrostatic Actuation	33
Chapter 6:	User Studies	35
6.1	User Study I: Vibrotactile Flow	35
6.1.1	Experiment 1: Vibrotactile flow between two fingers	36
6.1.2	Vibrotactile Flow Under Hand	38
6.1.3	Understanding the effect of sound levels while actuating piezos	42
6.1.4	Discussion	47
6.2	User Study II: Haptic Knob	49
6.2.1	Experiment	49
6.2.2	Results	52
6.2.3	Discussion	56
Chapter 7:	Contributions and Future Directions	59
Appendix A:	Surface motion detection technologies	69
A.1	Surface motion detection technologies	69
A.2	Pressure-requiring technologies	69
A.2.1	Resistive touch	70
A.2.2	FlexiTouch	70
A.3	Capacitance-based technologies	71
A.3.1	Surface Capacitive Touch	72
A.3.2	Projected Capacitive Touch	72
A.4	Optics-based technologies	73
A.4.1	Infrared Touch Screens	73

A.4.2	Frustrated Total Internal Reflection	74
A.4.3	Rear Diffused Illumination	75
A.4.4	In-Cell Light-Sensing Touch	75
Appendix B:	Examples for Hand Motion Taxonomy	76
B.1	Examples for Hand Motion Taxonomy	76
Appendix C:	Parameters Used in the Human Studies	82
C.1	Parameters used in Flow Experiment	82
C.2	Parameters used in Knob Experiment	84
Appendix D:	Instructions Used in the Human Studies	85
D.1	User Instructions for Flow Experiment	85
D.1.1	User Instructions for Flow Experiment Between Two Fingers .	85
D.1.2	User Instructions for Flow Experiment Underneath Hand . . .	86
D.2	User Instructions for Knob Experiment	90
D.2.1	Instructions for Pilot and Actual Experiment	92
D.2.2	Instructions for Subjective Evaluation	93
Appendix E:	Questionnaires Used in the Human Studies	95
E.1	User background questionnaire for all experiments	95
E.2	Questionnaire used in Subjective Evaluation for Knob Study	96

LIST OF TABLES

3.1	Surface haptic technologies that may possibly be used to convey properties of objects that users interact with, as defined in [28].	11
3.2	This table presents the co-existence matrix of the actuation technology with the touch registration technology. Camera-based touch registration is compatible with considered actuation methods. For detailed overview of touch technologies and their coexistence with haptic technologies, please refer to Appendix A.1.	12
4.1	Confusion matrix for static gestures	23
4.2	Confusion matrix for dynamic gestures	24
6.1	The sound level when HapTable surface is actuated with signals used in “Vibrotactile flow under hand” user study in previous Section 6.1.2, along with the excitation frequencies.	44
B.1	Examples for relative (dynamic) hand motion categories	76
B.2	Examples for non-relative (static) hand motion categories	79
C.1	The distance between the test points for each pair, actuation frequencies (f_1, f_2), the piezo patches used for actuation (p_1, p_2), and the displacement differences between the test points ($\Delta d_1, \Delta d_2$) are given in the table on the right. The excitation voltage for each pair is $100V_{pp}$.	82
C.2	Actuation frequencies (f_1, f_2) and the piezo patches used for actuation (p_1, p_2) are given for the flow experiments using the hand region. The excitation voltage for each pair was adjusted by human sensitivity curve.	83

C.3 Haptic stimuli rules for four different sensory conditions tested in knob experiments. 84

E.1 The questionnaire displayed digitally on the table surface, along with the four knobs -one for each sensory condition. 96



LIST OF FIGURES

2.1	Related work with project names, component diagrams, and prototype photos: (a) Feelex [19], (b) MudPad [20], (c) TeslaTouch [2], and (d) Electrostatic tactile display with thin film slider [58].	9
3.1	(a) User performing a gesture on the proposed table to interact with a digital scene while receiving suitable haptic feedback. The hardware components of the proposed table are shown in (b) rear and (c) front views.	12
3.2	Schematic showing how voltage is transmitted to piezo patches for vibrotactile feedback, and to touch screen for electrostatic feedback. This design allows HapTable to send different stimulus to an individual or combination of piezo patches and to the electrostatic touch screen. . .	14
4.1	Taxonomy for hand gestures on two dimensional surfaces (number of hands/fingers used are applied to all categories under “ <i>Intention of Motion</i> ”)	18
4.2	Selected gestures for HapTable: (a) static (from left to right: 1-finger, 2-finger, L-shape, hand with closed and open fingers), and (b) dynamic (from left to right: dragging, rotation, spread/pile, wipe, zoom in/out) gestures.	20

4.3	The steps of rotating a hand pose according to a reference edge: (a) image frame obtained by the infrared camera is subtracted from the background, (b) a high-pass filter is applied to reveal parts contacting the table surface, (c) smallest circle enclosing the hand posture is found, (d) the wrist (red arc) and the center point of the hand (point c) are determined, (e) the angle (θ) that the wrist makes with the reference line (l_1) is estimated, and (f) the adjusted hand pose perpendicular to the reference edge is obtained.	21
4.4	Change in the dynamic gesture frames recognized by our system over time.	23
5.1	HapTable's system diagram for haptic actuation.	25
5.2	(a) The setup for vibration measurements: (1) Laser doppler vibrometer (LDV), (2) signal generator, (3) signal analyzer, and (4) tabletop surface. (b) The tabletop surface was divided into 84 equally-spaced grid points for measurements (7 rows by 12 columns. P_A , P_B , P_C , and P_D represent the piezo patches glued to the edges of the bottom side of tabletop surface.	27
5.3	Mean displacement FRFs of 84 measurement points on HapTable, for five excitation cases: patches P_A , P_B , P_C , and P_D are excited individually and together in a parallel configuration (P_{ALL}).	28
5.4	To create a flow from point L to R on the touch screen (a), the FRF graph of point R is subtracted from that of point L for the five excitation cases: when piezo-patches are excited individually and all together (b). The maximum and minimum differences in displacement are marked by orange and blue circles, respectively. A negative displacement difference occurs when point R has a higher displacement than that of point L.	29

5.5	Excitation lookup tables for HapTable: to create a vibrotactile flow from an “active” grid point to a “passive” one, our haptic rendering algorithm acquires maximum displacement difference in vibration amplitudes from table (a), the corresponding excitation frequency from table (b), and the actuator ID (i.e. which actuator to use to create that displacement difference at the corresponding excitation frequency) from table (c). The displacement at each grid point is higher than the human vibrotactile absolute threshold.	31
5.6	(a) To create a vibrotactile flow from left (L) to right (R), we first actuate the surface at a certain frequency such that the vibration amplitude of point L is significantly higher than that of the point R, and then actuate the surface at a different frequency such that the vibration amplitude of point R is significantly higher than that of the point L. Note that different piezo actuators could be used to play the voltage signals shown on the first (0–1.5 seconds) and second (1.5–3.0 seconds) parts in the figure.	32
6.1	(a) The locations of the test pairs selected for the familiarization (pair: F–F) and the actual experiment (pairs: 1–1, 2–2, 3–3, 4–4) sessions. (b) The distance between the test points for each pair, actuation frequencies (f_1, f_2) , the piezo patches used for actuation (p_1, p_2) , and the displacement differences between the test points $(\Delta d_1, \Delta d_2)$ are given in the table on the right. The excitation voltage for each pair is 100Vpp.	37

6.2	(a) The area under hand is divided into nine equal squares, $s(i, j)$ where i and j represent the column and row numbers. In the example shown above, the goal is to create a travelling vibrotactile flow from left to right. The active and passive squares shown in (b) and (e) are symmetric with respect to the vertical line, but (c) and (d) are not. Note that the line of symmetry is vertical (horizontal) for a horizontal (vertical) flow.	39
6.3	(a) First, a preliminary experiment was conducted at the region R_{prelim} and then the actual experiment was conducted in four different regions, R_1 , R_2 , R_3 , and R_4 . The size of each region was 12 by 12 cm. (b) Subjects were guided to align their hand position according to the hand image displayed on the screen. After the haptic stimulus was displayed, they were asked to determine the direction of vibrotactile flow by pressing one of the four arrow buttons on the screen.	41
6.4	Vibrotactile flow under hand: a) percentage of correct responses for each direction, b) percentage of correct responses for each region in the second experiment. The bars represent the mean values while deviations are the standard error of means.	42
6.5	Evolution of vibration maps for vibrotactile flow under the hand: a) left-right direction at R_3 recognized with 95.5% accuracy (SD=6.6%). The first and second parts of the input voltage signal successfully create localized vibrations on the left and right sides of the hand sequentially, resulting in high accuracy in the subjects' perception of flow direction. b) left-right direction at R_4 recognized with 66.4% accuracy (SD=17.7%). The first part of the signal vibrates the bottom left and right sides of the hand region at the same time, causing a possible confusion in subject's perception of the direction of flow.	43

6.6	(a) The sound level on tabletop surface when all piezos actuators are actuated at different amplitudes, between 0 and 100 Vpp. (b) The sound level on tabletop surface when all four piezo actuators are actuated at 100Vpp, at frequencies between 100 and 625 Hz. Corresponding familiar noise sources for dB levels is marked with dashed lines and labeled [50, 7].	46
6.7	Average and standard deviations of responses from all seven subjects, given in 5-point Likert scale for five dimensions : (a) softness, (b) pleasantness, (c) comfort, (d) noise, and (e) disgust for left-right (L-R) and up-down (U-D) flow directions in four regions (R_1 , R_2 , R_3 , and R_4). Adjectives corresponding to scores one and five given on y-axis, next to the relevant score. Signals presented are the same signals used in vibrotactile flow experiment, under hand.	47
6.8	(a) A knob with eight sectors where each sector is mapped to an item on the menu. In our experiments, subjects navigate on the menu under four different sensory conditions: 1) virtual (no artificial haptic feedback), 2) haptic detent at sector crossings (b), 3) haptic detent and constant friction (c), and 4) haptic detent and velocity-based friction (d). The input voltage for each sensory condition is 100Vpp.	51
6.9	(a) A knob with eight sectors used in the actual experiments, and the menu is shown on the left, (b) user interface for the subjective evaluation phase.	53
6.10	Means and standard errors of the subjective measures for each sensory condition (* The mean difference is significant at $p=0.05$ level). . . .	57

A.1	Resistive touch screen technology consists of two conductive layers, with an insulating gap with spacers in between. When user applies pressure, the two conductive layers become closer and produce a change in the capacitance value. By looking at this value, these screens can detect a finger press.	70
A.2	Output of a FlexiForce pressure mapping system for a hand press. Colors indicate the amount of pressure.	71
A.3	Layers of a surface-capacitive screen.	72
A.4	Matrix infrared touch screen: (a)structure, (b)hand occluding light for detection, and (c)object in contact perceived by controller.	74
D.1	(a) One of the four flow directions will take place underneath your hand: Left to right, right to left, down to up, and up to down as shown with arrows. (b) Hand image changes for each task, indicating whether you should place your left or right hand.	87
D.2	Screenshot of the experiment at a given time : (a) System will present you a designated location to place your hand. Once you place your hand, system will recognize it and actuate the screen. Once the signal is finished, it will switch to the screen in (b). It will provide you four arrow buttons to select the direction from, and the replay button. . .	88
D.3	Screenshots of the experiment user interface at two stages : (a) Before starting rotation : The menu with city names is shown on the left. Blue box indicates the start city, and the red-colored text indicates the end city. The task is to go from start to end city using the knob at the center. If you are left handed, please ask the experimenter to switch the locations for knob and the menu. (b) After completing the task: "target found!" will appear along with a "Next" button. Please press "Next" to proceed to the next trial.	91

D.4	Experimenter showing the rotation gesture.	93
D.5	(a) Screenshot of the experiment at a given time : On left, you can see four different knobs. You can repeat the task as many times as you want, with any knob shown before your final decision. (b) Each knob with each condition has a button to answer presented question using 7-point Likert scale. In this scale, 1 means "not at all", and 7 means "very much".	94

NOMENCLATURE

ANOVA	Analysis of variance
SD	Standard deviation
SEM	Standard error of means
IR	Infrared
LED	Light-emitting diodes
FRF	Frequency Response Function
P_x	Piezo actuator named ‘x’
P_{ALL}	All piezo actuators
LR	Left to right
RL	Right to left
UD	Up to down
DU	Down to up
R_x	Region with number ‘x’
V	Visual display only
HD	Haptic detent
HD+CF	Haptic detent with constant friction
HD+VF	Haptic detent with velocity-based friction
MR	Magnetorheological
n/a	Not applicable

Chapter 1

INTRODUCTION

The research presented in this dissertation aims to provide augmented touch screen displays that combines haptic, audio, and visual feedback. In particular, we discuss the design of a large multimodal tabletop that enables users to interact with digital content through natural hand gestures while providing appropriate visual and haptic feedback and present user studies to explore possible tactile signals to augment the interaction and the impact of these signals on the interaction.

1.1 Problem Definition and Approach

Invented more than a century ago, computers have been an essential aid to humans in a variety of complex tasks. Since the early days, humans have been specially trained to learn how to execute tasks on computers due to their complexity. With computerized systems becoming widely available, there have been advancements to provide a more natural human-computer interface to make task execution easier for novices. For example, until recently, the main input methods to computerized systems were indirect; such as a keyboard and a mouse. With the introduction of smartphones, tablets, and interactive tabletops, our interaction with computers is switching from using indirect to direct inputs. These systems allow users to manipulate the digital content on screen through touch gestures. Instantaneous visual feedback in response to these gestures allows users to couple the gestural input with the direct graphical output. Although these systems eliminate the requirement of an additional device (such as a mouse and a keyboard) for interaction, they lack the tactility that these devices provide. Consequently, touch screens require full visual attention of the user

and this results in fatigue and deterioration in task performance [48].

Tactile response during an interaction is known to require less visual attention, to improve task performance and the realism of the interaction [59]. There has been ongoing efforts to implement haptic technologies to provide tactility for human-computer interactions. Earliest efforts mainly focused on shape-changing surfaces, such as Feelex [19]. Feelex had an array of 36 linear actuators on a tabletop, each moving individually in vertical direction to create the surface contour of a digital image, projected on a flexible surface placed on the actuators. Follmer et al. developed inFORM [10], which uses 900 motorized pins to actuate a hundred and fifty boards moving up and down to render dynamic shapes on a surface. Shape-changing technologies focus on contour information of objects, and they are very large in size and costly to manufacture.

Touch surfaces can also provide tactile feedback through electromechanical and electrostatic actuation. Electromechanical actuation technologies provide tactility through creating physical displacement on the interaction surface. Poupyrev et al. attached four piezo-bending actuators to the corners of a touch display to provide haptic feedback to users while using a single stylus input [36]. Authors created tactile signals for clicks, sliders, and pencil textures. Their study showed that click-and-drag can be significantly improved by texture feedback for small targets. Bau et al. modified a touch screen to provide electrostatic haptic feedback to the users [2]. In order to create electrostatic actuation, conductive layer of the touch screen is excited by a voltage. This applied voltage creates an electrostatic force between user's finger and the display surface. By modulating this voltage, different tactile effects can be created at the user's fingertip without physically moving the display surface.

In our daily lives, we receive multiple different tactile feelings to understand an interaction or an object. Lederer et al. that we explore objects through different gestures, and we receive a different haptic information through these gestures [28]. For example, we apply lateral motion to understand surface texture. We follow the contour to understand the global shape of the object, and to understand the temperature, we

stay in static contact with the object for a while. Haptic technologies proposed so far can only provide feedback to one of the attributes of the objects. For example, we can use shape-changing surfaces to understand the global shape of the object, but they cannot provide information on the surface texture. Electromechanical actuation can provide information on the object function (i.e. button clicking), but it cannot inform us on the surface texture. On the other hand, electrostatic actuation can provide surface texture, but since it cannot physically displace a surface, it cannot provide on the object function. Therefore, we need to combine multiple haptic technologies to provide rich set of haptic feedback for different human-computer interactions.

Another important factor in human-computer interaction is the timeliness and the appropriateness of the feedback. Currently, users receive visual feedback as they gesture on touch screens. For example, while performing pinch gesture, as user moves their fingers far from each other, the pictures zooms in at the same rate. Receiving this timely visual feedback allows users to understand what the gesture does, and how far they are with the gesture so that they can stop at any point. The same applies to haptic modality. Receiving the appropriate and timely haptic feedback could potentially allow users to control their input with respect to the feedback received, resulting in improved task accuracy. Haptic feedback can also add realism to the interaction.

In order to provide real-time suitable haptic feedback for touch gestures, we designed and built HapTable -a touch-based interactive tabletop display that incorporates electromechanical and electrostatic haptic feedback. Using this hybrid actuation approach, HapTable can display a variety of haptic feedback from simple frictional effects to more complex localized vibrotactile flow effects. We demonstrated that HapTable can provide vibrotactile flow effect underneath a hand using electromechanical actuation, and electromechanical haptic feedback to create knob detents.

1.2 Applications

We believe that adding a rich variety of real-time haptic feedback to current touch-based interaction surfaces has potential to provide benefits in following areas:

- *education*: Students can use HapTable collaboratively, and receive feedback while collaborating. Through haptic feedback and touch-based interaction, HapTable could provide a more immersive environment for students. For example, while students are learning about planets, electromechanical haptic feedback could provide the direction that each planet rotates around itself. For example, Uranus rotates clockwise on its side, whereas Earth rotates counter-clockwise around its vertical axis.
- *aiding visual input*: In climate visualization, users are visually overloaded with multiple layers of different information [59]. With Haptable, users can place their hand(s) on the tabletop surface to feel the direction and the strength of the wind forces. Similarly, this technology can be applied to online shopping, where users could feel the texture of a cloth, or the material of an object.
- *gaming*: HapTable could increase the realism of the games, and help gamers to understand the current state of the game. For example, if the gamer is trying to adjust slingshot to hit a target, HapTable can provide how much the rubber is stretched. In case of a car driving game, HapTable could provide the texture of the road to the user for a more realistic experience.
- *digital controls*: Visual displays have digital controls such as sliders and knobs. For example, feeling the detents on these controls could provide users more confidence and precision while using them.
- *providing confirmation*: Since HapTable creates localized physical displacement, it can provide localized click feelings to confirm an interaction.
- *aiding training simulations*: For example, HapTable could use real-time haptic feedback to communicate the state of the plane to the pilots in a training simulation. With the appropriate and real-time feedback, pilots can correct their course accordingly.

- *haptic research*: HapTable provides a sandbox for future research on testing appropriate feedback and how to combine multiple haptic technologies to enhance the touch interaction.

1.3 Contribution

To our knowledge, HapTable is the first interactive multitouch tabletop that provides real-time hybrid haptic feedback for touch-based interactions. HapTable incorporates a camera-based gesture recognition hardware and software, and currently, it can recognize five static and five dynamic gestures. In response to these gestures and the object that the user is interacting with, HapTable could provide real-time haptic feedback accordingly using its hybrid actuation technique. The design of HapTable is explained in depth in Chapter 3. Using this design, developers can create feedback using any combination of piezoelectric bending actuators and electrostatic feedback.

In our studies, we proposed a novel approach to create localized haptic feedback at any point on HapTable using four piezo-bending actuators. Adding additional constraints on this approach, HapTable was able to provide traveling directional flow effect underneath a hand. Our user studies concluded that users are able to identify the direction of the flow with 90% accuracy. This could have many applications in current touch interactions.

Using HapTable, we designed three different haptic stimuli for a virtual knob using electrostatic actuation. We investigated the benefits of frictional haptic feedback on task performance and user experience. HapTable recognized the rotation gesture, tracked individual fingers, and provided haptic feedback to the participants as they are performing the gesture. We provided four haptic feedback configurations to the participants for testing (no haptic feedback, haptic detents, haptic detents with constant texture, haptic detents with velocity-controlled texture). In terms of task performance, we did not see a significant difference between providing or not providing haptic feedback. However, a qualitative questionnaire showed that participants felt that they were significantly more effective and accurate with the presence of

haptic feedback. Participants also agreed that the interaction quality was increased with haptic feedback, and that they would prefer interfaces with haptic feedback to the ones without. Haptic feedback also allowed users to feel more confidence while completing the task.

1.4 Outline

This dissertation is organized as follows: In Chapter 2, we present an extensive summary of the related work on visual displays with haptic feedback, and current haptic technologies. Following chapter, Chapter 3, discusses the detailed hardware design of our tabletop along with the design considerations and co-existence of components. Chapter 4 outlines the software system diagram and simple gesture recognition algorithm used in HapTable. Chapter 5 focuses on hybrid haptic technology in HapTable, and the user experiments associated with each technology. Section 5.1 provides the vibration map and the process of creating localized vibrational haptic feedback on HapTable, and Section 5.2 elaborates on electrostatic actuation technology. Related user studies, the protocols and results along with detailed discussion are presented in Chapter 6. Chapter 7 elaborates on the results, and the last chapter, (Chapter 7), concludes this thesis by revisiting our contributions and providing a discussion on possible applications and future directions.

Chapter 2

RELATED WORK

In this chapter, we present related work on tabletop and surface displays that has integrated haptics as an additional modality, and a background on these haptic technologies.

2.1 *Tabletops with haptic modality*

There is an ongoing effort in the research community for adding haptic feedback to interactive tabletops and surface displays. One such effort authors used in [19] is shape-changing surfaces. FEELEX is made of an array of 36 linear actuators, each moving individually in vertical direction to project the surface contour of a digital image on a flexible surface [19]. Lumen is an array of movable light guides whose height and color can be controlled individually to create images, shapes and physical motions [37]. The motion of each light guide is controlled by a string, made of shape memory alloy (SMA), attached to the guide. More recently, Follmer et al. [10] developed inFORM, which enables dynamic affordances, constraints and actuation of passive objects. This system utilizes 900 motorized pins (30×30) to actuate 150 boards moving up and down to render dynamic shapes on the surface. Haptic feedback is displayed to the user by adjusting the stiffnesses of pins via a PID control. As stated by the authors, shape-changing displays are currently not practical due to their large size and cost of manufacturing.

2.2 *Surface displays with haptic modality*

Another common line of effort for displaying haptic feedback through a touch surface is to utilize electromechanical or electrostatic actuation. Poupyrev et al. attached

four piezo actuators to the corners of a pen-based touch display, in between the LCD and the protective glass panel, to convey vibrotactile haptic feedback to users by varying amplitude and frequency of input signal [36]. The results of their user study showed that the subjects preferred haptic feedback when it was combined with an active gesture, such as dragging a slider or highlighting text using the pen interface.

Jansen et al. developed MudPad, a device that uses magnetorheological fluid combined with small electromagnets placed under the display surface [20]. The fluid's physical properties are altered using electromagnets, thus the frictional properties of the surface are controlled to provide active tactile feedback to the user. Due to the electromagnets under the surface, this system is not compact and requires visual projection from the top. Bau et al. presented TeslaTouch, a capacitive touch screen utilizing electrostatic actuation [2]. The device controls the attractive electrostatic force between user finger and display surface by modulating the voltage applied to the conductive layer of the screen. Yamamoto et al. also used the same principle earlier in a tactile telepresentation system to realize explorations of remote surface textures with real-time tactile feedback to the user [58].

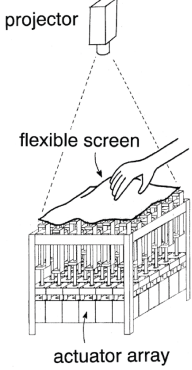
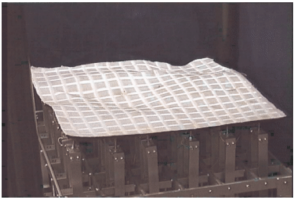
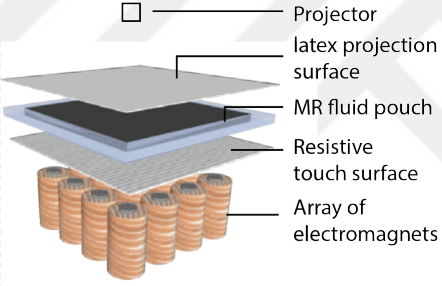
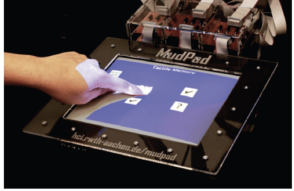
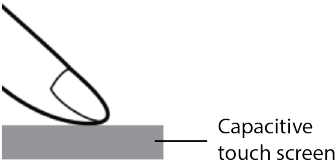
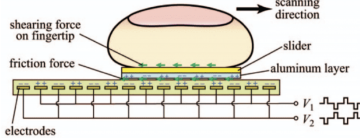
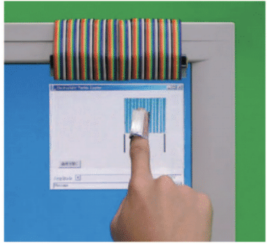
	Project	Components	Prototype
(a)	Feelex	 projector flexible screen actuator array	
(b)	MudPad	 Projector latex projection surface MR fluid pouch Resistive touch surface Array of electromagnets	
(c)	TeslaTouch	 Capacitive touch screen	
(d)	Electrostatic Tactile Display with Thin Film Slider	 shearing force on fingertip friction force scanning direction slider aluminum layer electrodes V_1 V_2	

Figure 2.1: Related work with project names, component diagrams, and prototype photos: (a) Feelex [19], (b) MudPad [20], (c) TeslaTouch [2], and (d) Electrostatic tactile display with thin film slider [58].

Chapter 3

DESIGN OF HAPTABLE

In this chapter, we will discuss our goal while designing HapTable and the rationale behind the selection of integrated hardware components.

3.1 Design considerations for HapTable

In real life, we interact with our environment by relying mostly on our touch and visual sensors. When we see an object, our visual sensory system tells us the color of the object, its physical distance to us, and a guess for its texture depending on its color texture. To understand more of the object's properties, we perform different hand gestures to get information through our haptic sensory system. We stroke our hand on it to understand its temperature and surface texture. We squeeze or dent it to understand how soft its material is. We stroke our hand to understand its three-dimensional shape. We follow its edges to understand its shape, as well as the sharpness of its edges. We hold it in our hand to understand its weight. If the object is moving, we can touch it to understand its motion -how fast it is moving, which way it is moving towards [28].

In real life, our haptic sensory system receives a wide range of unique information about our interaction that cannot be conveyed through other sensory systems. Haptic sensory system creates a loop of events where we perform a gesture, receive haptic and visual feedback, and adjust our action accordingly to successfully complete our task.

Object Property	Exploratory Procedure	Haptic Technology					
		Ultrasonic actuation	Mechanical vibration	Electrostatic actuation	Microfluids/ Shape-shifting	Electrocutaneous actuation	Peltier elements
Texture	Lateral motion	✓	✓	✓	✓	✓	✗
Hardness	Pressure	✓	✗	✗	✓	✗	✗
Temperature	Static contact	✗	✗	✗	✗	✗	✓
Weight	Unsupported holding	✗	✗	✗	✗	✗	✗
	Dragging/Pushing	✗	✗	✓	✗	✗	✗
Global Shape	Enclosure	✓	✓	✓	✓	✗	✗
	Contour-following	✓	✓	✓	✓	✗	✗
Motion	Static contact	✓	✓	✗	✓	✓	✗
	Motion Test	✗	✗	✗	✗	✗	✗

Table 3.1: Surface haptic technologies that may possibly be used to convey properties of objects that users interact with, as defined in [28].

	Resistive touch	Ultrasonic touch	Capacitive touch	Camera-based touch
Mechanical vibration	✓	✓	✓	✓
Ultrasonic vibration	✗	✗	✓	✓
Micro-fluids	✗	✗	✗	✓
Electrostatic	✓	✓	✗	✓

Table 3.2: This table presents the co-existence matrix of the actuation technology with the touch registration technology. Camera-based touch registration is compatible with considered actuation methods. For detailed overview of touch technologies and their coexistence with haptic technologies, please refer to Appendix A.1.

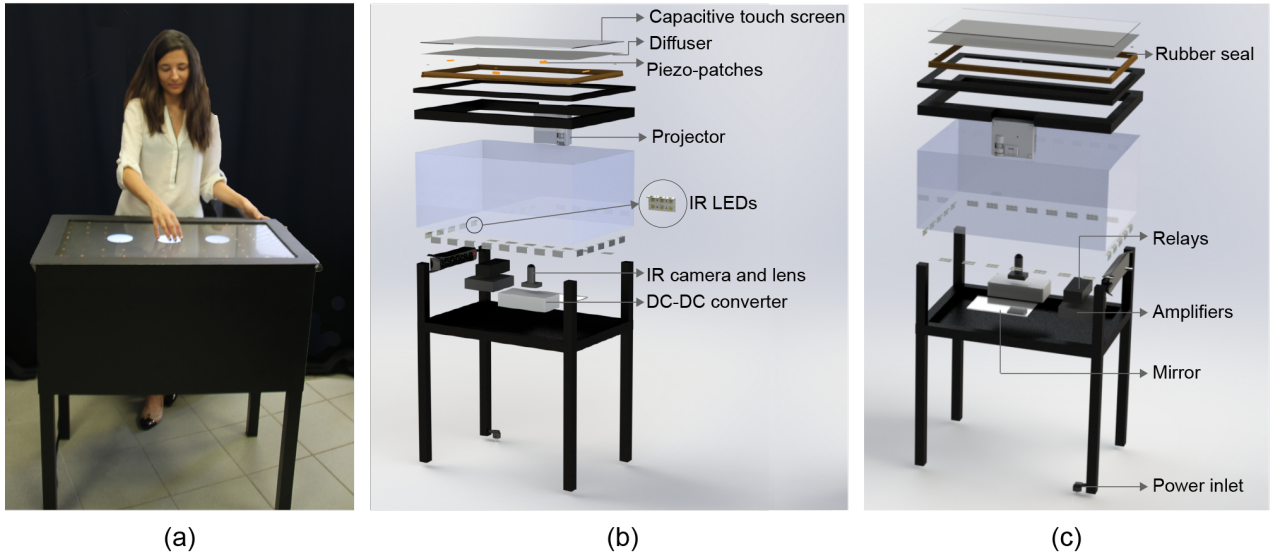


Figure 3.1: (a) User performing a gesture on the proposed table to interact with a digital scene while receiving suitable haptic feedback. The hardware components of the proposed table are shown in (b) rear and (c) front views.

3.2 Design of HapTable

HapTable is an interactive tabletop of dimensions $85 \times 55 \times 75$ cm (width $\times$ length $\times$ height). HapTable system consists of three main modules: gesture detection, visual display, and haptic feedback (Fig. 3.1).

Gesture detection module is responsible for registering and detecting high resolution images of static and dynamic hand gestures performed on HapTable surface. Although there are touch surfaces commercially available in the market for detecting finger and/or hand gestures, they may potentially interfere with our haptic feedback module and may not capture hand contour in sufficient detail for correct recognition of hand gestures. We carefully reviewed available touch technologies (please see detailed review in Appendix A.1). For example, piezo actuators used to generate vibrotactile haptic effects in HapTable may interfere with the travelling sound waves utilized in surface acoustic touch sensors. Similarly, infrared touch frames have occlusion problems and are not good at detecting hand contour. For these reasons, HapTable uses rear diffused illumination (Rear DI) to register hand poses [33]. The tabletop surface is evenly illuminated with wide-angle infrared LEDs (50-Module IR Kit, Environmental Lights) in three-row configuration: top row is placed parallel to the table surface to illuminate its edges, whereas the remaining two rows are perpendicular to the first row to illuminate the surface center (Fig. 3.1b). When a user touches the HapTable surface, light is reflected from contact points and captured by an infrared camera (Eye 3, PlayStation). This camera captures 60 frames per second with a resolution of 640×480 pixels. The visual display of digital images on the tabletop surface is achieved by a projector (B1M, Asus). We selected this projector specifically because it does not emit infrared light that may interfere with gesture detection module, and it has a short throw distance that allows minimal table depth. The throw distance is extended by using an additional mirror (Fig. 3.1c), allowing users to interact with HapTable even in a sitting position. The haptic feedback module integrates electromechanical and electrostatic actuation techniques to display a wide range of haptic effects while users interact with digital images and objects through static and dynamic gestures.

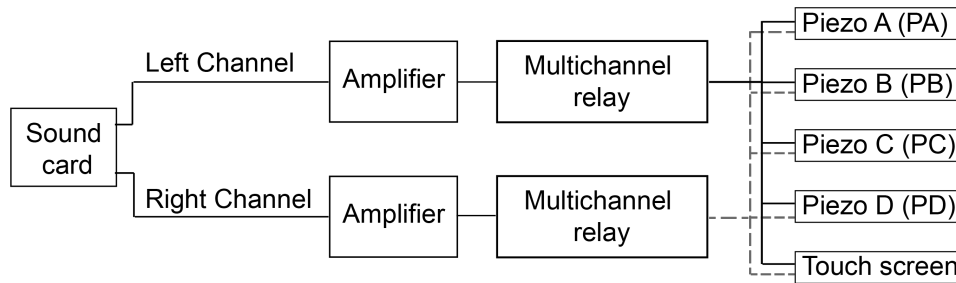


Figure 3.2: Schematic showing how voltage is transmitted to piezo patches for vibrotactile feedback, and to touch screen for electrostatic feedback. This design allows HapTable to send different stimulus to an individual or combination of piezo patches and to the electrostatic touch screen.

These two actuation techniques complement each other. For static gestures, HapTable displays vibrotactile haptic feedback to the user. Four piezoelectric patches (PI-876.A 12, Physik Instrumente, 61 x 35 x 0.5mm) are glued beneath the touch surface to generate mechanical vibrations on the surface. The propagation of the vibrations from the touch surface to the table itself is isolated through rubber seals placed under the tabletop surface (Fig. 3.1c). We utilize electrostatic haptic feedback for dynamic gestures. This technology does not use any form of mechanical actuation but tactile sensations can be created by controlling frictional forces between the tabletop surface and the user's fingers. In order to generate friction on the surface based on electrostatic actuation, a large surface capacitive screen (SCT-3250, 3M, 743.46 x 447.29 x 3.18mm) is used as the touch surface of the table. When a periodic voltage is applied to the conductive layer of the screen, normally used for sensing the finger position, an attractive electrostatic force develops between the finger skin and the touch screen in the normal direction. This electrostatic force is small and cannot be sensed directly by the finger while it is stationary on the surface. However, if the finger slides on the surface of the touch screen, a resistive frictional force is felt by the user in tangential direction.

To control the voltage transmitted to the piezo patches for vibrotactile haptic

feedback and also to the touch screen for electrovibration independently; a sound card, two high-voltage amplifiers (E413.D2, Physik Instrumente, Gain: 50), and two solid state relay arrays (Yocto-MaxiCoupler, Yoctopuce) are used (Fig. 3.2). The haptic signals generated by the left and right output channels of the sound card of a personal computer (PC) are first transmitted to the high-voltage amplifiers. Each amplifier's positive output is connected to a multichannel solid-state relay array, controlled and powered by the USB ports of the PC. This relay is fast, can switch voltages up to 350 Vpp for small loads of current (up to 100 mA), and does not require any external power. The outputs of these relays are connected to each piezo patch and the touch screen, as shown in Fig. 3.2. This architecture enables us to excite any number of patches and the touch screen simultaneously. However, we can only apply independent voltage signals to at most one piezo patch and the touch screen since the sound card has only two output channels.

Chapter 4

GESTURE SELECTION AND RECOGNITION FOR HAPTABLE

In order to interact with HapTable, we aimed to use gestures that are natural to the users while interacting with digital content on HapTable. As a first step to create a gesture set for HapTable, we created a taxonomy of hand motions that can be performed on two-dimensional surfaces. We omitted the third dimension, because HapTable incorporates surface haptics that can only be felt while user is in-contact with the tabletop surface. Then, we selected a total of ten gestures to be recognized on HapTable to provide haptic experiences to users. In this chapter, first section elaborates on the hand motion taxonomy, and the second section gives a detailed explanation on selection and recognition of ten gestures.

4.1 A taxonomy of hand motions on two-dimensional surfaces

There exist taxonomies regarding classification of hand gestures. However, these taxonomies include hand grasping motions and motions involving an object. Our taxonomy aims to categorize natural hand motions on a two-dimensional surface without an object.

In [4], Bullock and Dollar presented taxonomy on human manipulation behavior with respect to an object. This taxonomy classifies manipulation motions according to contact with the object, motion of the hand, and presence of object grasping. However, surface interactions differ greatly from this taxonomy since object involvement and hand grasping is not included. In [28], Lederman and Klatzky classify exploratory hand motions, giving a mapping between hand motion and the object property that is being explored. However, this taxonomy does not cover all interac-

tive hand motions. In [6], empty-handed gestures are classified as semiotic, epistemic and ergotic. Semiotic gestures are gestures that convey meaningful information to the correspondent. Ergotic gestures are gestures that manipulate the environment. Lastly, epistemic gestures are the object interactions from which we learn the environment. Further classifications have been applied to this taxonomy by other researches. However, these taxonomies lack the physical requirements of hand motions.

In [5], easily recognizable tabletop motions have been assigned to tabletop motions. However, our work differs in the sense that it aims to provide natural motions as we do in our daily lives. Therefore, we focus on how we perform hand motions normally when we try to convey the meaning of a motion verb, instead of assigning motions to verbs.

In [3], taxonomy for force-feedback haptic devices has been proposed. This paper classifies disassembly tasks according to their requirement for fine motor control, significant arm strength, tactile friction, cooperative two-handed tasks, braced two-handed tasks, manipulation of a deformable object, tool-assisted tasks, and multiple finger tasks. However, this taxonomy is specific to force-feedback devices and does not cover all hand motions.

We classified hand motions based on three criteria: presence of relative movement with respect to the surface, motion intention (manipulative, exploratory, and gestural), and number of hands and fingers involved in performing motions. All the hand gestures in this classification given in Fig. 4.1 require user hands to stay in-contact with the surface because the haptic technologies considered gives haptic feedback on the surface.

First classification of hand motions divides the set by examining whether the gesture requires relative motion or not. Then, these classes further classified according to the intention of the motion –manipulative, exploratory, or gestural. Then, we classify gestures in each category according to the hand movement defining the gesture. In order to avoid extensive categories in taxonomy, the further divisions are given along with the examples.

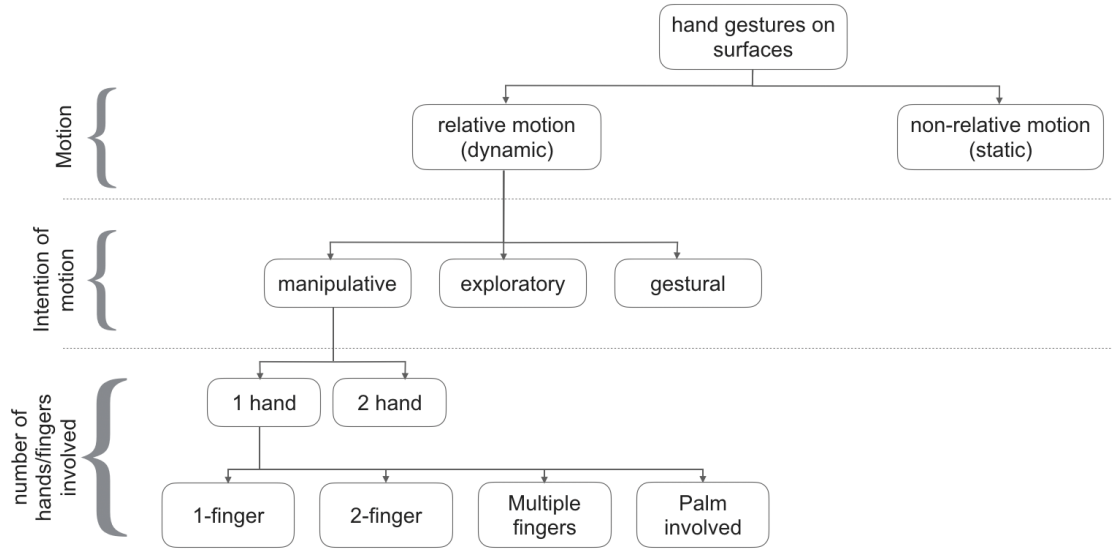


Figure 4.1: Taxonomy for hand gestures on two dimensional surfaces (number of hands/fingers used are applied to all categories under “*Intention of Motion*”)

At the second level of classification, the relative and non-relative hand motions are classified according to the intention of the user motion as manipulative, exploratory, and gestural:

- *Manipulative gestures* change the properties of an object, such as their size, shape, placement and orientation. For example, users may smudge paint on a paper and change a physical object from one state to another. These gestures may also change how we view the environment. While we are exploring a room, we may change the angle and the placement of the camera that we see the room through.
- *Exploratory motions* are made in order to understand the object and the environment. [29] defined six gestures to explore the following object properties: texture, hardness, global shape, exact shape, volume, function, weight, temperature. Environment, for example a windy weather, can be explored simply by keeping our hand stable.

- *Gestural motions* are made in order to convey a meaningful message to the corresponding computer. These motions may mimic their real-life correspondences, or may be preset by the application developer for the ease of gesture recognition.

To clarify the scope of each category, we supply practical examples of associated hand motions. A list of words for each category is given along with the examples in order to assist hand-surface interaction designers in future applications. Furthermore, to assist interface designers in finding suitable hand gestures for various tasks, we provide a detailed mapping between motion verbs (e.g., squeezing, stretching, moving) and hand motion categories (manipulative, 2-hand, 1-finger gesture).

4.2 Selection and Recognition of Hand Gestures on HapTable

The suggested taxonomy in previous section serves as a useful foundation to guide research in registration, recognition, and haptic feedback creation in hand-surface interactions. To start to build HapTable and appropriate haptic feedback, we selected five static and five dynamic gestures from our taxonomy. These selected gestures are shown in 4.2. For example, gesture hand with closed fingers is a static, exploratory, palm-involved motion. It can be used to explore the speed or direction of the wind. Gesture zoom in/out is a dynamic, gestural 2-finger motion. It can be used to zoom in on a map, or a picture for detailed view.

An important feature of HapTable is the real-time recognition of hand gestures performed on its touch surface. In general, hand gestures performed on touch surfaces can be classified as: (a) static and (b) dynamic. In static gestures (e.g. pressing a button, pointing an object), the hand has fixed position and orientation, while in dynamic gestures (e.g. dragging a folder, rotating a virtual knob), it has time-varying position and orientation. In [35], authors differentiate static gestures from dynamic ones by examining the positional change of hand pose for a specific time window. If its position does not change in time, then the gesture is classified as static. However, this algorithm recognizes the trajectory of hand gesture, rather than

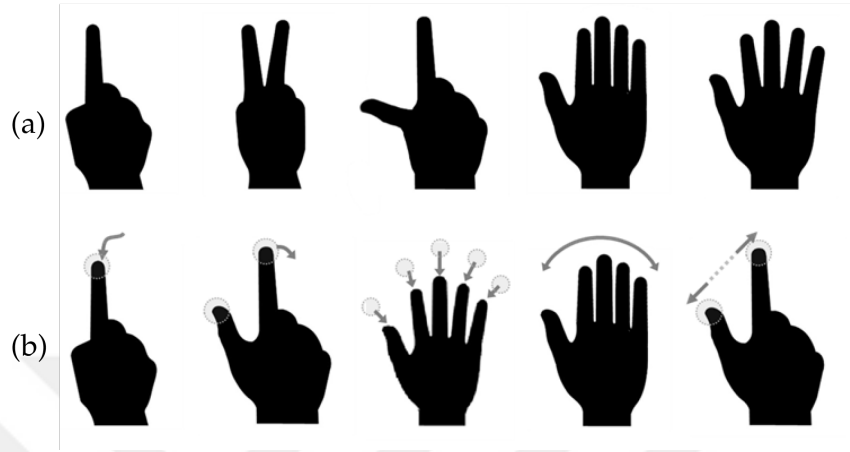


Figure 4.2: Selected gestures for HapTable: (a) static (from left to right: 1-finger, 2-finger, L-shape, hand with closed and open fingers), and (b) dynamic (from left to right: dragging, rotation, spread/pile, wipe, zoom in/out) gestures.

hand contour. Authors in [41] examine the hand shape and recognize a gesture in 1.5 seconds using Self-Growing and Self-Organized Neural Gas (SGONG) algorithm. However, this duration is long and not feasible for real-time haptic interactions on our table. According to [44], users expect a response in less than 20 milliseconds in interactive systems. Hence, to provide real-time haptic feedback for a gesture, our system has to recognize the gesture at its early stage of evolution. For this reason, it is crucial for us to select simple but discriminative features for gesture recognition. Since the user can make gestures anywhere on the table, the selected features should also be independent of translation, orientation, and hand size. We developed a simple yet efficient algorithm that can recognize five preselected static (Fig. 4.2a) and five dynamic hand gestures (Fig. 4.2b). The first step in our algorithm is to decide if a gesture is static or dynamic based on the change in position and orientation of the hand. Then, the camera images are sent to the relevant classifier accordingly for further processing.

If a hand gesture is static, it is rotated into a canonical orientation with respect to a reference edge and wrist is removed from the pose since users can approach the table

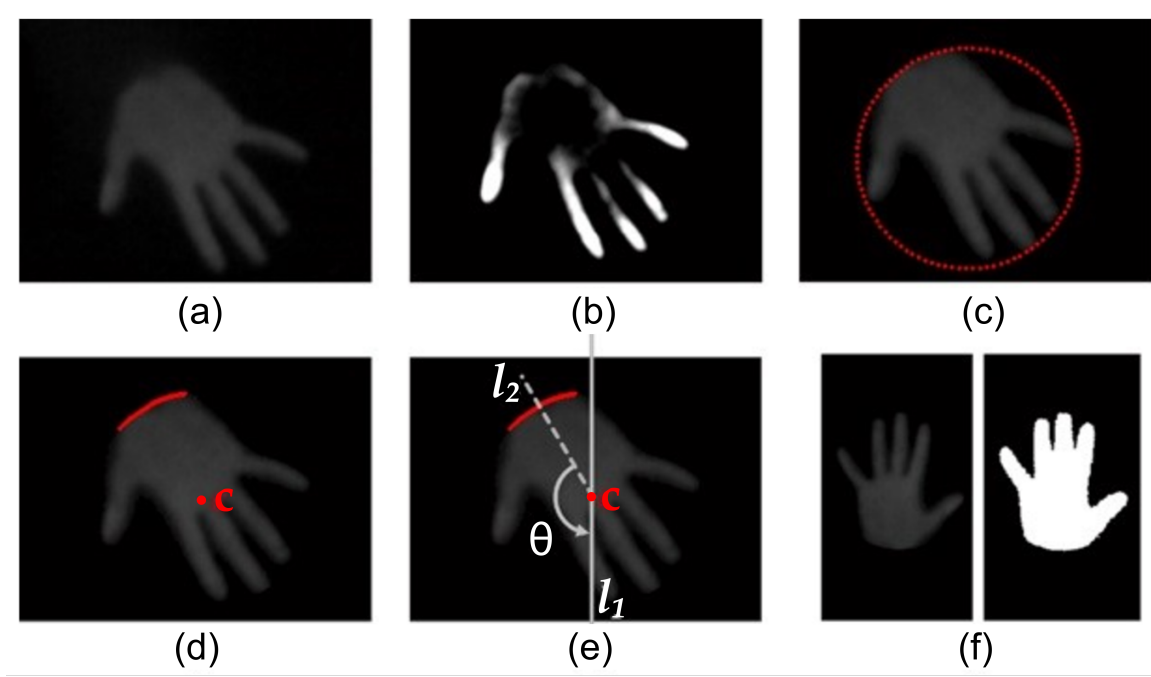


Figure 4.3: The steps of rotating a hand pose according to a reference edge: (a) image frame obtained by the infrared camera is subtracted from the background, (b) a high-pass filter is applied to reveal parts contacting the table surface, (c) smallest circle enclosing the hand posture is found, (d) the wrist (red arc) and the center point of the hand (point c) are determined, (e) the angle (θ) that the wrist makes with the reference line (l_1) is estimated, and (f) the adjusted hand pose perpendicular to the reference edge is obtained.

from any side (Fig. 4.3). Aligning a hand pose with respect to the reference edge is achieved as follows: we first apply a high-pass filter to the raw image in order to highlight the parts that are in contact with the table (Fig. 4.3b). Then, the smallest circle enclosing the highlighted hand (bounding circle) is calculated (Fig. 4.3c). The arc intersecting the bounding circle is defined as the wrist as shown in Fig. 4.3d. To rotate the hand and make it perpendicular to the reference edge, the angle θ between this reference edge (l_1 , Fig. 4e) and the line connecting the midpoint of the wrist to the center of the bounding circle (l_2) is calculated. If the hand pose is rotated by an angle of θ degrees in counter-clockwise direction about the center point (marked with letter c in Fig. 4.3e), then it becomes perpendicular to the reference edge as shown in Fig. 4.3f. Then, the silhouette of the hand posture is recognized via Fourier descriptors [27] using Support Vector Machine [8].

Compared to a static hand gesture, we need to recognize a dynamic hand gesture at its early stage of evolution to provide the user with haptic feedback immediately and also continuously track its pose to adjust the haptic feedback accordingly. You can see the evolution of dynamic gestures in Fig. 4.4. For this reason, our algorithm utilizes the first four frames of a dynamic gesture for feature extraction. In addition to Fourier descriptors, the number of contact points for fingers and their trajectory are also used as discriminating features to classify the dynamic gestures.

The gesture evaluation experiments were conducted with 5 subjects (2 males and 3 females). A sketch for each gesture was presented to the subjects, and they were asked to repeat this gesture 40 times in different pre-selected random positions and orientations on touch surface. Hence, the total number of gestures performed on the tabletop surface was 2000 (5 subjects x 10 gestures x 40 repetitions). We trained and tested our recognition algorithm using two-fold cross validation approach, and results are shown in Table 4.1 and 4.2. Recognition rates of 98 and 91 percent were achieved for static and dynamic gestures, respectively, without compromising the responsiveness of the system.

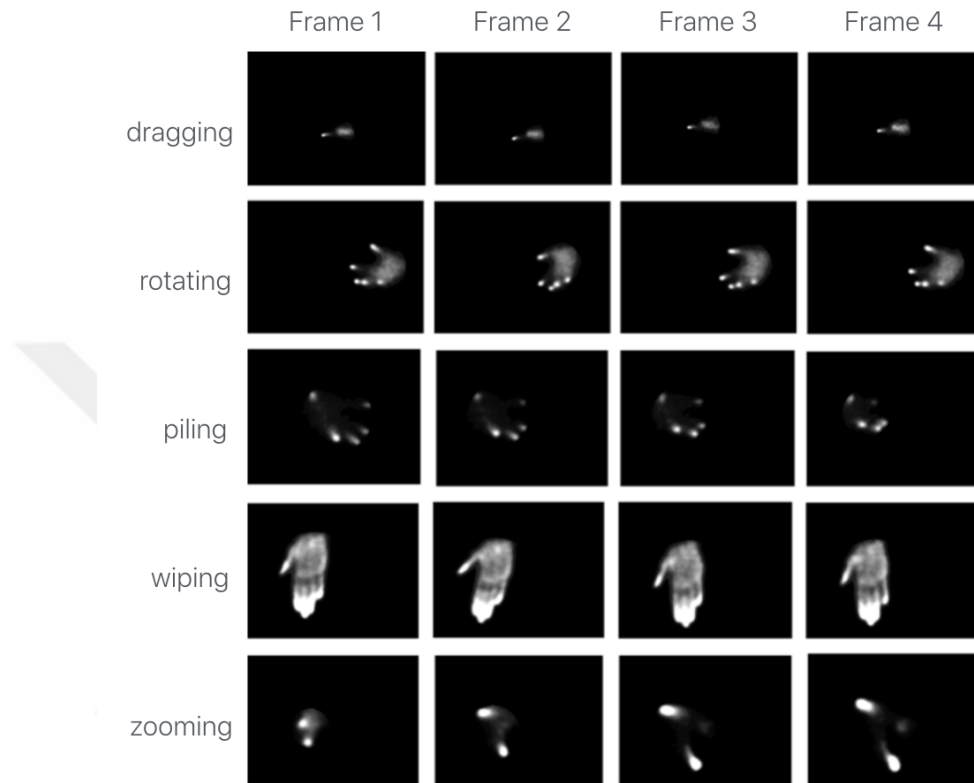


Figure 4.4: Change in the dynamic gesture frames recognized by our system over time.

Static Gestures (predicted)	Static Gestures (actual)				
	1-finger	2-finger	L-shape	Hand with closed fingers	Hand with open fingers
1-finger	1.00	0.00	0.00	0.00	0.00
2-finger	0.08	0.97	0.00	0.22	0.00
L-shape	0.02	0.18	0.98	0.00	0.00
Hand with closed fingers	0.00	0.00	0.00	0.99	0.01
Hand with open fingers	0.00	0.00	0.00	0.02	0.98

Table 4.1: Confusion matrix for static gestures

Dynamic Gestures (predicted)	Dynamic Gestures (actual)				
	Drag	Rotate	Spread/Pile	Wipe	Zoom in/out
Drag	0.94	0.00	0.00	0.01	0.05
Rotate	0.00	0.90	0.02	0.00	0.08
Spread/Pile	0.00	0.06	0.90	0.04	0.00
Wipe	0.00	0.00	0.03	0.92	0.05
Zoom in/out	0.02	0.06	0.00	0.02	0.91

Table 4.2: Confusion matrix for dynamic gestures

Chapter 5

HAPTABLE : HYBRID HAPTIC ACTUATION

HapTable recognizes an interaction using the images coming from infrared cameras, and in response, it can provide haptic feedback using either electromechanical actuation, electrostatic actuation, or both at the same time. 5.1 shows the system diagram for haptic actuation system. Using two multichannel relays, HapTable can successfully actuate any combination of four piezo-electric actuators and the electrostatic haptic feedback. Furthermore, haptic actuation mechanism has two input signal sources - left and right channels of the sound card. Therefore, it is able to provide two different signals to any combination of actuators. For example, HapTable can render a sandstorm: sand texture with electrostatic feedback, while providing flow information via electromechanical actuation.

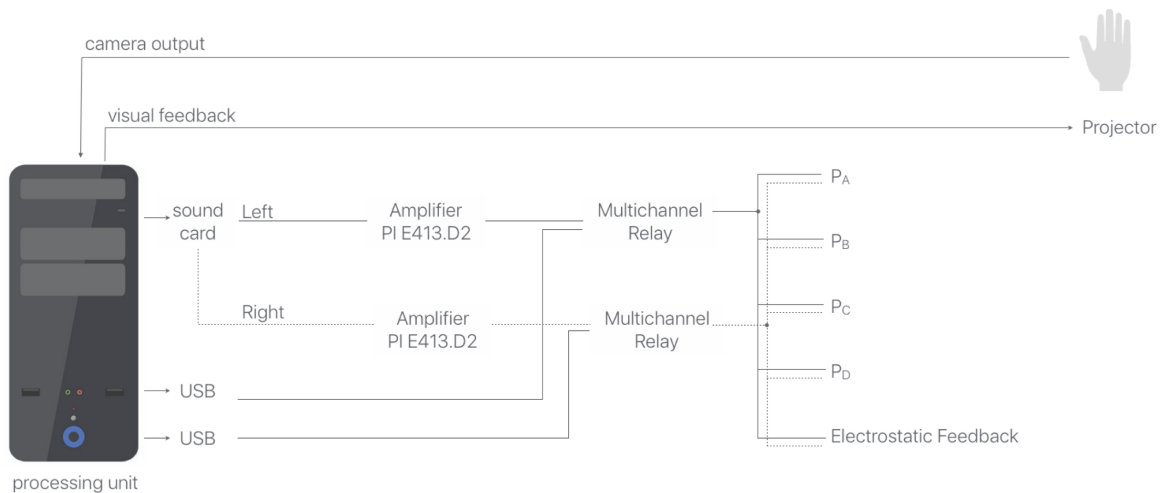


Figure 5.1: HapTable's system diagram for haptic actuation.

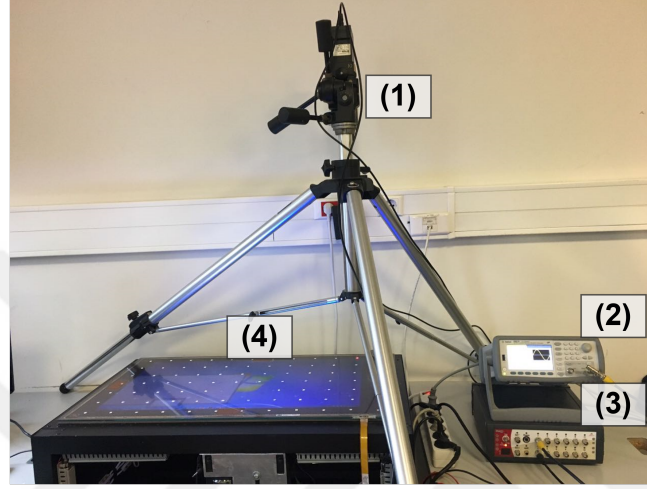
5.1 Haptic Feedback via Electromechanical Actuation using Piezoelectric Bending Actuators

HapTable displays vibrotactile haptic feedback for using four piezo-bending actuators (PI-876.A12, Physik Instrumente, $61 \times 35 \times 0.5$ mm). Each piezo patch is glued to the bottom along the middle of 3M capacitive touch screen's each edge. The touch screen is placed on top of HapTable using rubber seal to constrain the vibration on the touch surface, aiming to prevent its propagation to the rest of the table. Piezo -bending actuators create haptic feedback by physically deforming the glass surface. However, the displacement map created on the glass surface depends on many factors -actuated piezo(s), signal waveform and frequency, boundary conditions of the plate, adhesion between the patches and glass surface. To understand the effect of piezo-patches for different frequencies and different combination of piezos, we first constructed a vibration map of the tabletop surface as explained in the following subsection.

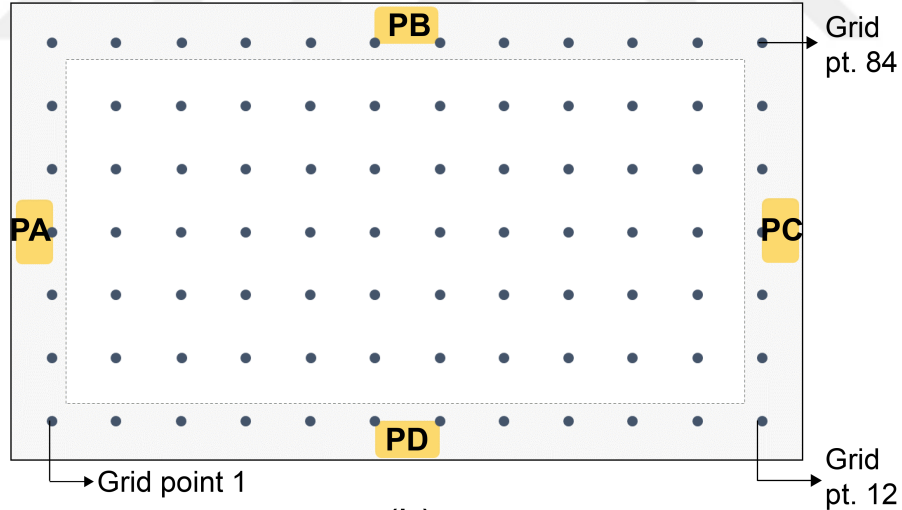
5.1.1 Creating vibration map for HapTable

To construct the vibration map of the tabletop, we divided its surface into 84 grid points (7 rows by 12 columns, Fig. 5.2b). The size of each grid was 6×6 cm. This grid size was chosen carefully after experimenting and collecting data with various grid sizes. The purpose for this was to validate that when we interpolate actual measurements to approximate a displacement value at a point that was not measured, we would get the best approximation. The out-of-plane vibrations at each grid point were measured when each piezo patch was excited individually and when all patches were excited together.

For this purpose, a linear sine sweep signal varying in frequency from 0 to 625 Hz was generated by a signal generator, amplified by one of the high-voltage amplifiers in our setup (E413.D2, Physik Instrumente, Gain: 50), and then transmitted to the terminals of the piezo patch. A Laser Doppler Vibrometer (LDV, PDV -100, Polytec) was used to measure the out -of -plane vibrations at each grid point (Fig.



(a)



(b)

Figure 5.2: (a) The setup for vibration measurements: (1) Laser doppler vibrometer (LDV), (2) signal generator, (3) signal analyzer, and (4) tabletop surface. (b) The tabletop surface was divided into 84 equally-spaced grid points for measurements (7 rows by 12 columns). P_A , P_B , P_C , and P_D represent the piezo patches glued to the edges of the bottom side of tabletop surface.

5.2 a). A signal analyzer (NetDB, 01dB –Metravib) was used to record and analyze signals coming from the LDV and the signal generator. Having defined the signal generator's output as the reference channel in the signal analyzer, the experimental frequency response functions (FRFs) between the velocity output and piezoelectric voltage input were obtained. The same process was repeated 3 times for the case when each piezo patch was active and for the case when all piezo patches were active together in a parallel configuration. The velocity FRF of each grid point was estimated by averaging the data of three full sweeps, and then converted to displacement FRFs (Fig. 5.3).

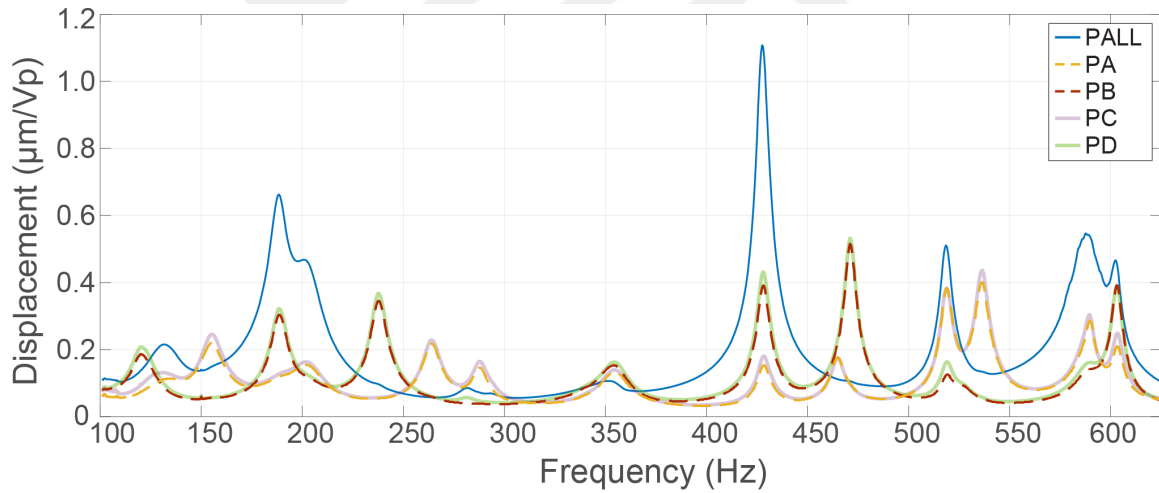


Figure 5.3: Mean displacement FRFs of 84 measurement points on HapTable, for five excitation cases: patches P_A , P_B , P_C , and P_D are excited individually and together in a parallel configuration (P_{ALL}).

The averaged FRFs for patches P_A and P_C , and P_B and P_D are similar due to their symmetrical positions on HapTable surface, as shown in Fig. 5.2b.

5.1.2 Creating localized vibrotactile haptic feedback on HapTable

In order to display localized vibrotactile haptic feedback on the touch surface, we utilize the five FRF functions (one for individual piezo patches and one for all) of 84

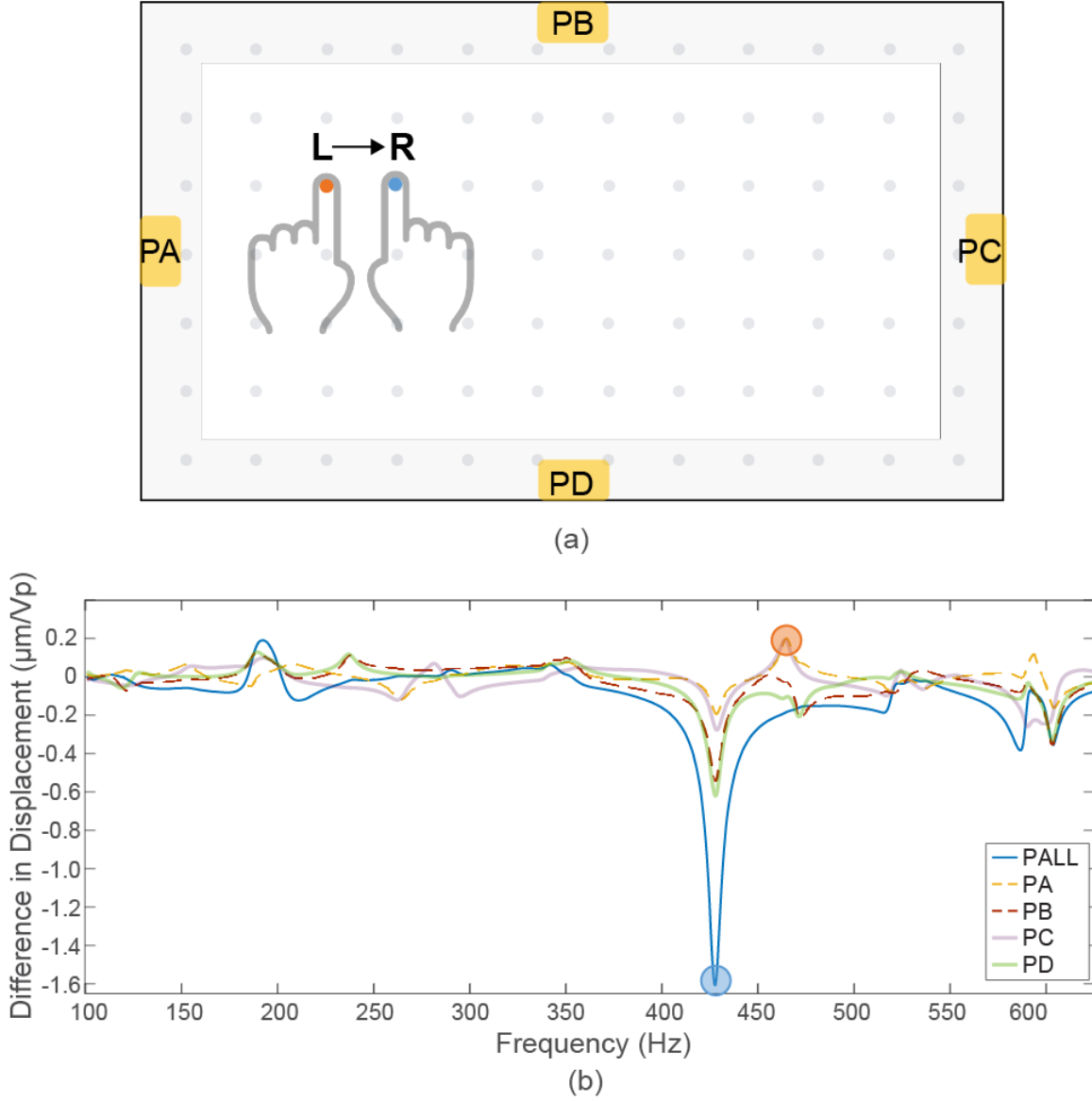


Figure 5.4: To create a flow from point L to R on the touch screen (a), the FRF graph of point R is subtracted from that of point L for the five excitation cases: when piezo-patches are excited individually and all together (b). The maximum and minimum differences in displacement are marked by orange and blue circles, respectively. A negative displacement difference occurs when point R has a higher displacement than that of point L.

grid points shown in Fig. 5.3. For each grid point, there is an excitation frequency at which the displacement is maximum. If the surface is excited at this frequency, a localized haptic effect can be generated at and around that point. Furthermore, we achieve localized haptic feedback by maximizing the vibration at one region under the contact area, while minimizing it at other regions under this contact area. This contact area can be determined using our camera-based gesture recognition system. Using localized haptic effects, it is possible to generate directional vibrotactile flow between any two points on the screen by simply switching between the excitation frequencies corresponding to the maximum difference in their displacements (for non-grid points, FRFs can be estimated using bilinear interpolation). For instance, consider the two points illustrated in Fig. 5.4a, touched by the index fingers of the left and right hands. To generate a vibrotactile flow from point L to point R, two excitation frequencies are carefully chosen from the FRF difference plots (Fig. 5.4b) so that point L is the active point and has a higher vibration amplitude than that of point R in the first part of the stimulus, and vice versa in the second part of the stimulus. The difference in FRF plots for points L and R are shown in Fig. 5.4b.

This plot shows that the vibration amplitude of point L makes a maximum difference with that of point R (marked with the orange circle) at 465 Hz when the piezo patch P_A is active. Similarly, the blue circle indicates that the vibration amplitude of point R is significantly larger than that of point L at 428 Hz when all piezo patches are excited simultaneously (P_{ALL}). Fast solid-state relays shown in Fig. ?? can be used to switch between the actuators P_A and P_{ALL} .

In order to extend the vibrotactile flow concept to all grid points on the surface efficiently (and hence to all points on the surface through bilinear interpolation), we adopt a preprocessing approach. We construct and store three lookup tables (Fig. 5.5), which are used to determine the excitation parameters during user interaction in real time.

These tables store the maximum difference in vibration amplitudes of the grid points (Fig. 5.5a), the corresponding excitation frequencies (Fig. 5.5b), and the

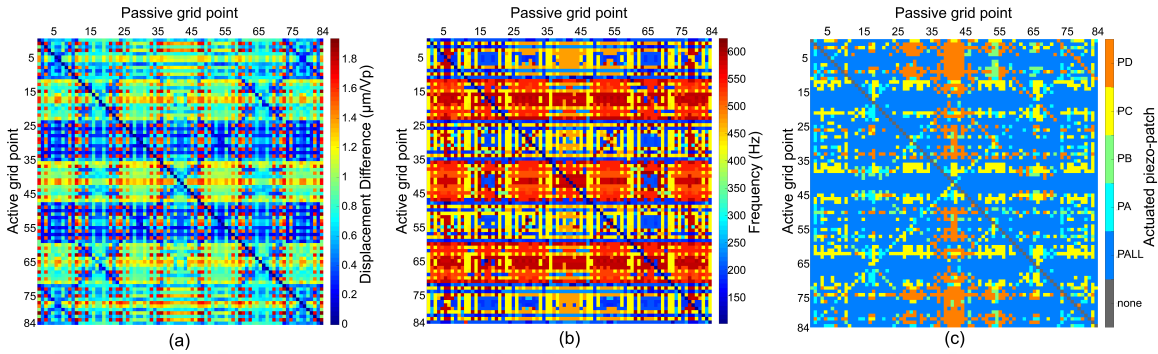


Figure 5.5: Excitation lookup tables for HapTable: to create a vibrotactile flow from an “active” grid point to a “passive” one, our haptic rendering algorithm acquires maximum displacement difference in vibration amplitudes from table (a), the corresponding excitation frequency from table (b), and the actuator ID (i.e. which actuator to use to create that displacement difference at the corresponding excitation frequency) from table (c). The displacement at each grid point is higher than the human vibrotactile absolute threshold.

actuator identifier (Fig. 5.5c; either the patch P_A , P_B , P_C , P_D , or P_{ALL}). For example, if the points L and R in Fig. 5.4a are selected as active and passive points respectively (they correspond to the grid points 51 and 52 on the surface) and inputted to the tables, a maximum vibration difference of $0.201 \mu\text{m/Vp}$ (Fig. 5.5a) at 465 Hz (Fig. 5.5b) is returned. This difference in amplitude is obtained when the surface is actuated by piezo patch P_A (Fig. 5.5c). On the other hand, if point R is active and point L is passive, the vibration difference now becomes $1.607 \mu\text{m/Vp}$ (Fig. 5.5a), which is obtained at a different actuation frequency of 428 Hz (Fig. 5.5b) and when the surface is actuated by P_{ALL} (Fig. 5.5c). Using this information, a haptic stimulus is created for displaying a vibrotactile flow effect from left to right as shown in Fig. 5.6b.

The first part of the stimuli excites P_A to create a substantially high vibration displacement at L compared to that of at R, whereas the second part excites P_{ALL} to accomplish vice versa. The amplitudes for both parts of the stimuli are adjusted according to the human sensitivity curve for vibration [32, 21] to create an equivalent

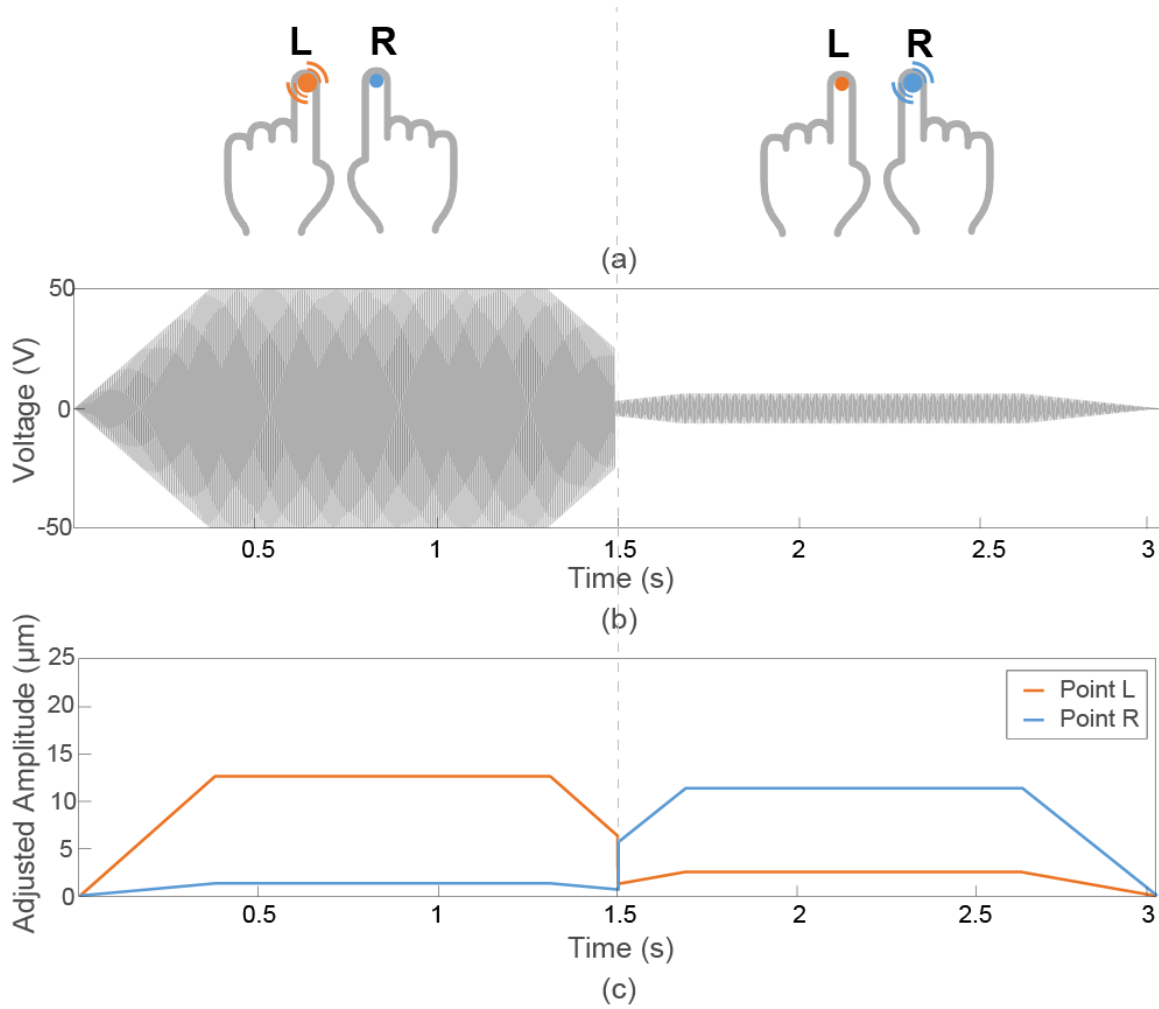


Figure 5.6: (a) To create a vibrotactile flow from left (L) to right (R), we first actuate the surface at a certain frequency such that the vibration amplitude of point L is significantly higher than that of the point R, and then actuate the surface at a different frequency such that the vibration amplitude of point R is significantly higher than that of the point L. Note that different piezo actuators could be used to play the voltage signals shown on the first (0–1.5 seconds) and second (1.5–3.0 seconds) parts in the figure.

haptic effect in magnitude at both parts (Fig. 5.6b). Then, a linear amplitude modulating envelope is applied to the beginning and end of the signals in each part of the stimulus to make the transitions smoother during the activation and deactivation

of piezo patches (Fig. 5.6b and c). We conducted a small user study with different actuation times to determine the rise, constant, and fall times for the actuation signals to create a smooth flow effect. We demonstrate in 6 how this information can be used to create a directional vibrotactile flow between the index fingers of left and right hands and also underneath a single hand placed on the tabletop surface.

5.2 Haptic Feedback via Electrostatic Actuation

Electrostatic actuation creates haptic feedback by modulating the frictional forces between the user's fingers and the tabletop surface of HapTable. Capacitive touch screen used in HapTable is constructed of three layers from bottom to top: (1)glass substrate, (2)continuous conductive indium-tin-oxide layer, and (3) insulating layer. When an alternating current voltage is applied to the conductive layer of the touch screen, electrostatic attraction force (F_e) develops between the finger(s) and the touch surface (Eq. 5.1). The magnitude of this attractive force is affected by the applied voltage, $V(t)$, contact area, A , permittivity of the vacuum, insulating layer of the touch screen, and outer finger skin (ϵ_0 , ϵ_i , and ϵ_s respectively), and the insulator and outer skin thicknesses (t_i , t_s), as written in below [22]:

$$F_e = \frac{\epsilon_0 V^2(t) A}{2(t_i + t_s) \left(\frac{t_i}{\epsilon_i} + \frac{t_s}{\epsilon_s} \right)} \quad (5.1)$$

Although there are many factors affecting the resulting electrostatic force between a finger and the touch surface, developers can only alter the voltage applied to the system. Therefore, this attractive force can be changed using the voltage applied to the conductive surface. The magnitude of this attractive force is too small to be perceived by a stationary finger. However, it results in a perceivable change in frictional force in tangential direction when human finger moves on the touch surface.

$$\vec{F}_f = \mu(\vec{F}_N + \vec{F}_e) \quad (5.2)$$

By controlling the frequency, amplitude, and the waveform of the applied voltage, it is possible to create different haptic effects on the surface [2]. In the upcoming section, we demonstrate the use of this technology in a case study involving a virtual knob, which is rotated by two fingers on the tabletop surface.



Chapter 6

USER STUDIES

We demonstrate the functionality of HapTable via two example applications supported by user studies. In the first one, as an example for static gestures, we render localized directional vibrotactile flow between index fingers of two hands and also underneath a single hand placed on the surface. We investigate if users can differentiate the direction of vibrotactile flow in Section 6.1. As an example for dynamic gestures, we render a virtual knob on the surface. The users receive frictional haptic feedback as they rotate the knob using two fingers to select an item from a menu. We investigate if haptic feedback improves task performance and the users' subjective sense of performing the task successfully in Section 6.2.

6.1 User Study I: Vibrotactile Flow

The vibrotactile flow, i.e. haptic illusion of apparent tactile movement on human skin, was investigated by Sherrick and Rogers in 1960s [40]. They attached two vibration motors on user's thigh separated by a distance. They adjusted the stimulus duration and the delay between the actuation times to create an effect of a traveling haptic stimulus. They showed that stimuli duration and the interstimulus offset interval (ISOI, i.e. the temporal interval between the offset of one vibration to the onset of another one), are the key parameters that affect the subjects' haptic perception. Tan and Pentland [45] and Israr and Poupyrev [17] extended this concept to 2D surfaces by placing an array of vibration motors on the cushion of a chair to create directional tactile strokes. In a separate study, Israr and Poupyrev [17] investigated the control parameter space for producing reliable continuous moving patterns on the forearm and the back. The results of their user study showed that ISOI space for the forearm

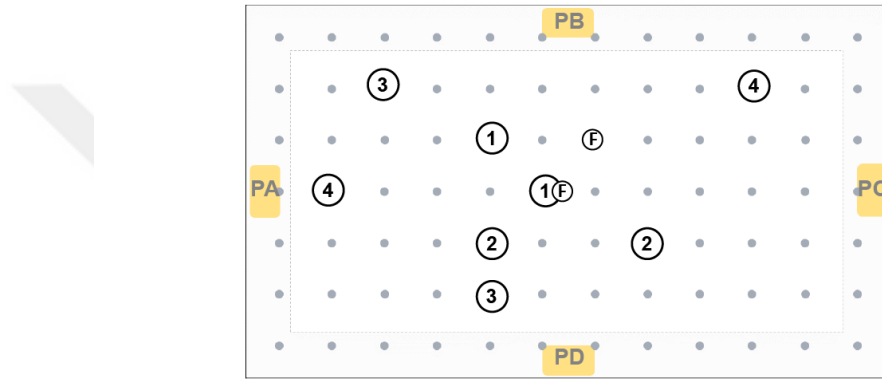
was influenced by both the motion direction and spacing of the actuators, whereas ISOI space for the back was affected only by the direction of actuation. Arasan et al. [1] applied the apparent tactile motion to a pen-based stylus that can be used with a tablet or a mobile device. Two vibration motors were placed at the proximal and distal ends of the stylus to create a tactile illusion of traveling vibrotactile stimulus along its long axis (up-down or down-up). They demonstrated the potential applications of this stylus in computer games and data visualization.

The illusion of tactile apparent motion can also be generated by amplitude or frequency modulation. Kim et al. [26] created the sensation of a traveling wave between two vibration actuators embedded in a cell phone by adjusting the magnitude and timing of the actuators. Lim et al. [31] used frequency modulation to create a vibrotactile flow between two hands holding a tablet equipped with vibration motors. Kang et al. [24] used piezo-patches glued to the short edges of a tablet-size glass plate for creating a vibrotactile flow via frequency modulation. They modulated the frequency from zero to the first mode of the plate to create an illusion of moving tactile stimulus from one short edge of the plate to its opposite one.

6.1.1 Experiment 1: Vibrotactile flow between two fingers

We conducted an experiment with 5 subjects (2 female, 3 male) having an average age of 31.4 years (SD=6.88) to investigate if they can detect a directional vibrotactile flow between two grid points on the touch surface. In order to create a directional vibrotactile flow, we used an amplitude-modulated voltage signal having two parts (see the profile of first and second parts in Fig. 5.6). Each part was played by the appropriate piezo actuator. The frequency of the signals in each part and the actuator that plays the signal were carefully selected using the excitation lookup tables, as discussed in the previous section. The resulting displacement at each grid point used in the experiment was above absolute vibration threshold for that frequency [32, 21]. Prior to the experiment, all subjects were informed about the experimental procedure. They were asked to wear active noise-canceling headphones playing white

noise to prevent them from hearing auditory cues caused by the vibrations. Subjects placed their left and right index fingers on the designated locations (test points) of the tabletop surface (Fig. 6.1a) and were asked the perceived direction of vibrotactile flow: left to right, or right to left hand.



(a)

Pair	distance (cm)	L active, R passive grid point			R active, L passive grid point		
		f_1 (Hz)	Δd_1 ($\mu\text{m}/\text{Vp}$)	p_1	f_2 (Hz)	Δd_2 ($\mu\text{m}/\text{Vp}$)	p_2
F	8.49	471.0	0.27	PB	578.0	1.32	PALL
1	8.49	595.5	1.42	PALL	236.5	0.39	PD
2	12	129.0	0.10	PD	426.5	0.28	PALL
3	26.83	538.0	0.70	PA	586.0	0.88	PALL
4	49.48	428.0	1.61	PALL	187.5	0.74	PALL

(b)

Figure 6.1: (a) The locations of the test pairs selected for the familiarization (pair: F–F) and the actual experiment (pairs: 1–1, 2–2, 3–3, 4–4) sessions. (b) The distance between the test points for each pair, actuation frequencies (f_1, f_2), the piezo patches used for actuation (p_1, p_2), and the displacement differences between the test points ($\Delta d_1, \Delta d_2$) are given in the table on the right. The excitation voltage for each pair is 100Vpp.

Experiment started with a familiarization session, consisting of 10 trials (5 rep-

etitions for each direction in random order) performed with a single pair (pair F–F in Fig. 6.1a). Subjects were allowed to replay the stimuli as many times as needed during the familiarization session. Afterwards, the actual experiment was conducted with 4 pairs of test points, located at different regions on the touch screen. Subjects could replay the stimuli only once in the actual experiment. More information about the selected test pairs, the physical distance between them, the actuators that played the voltage signal in each part, and the difference between their vibration amplitudes are given in Fig. 6.1b. All vibration amplitudes in the experiment were above the absolute vibrotactile threshold of the human finger for the excitation frequencies given in Fig. 6.1b [32, 21]. The experiment consisted of 40 trials ($4 \text{ pairs} \times 2 \text{ directions} \times 5 \text{ repetitions}$) displayed in random order.

All subjects identified the direction of vibrotactile flow with a perfect accuracy of 100% for all pairs. The results of this experiment showed that subjects could easily differentiate the direction of vibrotactile flow with their index fingers even if the test points are diagonal to each other, as in the pairs of 1–1, 3–3, and 4–4.

6.1.2 Vibrotactile Flow Under Hand

Based on the encouraging results of the first experiment, we expanded our study to investigate directional vibrotactile flow under a single hand placed on the touch surface. We assumed that human hand covers an area of $12 \times 12 \text{ cm}$. We divided this area into nine equal squares as shown in Fig. 6.2(a), and each square is further divided into 15×15 subgrid points for finer resolution (FRFs for those points were calculated in advance using bilinear interpolation). Similar to the concept of active and passive points introduced in the first experiment, active and passive squares are defined in this experiment. A square is assumed to be active if the displacement of at least half of its subgrid points lie within three just noticeable difference (JND) of the maximum displacement value measured under the hand region. The absolute threshold and JND values for different excitation frequencies were obtained from the human vibrotactile sensitivity curve reported in [32, 21].

Using these active and passive squares, we aimed to generate a vibrotactile flow in horizontal and vertical directions. As in the case of the first experiment, we selected the proper excitation frequencies from the FRFs using the following constraints. In order to create a directional vibrotactile flow, the active and passive squares should be symmetric with respect to the horizontal (vertical) axis passing through the center point of the area representing hand (point C in Fig. 6.2a) for vertical (horizontal) flow. Fig. 6.2 illustrates example vibration maps that are acceptable (Fig. 6.2b, e) and unacceptable (Fig. 6.2c, d) based on our algorithm.

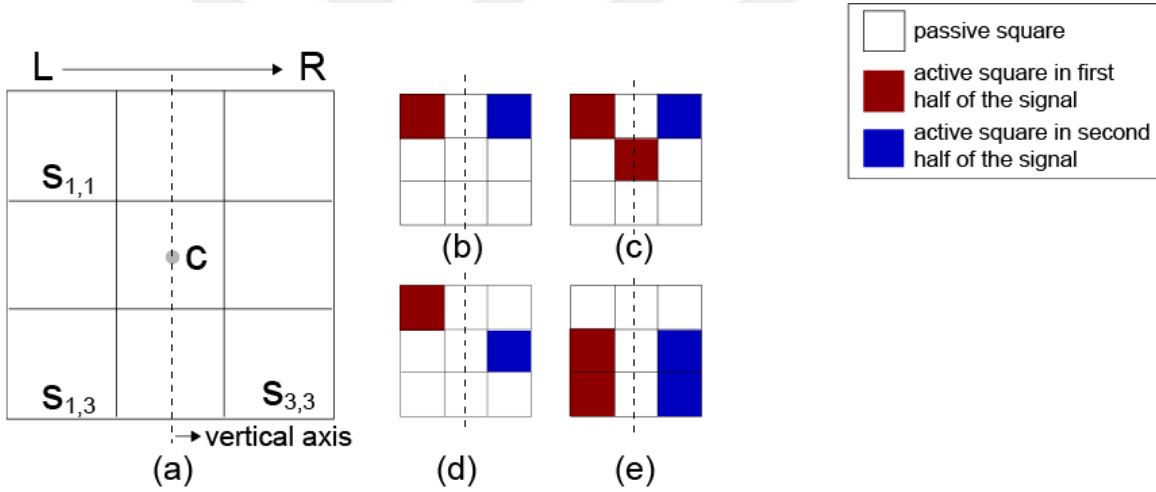


Figure 6.2: (a) The area under hand is divided into nine equal squares, $s(i, j)$ where i and j represent the column and row numbers. In the example shown above, the goal is to create a travelling vibrotactile flow from left to right. The active and passive squares shown in (b) and (e) are symmetric with respect to the vertical line, but (c) and (d) are not. Note that the line of symmetry is vertical (horizontal) for a horizontal (vertical) flow.

The second experiment was conducted with eleven subjects (4 female, 7 male) having an average age of 29.64 years (SD=5.98). Only two subjects were left-handed. The average hand width and length of the subjects were measured as 8.48 cm (SD=0.52 cm) and 18.42 cm (SD=6.24 cm), respectively. During the experiment, all subjects

stood in front of HapTable and placed their hand on the five designated regions (one for the preliminary and four for the actual experiment), randomly distributed on the tabletop surface (Fig. 6.3a). They wore active noise-cancelling headphones playing white noise to block any auditory cues.

Experiment started with a preliminary session to help subjects get familiar with haptic stimuli and interface. It consisted of 40 trials (10 repetitions $\times$ 4 directions) performed in the R_{prelim} region (Fig. 6.3a). During this session, subjects could replay the stimulus as many times as they wished, and they could ask questions to the experimenter about the experimental procedure. In the actual experiment, subjects completed 160 trials (4 regions $\times$ 4 directions $\times$ 10 repetitions). For each region, the flow directions were displayed in random order while the order was same for each subject. In regions R_1 and R_2 , the stimulus was applied to the left hand of subjects; whereas in other regions, R_3 and R_4 , it was applied to their right hand. Subjects were allowed to replay the stimulus only once. At the end of each trial, they were asked to select the direction of vibrotactile flow by pressing one of the four arrow buttons (representing the flow directions of travelling up, down, left, and right) displayed on the screen (Fig. 6.3b).

The recognition rates of the subjects for all directions and regions are shown in Fig. 6.4. The average accuracy of the subjects for all directions was 90% (SD=3.6%, Fig. 6.4a). Fig. 6.4b shows the regional recognition accuracy of all subjects (Mean=90%, SD=3.1%). A two-way repeated measures ANOVA was used to investigate the statistically significant effects of region and direction on recognition accuracy. Mauchly's test was applied to check the violation of sphericity assumption. If needed, the degrees of freedom were corrected using Greenhouse-Geisser correction. Finally, Bonferroni corrected post-hoc analysis was carried out to further investigate the statistical differences between the groups.

Two-way repeated measures ANOVA showed a statistically significant interaction between the region and direction ($p=0.006$, $\eta^2_{partial}=0.317$). However, simple main effect analysis of direction revealed that the direction was statistically significant only

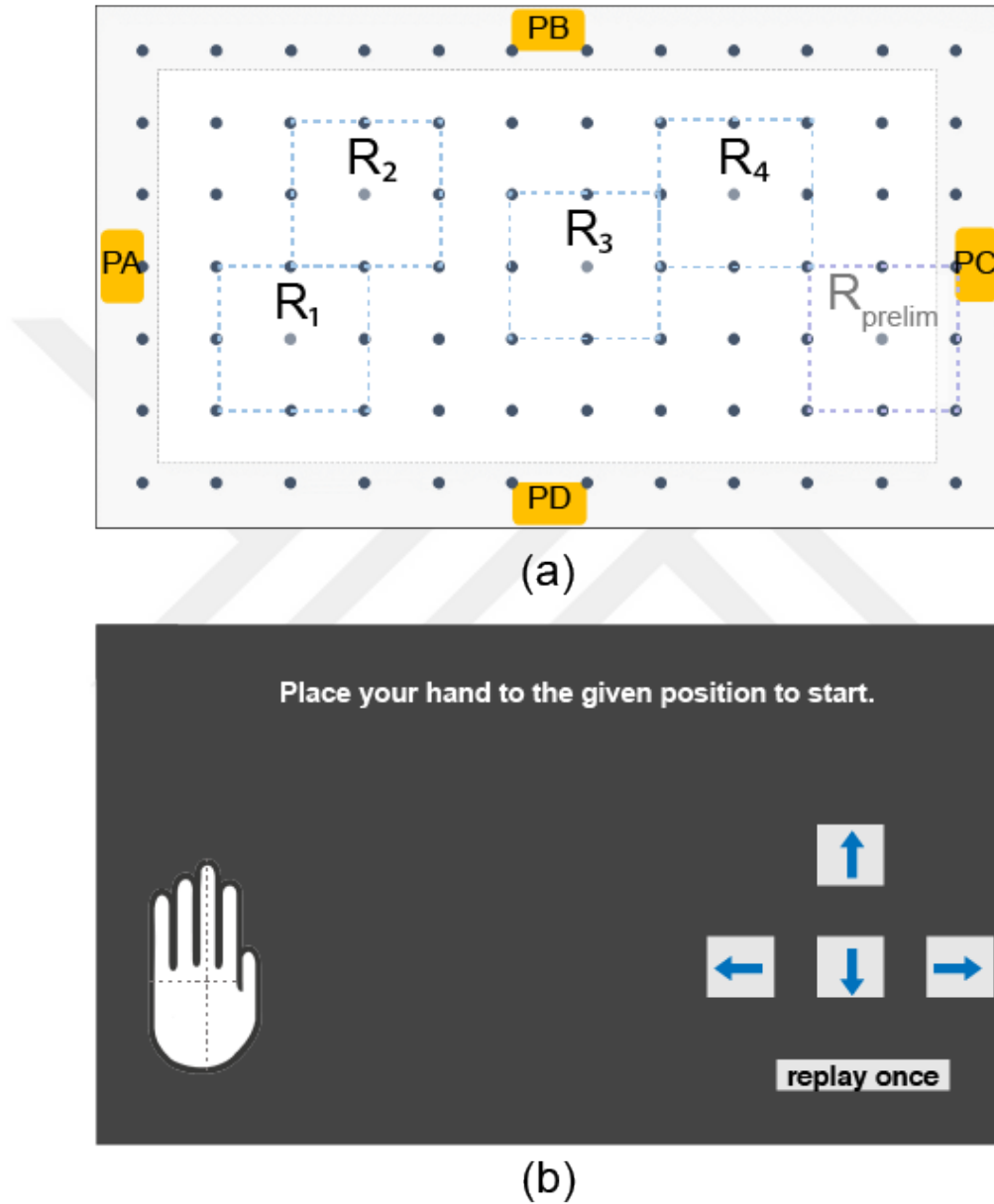


Figure 6.3: (a) First, a preliminary experiment was conducted at the region R_{prelim} and then the actual experiment was conducted in four different regions, R_1 , R_2 , R_3 , and R_4 . The size of each region was 12 by 12 cm. (b) Subjects were guided to align their hand position according to the hand image displayed on the screen. After the haptic stimulus was displayed, they were asked to determine the direction of vibrotactile flow by pressing one of the four arrow buttons on the screen.

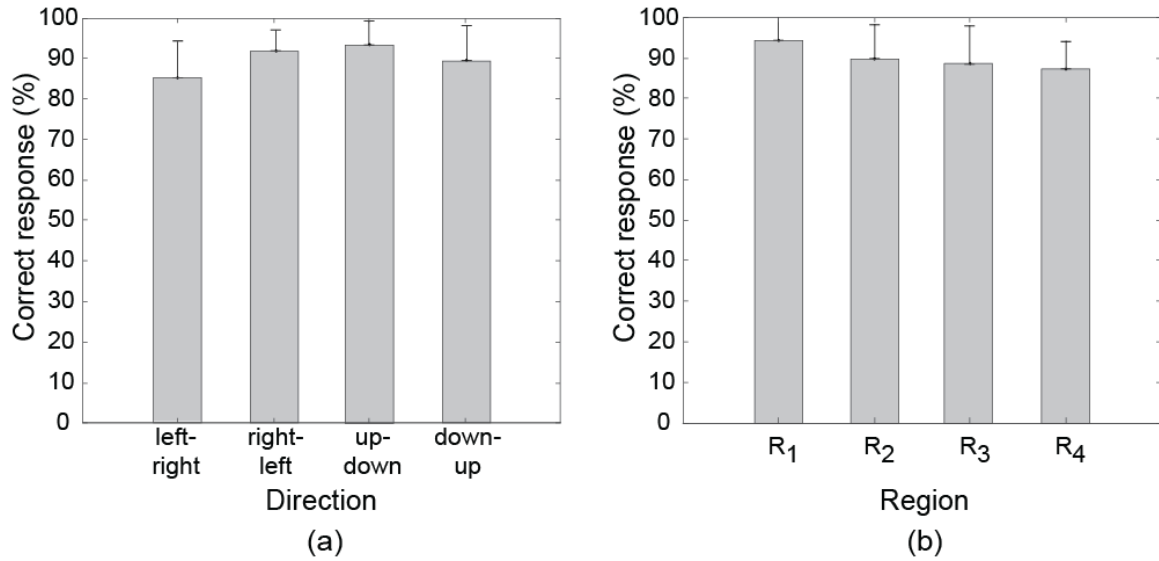


Figure 6.4: Vibrotactile flow under hand: a) percentage of correct responses for each direction, b) percentage of correct responses for each region in the second experiment. The bars represent the mean values while deviations are the standard error of means.

for R_4 ($p < 0.0005$, $\eta_{partial}^2 = 0.682$). Pairwise comparisons with Bonferroni correction for this region showed that the difference in the recognition accuracy between left-right and the other directions (down-up, up-down, and right-left) were statistically significant ($p = 0.001$, $p = 0.005$, and $p = 0.002$ respectively). Mode shape analysis revealed that during the first part of the stimulus displayed for the left-right direction in R_4 , there is a vibration on both sides of the hand, resulting in a possible confusion of the direction of vibrotactile flow (Fig. 6.5b).

6.1.3 Understanding the effect of sound levels while actuating piezos

Exciting the piezo patches in our system displaces air above the actuated surface, similar to a speaker, and results in audible noise. To understand the affect of this noise without the noise-cancelling headphones, we measured the sound levels for each excitation signal used during the second experiment with whole hand, given in Section 6.1.2.

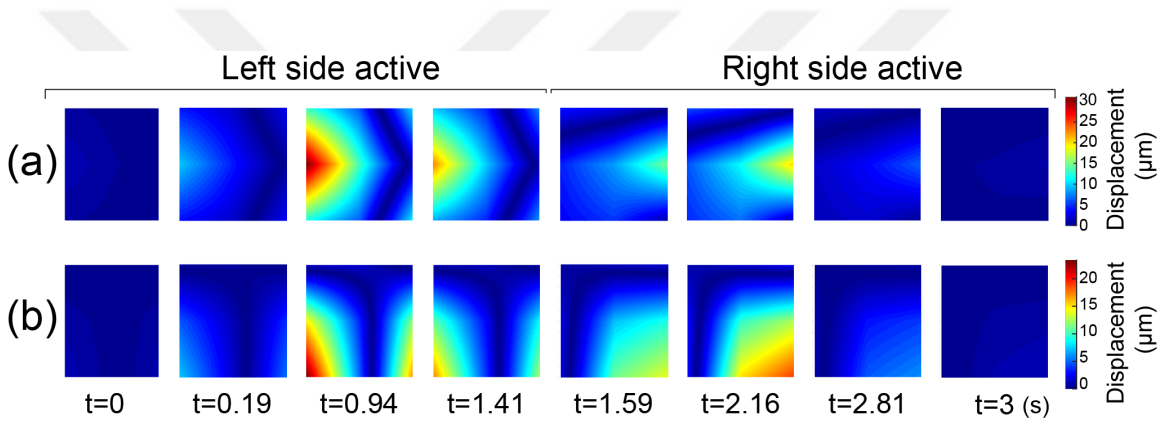


Figure 6.5: Evolution of vibration maps for vibrotactile flow under the hand: a) left-right direction at R_3 recognized with 95.5% accuracy (SD=6.6%). The first and second parts of the input voltage signal successfully create localized vibrations on the left and right sides of the hand sequentially, resulting in high accuracy in the subjects' perception of flow direction. b) left-right direction at R_4 recognized with 66.4% accuracy (SD=17.7%). The first part of the signal vibrates the bottom left and right sides of the hand region at the same time, causing a possible confusion in subject's perception of the direction of flow.

Region	Direction	First half of the signal (L/U active grid point)		Second half of the signal (R/D active grid point)	
		Frequency	Sound Level	Frequency	Sound Level
		(Hz)	(dB)	(Hz)	(dB)
R_1	left-right	194	38.0	263	22.0
	up-down	341	32.0	238	36.0
R_2	left-right	355	40.0	461	38.0
	up-down	238	23.0	354	36.0
R_3	left-right	589	25.0	538	41.0
	up-down	249	36.0	495	38.0
R_4	left-right	464	29.0	355	25.0
	up-down	471	39.0	415	41.0

Table 6.1: The sound level when HapTable surface is actuated with signals used in “Vibrotactile flow under hand” user study in previous Section 6.1.2, along with the excitation frequencies.

We used the microphone of an iPhone 5 with SoundMeter app, as suggested in [25]. Table shows the sound levels in decibels measured for each region in vibrotactile flow under hand region experiment. The maximum sound level measured is 41 dB, which is comparable to a quiet library [50, 7].

We conducted a second experiment to measure how sound level changed according to the amplitude of the actuation signal at maximum frequency (625Hz), and also according to the frequency of the actuation signal at maximum amplitude (100Vpp) while sweeping frequencies from 100 to 625Hz. The results are given in Fig. 6.6a and 6.6b, respectively.

Fig. 6.6a shows that sound level increases as the amplitude increases. However, in Fig. 6.6b, while keeping the amplitude constant at 100Vpp, sound levels are increased when the actuation frequency is closer to the resonance frequencies of the glass plate. According to the vibrotactile threshold for finger(s) and hand given in [32, 21], users can perceive the displacement at 600 Hz below 10 Vpp (displacement at 10Vpp can be calculated using FRF given in Fig. 5.3). At 10Vpp, the sound levels are considered as quiet.

To investigate the effect of sound levels on participants, we conducted a subjective evaluation with 5 subjects (4 male, 1 female) having an average age of 34.4 years (SD=7.0). Subjects did not wear headphones, and were asked to evaluate the sound levels in five categories, using a 5-point Likert scale:

- (a) softness
- (b) pleasantness
- (c) comfort
- (d) noise
- (e) disgust

The results for the qualitative experiment is given in Fig. 6.7. Subjects reported that traveling waves in horizontal direction in R_3 and vertical ones in R_4 felt harsher and noisier than the others. The sound levels measured for those signals were the highest (41 dB), and their frequencies were above 450 Hz. Moreover, the amplitudes

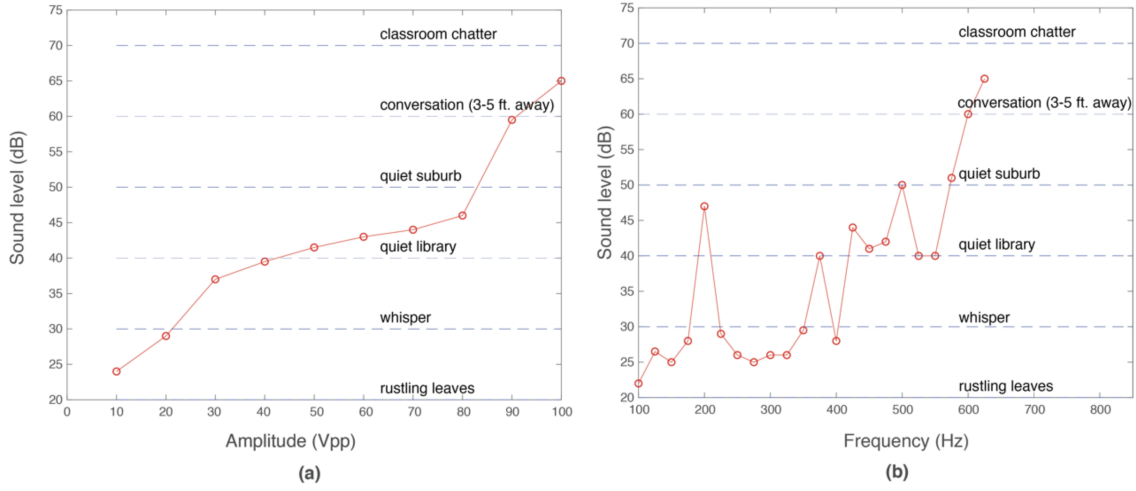


Figure 6.6: (a) The sound level on tabletop surface when all piezos actuators are actuated at different amplitudes, between 0 and 100 Vpp. (b) The sound level on tabletop surface when all four piezo actuators are actuated at 100Vpp, at frequencies between 100 and 625 Hz. Corresponding familiar noise sources for dB levels is marked with dashed lines and labeled [50, 7].

of the vibrations created by those signals on the touch surface were at least five times higher than the absolute detection thresholds reported for vibrotactile stimuli in [32, 21]. Piezo patches actuate the whole display, and the vibrations created on the surface displaces a large amount of air, similar to a speaker. Smaller surfaces and reduced amplitude will decrease the amount of the air moved, thus, decreasing the audible noise. Therefore, the sound levels caused by those excitation signals can be reduced by configuring our algorithm to

1. choose a lower frequency range, and/or
2. decrease the vibration amplitude to slightly above the absolute vibration thresholds.

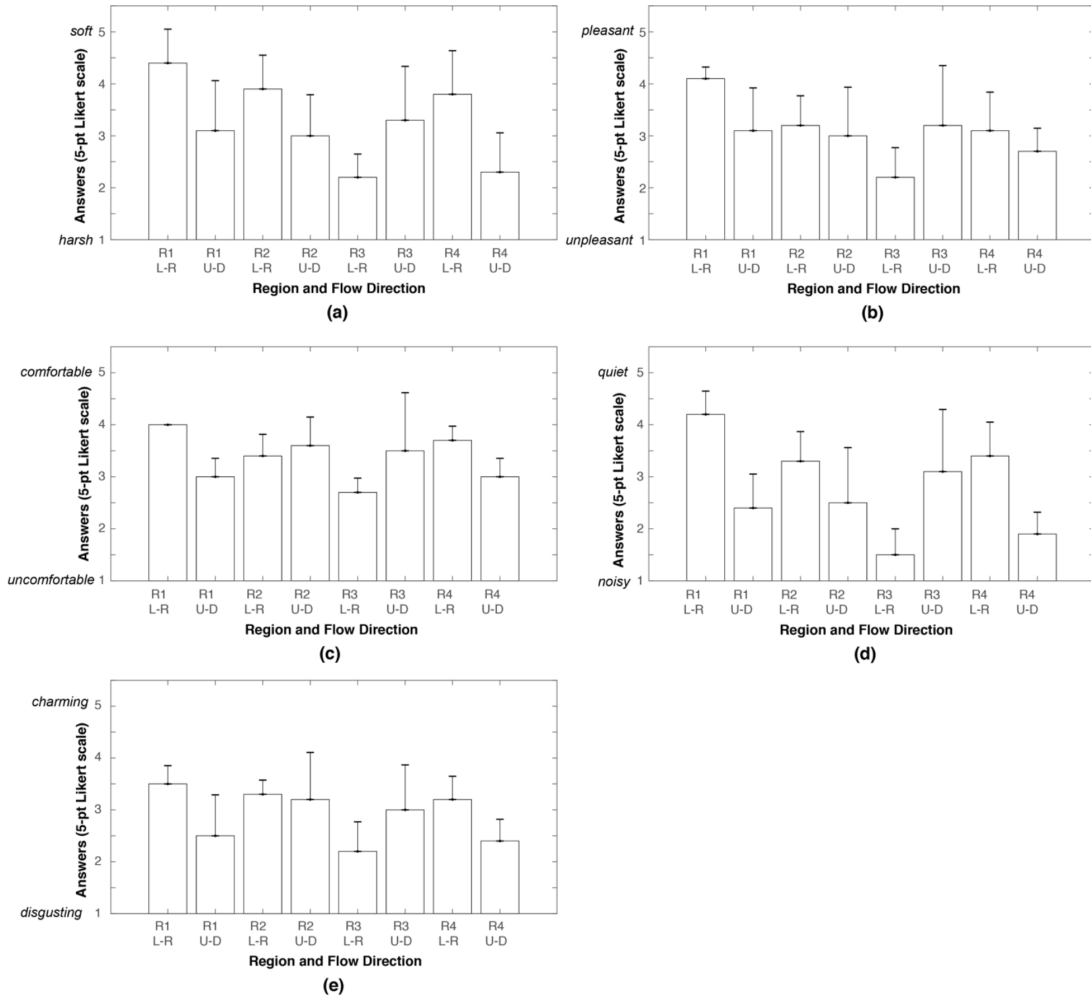


Figure 6.7: Average and standard deviations of responses from all seven subjects, given in 5-point Likert scale for five dimensions : (a) softness, (b) pleasantness, (c) comfort, (d) noise, and (e) disgust for left-right (L-R) and up-down (U-D) flow directions in four regions (R_1 , R_2 , R_3 , and R_4). Adjectives corresponding to scores one and five given on y-axis, next to the relevant score. Signals presented are the same signals used in vibrotactile flow experiment, under hand.

6.1.4 Discussion

In the first experiment, subjects were asked to put their index fingers of both hands on different locations on the table and then differentiate the direction of vibrotactile

flow (either from the left index finger to the right one or vice versa). For a wide range of positional configurations, the subjects achieved perfect performance (100% correct identification) in this task that had a chance level of fifty-percent baseline. On the other hand, when they were asked to differentiate the direction of the vibrotactile wave (up, down, left, right) travelling underneath their hand in the second experiment, the success rate dropped slightly. When rendering a vibrotactile flow underneath the subjects' hand, the rendering approach utilized for the first experiment had to be modified since the contact with the surface involved an area (hand) rather than a point (tip of an index finger). We divided the area under the user's hand into smaller regions and considered the amplitude of vibrations in those regions and their symmetry with respect to the horizontal and vertical axes dividing the area into two equal halves. The modified approach searched excitation frequencies between 0 and 625 Hz to identify the symmetric regions with a significant difference in vibration amplitude. The results showed that the subjects could differentiate the direction of haptic flow with an average accuracy of 90% (SD=3.6%) across the four directions. The slight drop in recognition accuracy compared to the first experiment is not surprising for several reasons. First of all, the sensitivity of index finger to vibrotactile stimulus is higher than palm [32, 21]. Second, the chance level in the second experiment was 25% compared to that of 50% in the first experiment. Third, vibrations can be better localized by index fingers of two separate hands rather than those traveling beneath only one hand due to contact area [32]. Finally, our current approach assumes a fixed-size area for human hand (within 12×12 cm square) and implements the haptic stimuli accordingly. Hence, a person with a hand smaller or larger than that assumed area could be at a slight disadvantage in our current approach. The recognition rate of directional flow can be further improved if the algorithm is auto-tuned with respect to the actual hand dimensions of the user. This can be accomplished using our gesture detection system that already extracts the hand contour and orientation.

6.2 User Study II: Haptic Knob

In contrast to physical controls, virtual controls displayed on tabletops cannot be felt. As a result, task precision and performance drop [48]. Moreover, lack of haptic feedback requires continuous visual attention on the controller. For example, graphical knobs with visual detents (notches) is frequently used in tabletop displays to rotate a virtual object in the scene or select an item from a menu using rotation gesture. Lack of haptic feedback makes it difficult for the user to precisely rotate the object or quickly select the item from the menu. Moreover, they cannot rest their fingers on the knob and focus on the virtual object or the menu.

An alternative to virtual control is tangible control. In this approach, portable physical controls are directly placed on a tabletop to augment visual interfaces with haptic feedback. These controls are detected with the help of touch sensing overlays or cameras. For example, PhotoHelix is a physical knob placed on a tabletop to interact with digital photo collection [14]. In this approach, one hand rotates the physical knob to control position on a helix-shaped calendar while the other hand inspects and modifies the digital photos. The translucent tangible knob in SLAP widgets can be used in various modes to interact with digital content depending on the application [55]. For example, the knob can be used in the “jog wheel” mode to find and mark specific frames in a digital video or in the “menu mode” to navigate through hierarchical menus. The user study conducted for “jog wheel” mode showed that the SLAP knob outperforms the virtual one in terms of task completion time and accuracy. While tangible controls provide increased task performance, they are physical, and are not configurable as virtual controls. Furthermore, they reduce the interaction area on the tabletop surface and restrict user movements.

6.2.1 Experiment

We used real-time dynamic gesture recognition ability of our table and electrostatic actuation technique to display a virtual knob with haptic feedback on our tabletop surface. In our experiments, subjects rotated the knob to navigate through a menu.

We modulated the frictional forces between their fingers rotating the knob and the touch screen to investigate if haptic feedback improved their task completion time, precision, and subjective sense of accomplishing the task. To modulate frictional forces, we applied a voltage signal to the conductive layer of the touch screen.

There were four sensory conditions (i.e. haptic feedback types) in our study (Fig. 6.8):

1. *Virtual (V)*: No artificial haptic feedback was displayed.
2. *Haptic Detent (HD)*: A pulse signal was transmitted to the touch screen to generate a “notch” (detent) effect while the subject crosses a sector during rotation (Fig. 6.8b). The purpose of haptic detent was to provide subjects with confirmation for the sector crossings, similar to a volume knob in a car.
3. *Haptic Detent with Constant Friction (HD+CF)*: In addition to the pulse signals at sector crossings, a sinusoidal voltage signal with a constant amplitude (100 Vpp) and frequency (180 Hz, at which minimum electrovibration detection threshold for human finger is obtained for constant voltage by authors in [2]) was transmitted to the touch screen within the sector boundaries to display frictional haptic feedback during rotation for better control and precision (Fig. 6.8c).
4. *Haptic Detent with Velocity-based Friction (HD+VF)*: The magnitude of the resistive frictional force was adjusted based on subjects' angular velocity. The motivation for this type of haptic feedback comes from a rate-controlled joystick used in gaming applications, which simply displays more feedback force for faster movements. This is achieved by modulating the frequency of the input voltage applied to the screen between 60 and 180 Hz while keeping the amplitude constant at 100 Vpp.

Sixteen subjects (2 female, 14 male) with an average age of 29 years (SD=5.24) participated in this experiment. Three subjects were left-handed, and none of the

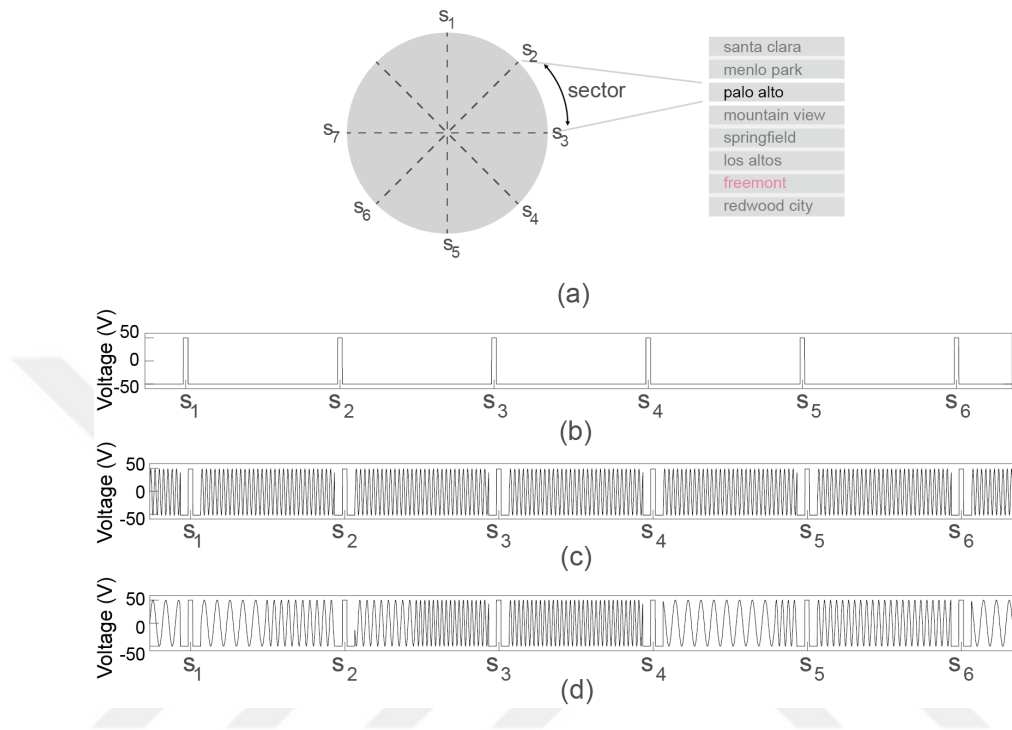


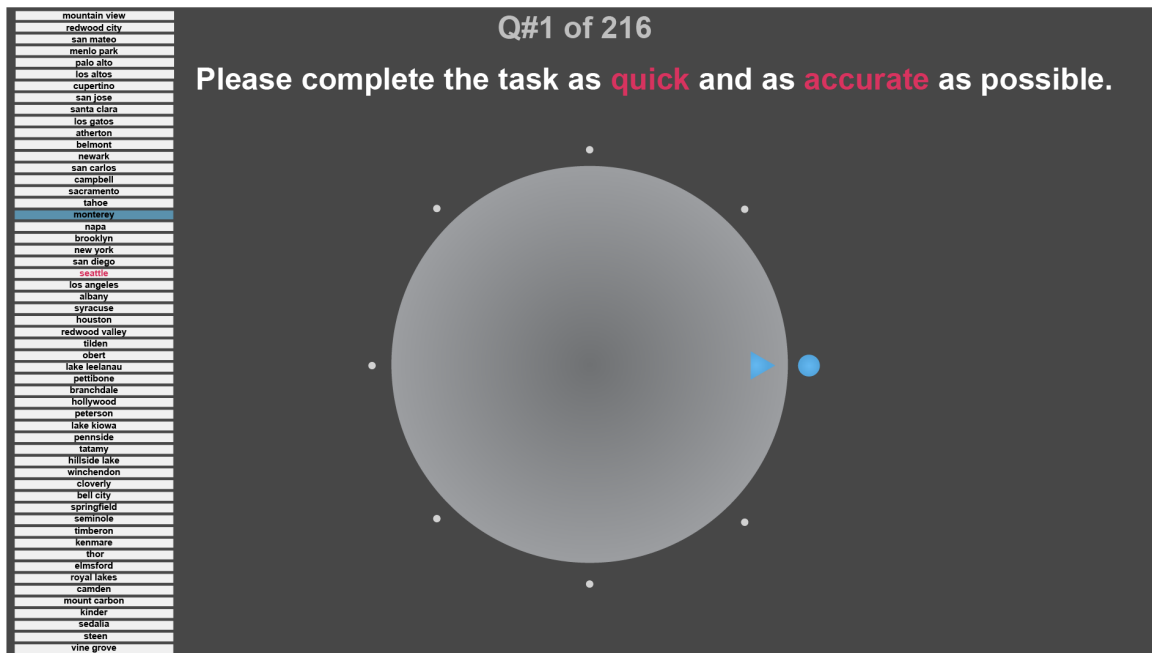
Figure 6.8: (a) A knob with eight sectors where each sector is mapped to an item on the menu. In our experiments, subjects navigate on the menu under four different sensory conditions: 1) virtual (no artificial haptic feedback), 2) haptic detent at sector crossings (b), 3) haptic detent and constant friction (c), and 4) haptic detent and velocity-based friction (d). The input voltage for each sensory condition is 100Vpp.

subjects had prior experience with electrostatic haptic feedback. They wore an anti-static wristband to their non-dominant hand, to connect their bodies directly to the ground, thus increasing the intensity of electrovibration. Subjects also wore active noise-cancelling headphones, playing white-noise, to block the environmental noise and help them focus on the task. The experiment took approximately sixty minutes to complete. The experiment consisted of three consecutive sessions: (i) preliminary, (ii) testing, and (iii) subjective evaluation. Prior to the experiment, all subjects were informed about the experimental procedure. The preliminary session helped subjects to get familiar with frictional haptic feedback displayed by electrovibration, rotation gesture, and the task itself (i.e. rotating the knob to navigate through a menu of

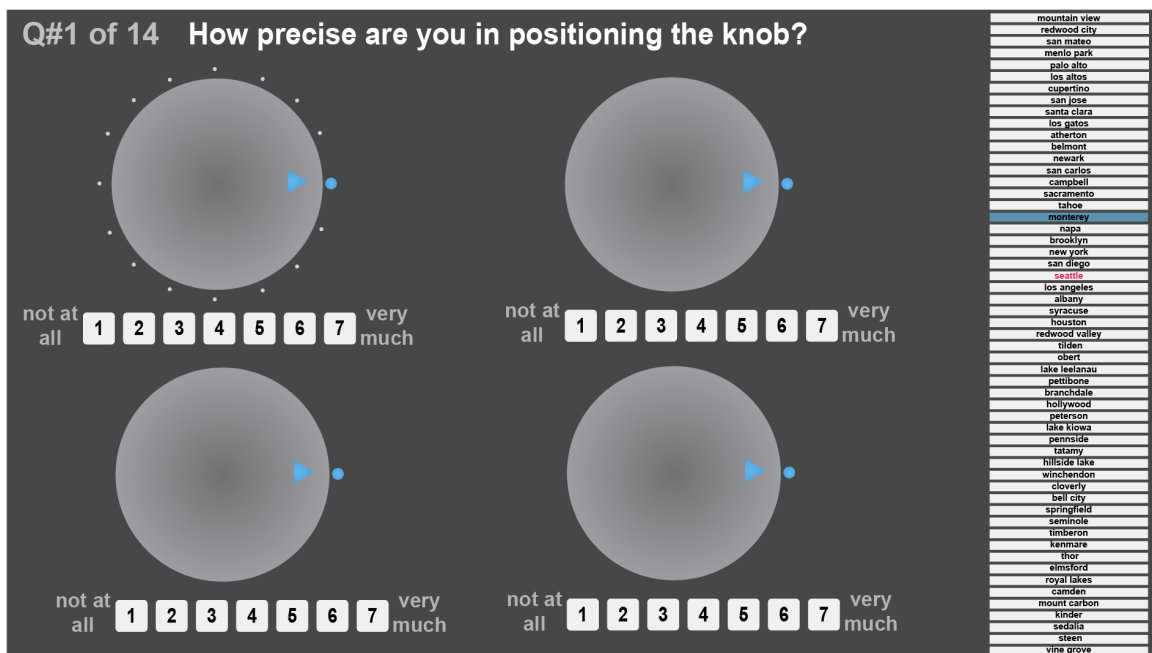
items). A particular rotation gesture was chosen to provide comparable interaction experience across subjects. This gesture is performed with two fingers; thumb was the pivot point while index finger followed a circular arc. During the experiment, subjects were asked to rotate the knob to navigate from a start city to a target city (marked with red color) on the menu consisting of randomized city names (Fig. 6.9a). As they navigated on the menu, a blue box highlighted the city that they were currently located. We investigated the effect of sector size, angular distance between the start and target cities, and the sensory conditions on the task performance in terms of task completion time and accuracy. There were three sector sizes (8, 16, 32 sectors) and three different angular distances between the start and target cities (135, 270, 450 degrees). For a given angular distance, the number of cities on the menu and the frequency of haptic detents between start and target cities varied since each sector always corresponded to one item on the menu. Subjects completed a total of 216 trials ($4 \text{ sensory conditions} \times 3 \text{ sector sizes} \times 3 \text{ angular distances} \times 6 \text{ repetitions}$). The trials were displayed in random order while the order was same for all subjects. After the experiment, subjects were asked to fill a questionnaire, displayed digitally on the table surface, containing a total of fourteen questions ($7 \text{ categories} \times 2 \text{ rephrased questions for each category}$). The questions aimed to measure their subjective experience under four sensory conditions (V, HD, HD+CF, HD+VF). For each question, 4 knobs (one for each sensory condition) were displayed on the screen at the same time (Fig. 6.9b), allowing subjects to experience and compare the sensory conditions, and enter their experience for each condition using a 7-point Likert scale. As a reminder of the task performed in the actual experiment, we also provided the subjects with the menu (list of cities) in each question.

6.2.2 Results

We evaluated the results of haptic knob experiments using quantitative metrics, as well as qualitative scales to understand the subjective responses to the haptic knob.



(a)



(b)

Figure 6.9: (a) A knob with eight sectors used in the actual experiments, and the menu is shown on the left, (b) user interface for the subjective evaluation phase.

Quantitative Results

To investigate the effects of sector size, the angular distance between start and target cities, and sensory condition, we applied three-way repeated measures ANOVA on dependent variables of task completion time, overshoot rate, and recovery time. Mauchly's test of sphericity was first performed to check whether the differences between the levels of the within-subject factors have equal variance. If the sphericity assumption was violated, the degrees of freedom was corrected using the Greenhouse-Geisser correction. Finally, Bonferroni corrected post-hoc analysis was carried out to investigate where the statistically significant differences between the levels of within-subject factors lie. The results for each quantitative metric can be summarized as follows:

1. *Task completion time* is the time it takes for a subject to navigate from start to target city in milliseconds. The results showed that number of sectors and angular distance significantly affected the task completion time ($p < 0.001$ for both variables). There was no significant three-way interaction ($p = 0.399$). However, there was a significant two-way interaction between sector size and angular distance ($p = 0.013$). Observations from simple main effects of these two factors showed that increasing either angular distance or number of sectors resulted in a statistically significant increase in task completion time. When the angular distance was fixed, although the physical distance that the fingers travel remained unchanged, subjects opted to slow down since they observed a greater number of cities had to be crossed between the start and target cities. Type of sensory feedback did not influence task completion time.
2. *Overshoot rate* is the total number of times that a subject missed the target city. Results indicated that number of sectors and angular distance have a statistically significant main effect on overshoot rate ($p < 0.001$ for both independent variables). Although there was no statistically significant three-way interaction, a statistically significant two-way interaction was observed between sector

size and angular distance again ($p=0.001$). Increasing sector size or decreasing angular distance increased overshoot rate. Subjects appeared to observe their rotation speed visually by looking at the blue indicator when the number of cities between start and target cities was increased, thus adjusted their speed to control the knob more precisely. Type of sensory feedback did not influence overshoot rate.

3. *Recovery time* is the time that it takes for a subject to reach target city after the first miss. Both number of sectors and angular distance were statistically significant main effects on this metric ($p<0.001$ for both independent variables). Subjects spent more time to recover the target when either sector size or angular distance was increased. Results showed that there was no significant interaction between any pair of independent variables. Type of sensory feedback did not influence recovery time.

Qualitative Results

The responses of the subjects to the questions (subjective scores) are given in Fig. 6.10. To evaluate these responses, we used one-way repeated measures ANOVA. Post-hoc tests with Bonferroni correction were used for multiple comparisons to understand the statistically significant differences between sensory conditions. The results of ANOVA for each category in the questionnaire are summarized below:

- *Effectiveness*: Subjects reported that the haptic knobs (HD, HD+CF, HD+VF) as being significantly more effective than the virtual knob (V) ($p=0.007$).
- *Ease of use*: Although the subjective scores suggest that the haptic knobs were easier to use compared to the virtual one, the difference between them was not statistically significant ($p=0.171$).
- *Efficiency (accuracy)*: Subjects stated that they selected the target more accurately when haptic feedback was present ($p=0.023$). This outcome does not

agree with the quantitative results for overshoot count and recovery time metrics.

- *Efficiency (time)*: Although subjects personally stated that they completed the task fastest with knobs displaying HD+CF and HD+VF feedback, the subjective evaluation scores were not statistically significant ($p=0.068$). This outcome agrees with the quantitative results for task completion time metric.
- *Interaction quality*: Subjects perceived that the haptic knobs were more intuitive than the virtual knob during their interaction ($p=0.026$).
- *Attractiveness*: The results suggest that the haptic knobs were more pleasant and attractive than the virtual one ($p=0.003$).
- *Dependability*: Subjects felt greater confidence while completing the task with the haptic knobs, since they perceived them to be more dependable and supportive than the virtual one ($p=0.013$).

6.2.3 Discussion

The quantitative results of the haptic knob experiment showed that frictional haptic feedback did not really improve the task performance in terms of completion time, number of overshoots, and recovery time after the first overshoot, when the same metrics were compared to that of no artificial haptic feedback. This result may initially appear to be surprising since several earlier studies in other domains have shown that haptic feedback improves task performance. However, it is important to emphasize that there is a major difference between our study and the earlier ones. In those studies, subjects who performed the task under visual feedback condition did not receive any haptic feedback at all. In our study, although there was no artificial friction under visual feedback condition, they still felt some friction when their fingers performed the rotation gesture. It appears that the additional friction displayed by

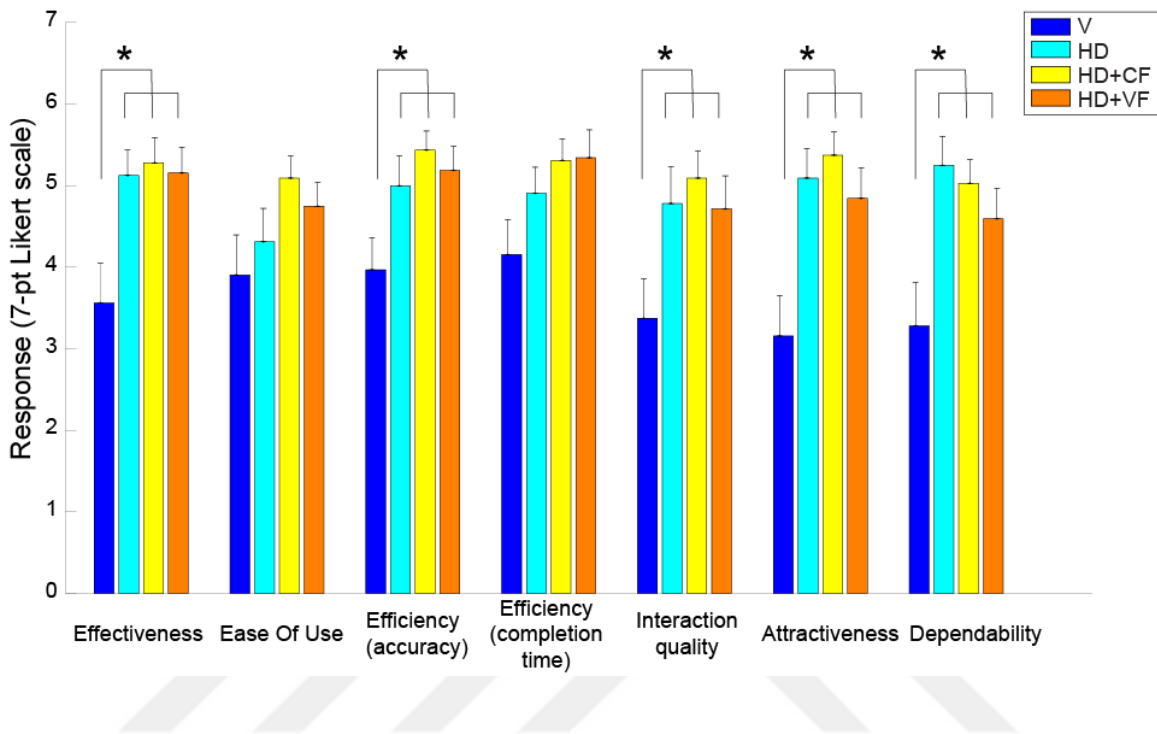


Figure 6.10: Means and standard errors of the subjective measures for each sensory condition (* The mean difference is significant at $p=0.05$ level).

electrovibration did not help them much in executing the task faster and with less error. This outcome may also be related to the nature of the rotation gesture used in our study. Two-finger rotation gesture provides more control to the user due to constrained wrist motion and slower rotational speed. Voelker et al. reported that the task accuracy with virtual rotary knob controlled with two fingers is comparable to those of tangible knobs, while the task completion is longer [ref32]. Finally, this outcome may also be related to the way that frictional haptic feedback displayed to the subjects in our study. Although we have tried a wide range of alternatives to provide haptic stimulus suitable for the knob, there are many other options that can be explored. For example, in HD condition, we utilized a pulse signal at sector crossings to imitate the feeling of detents. Alternatively, a detent can be, for example, rendered by leaving a gap between two subsequent pulses. A similar argument can be extended to the other haptic conditions. In our study, we utilized a sinusoidal voltage

to display constant frictional haptic feedback during knob rotation. Alternatively, an amplitude-modulated voltage signal can be utilized to display more friction close to the sector boundaries in order to slow down the knob rotation, and hence to improve task performance. As obvious from the short discussion above, there are several alternative choices for the design of haptic knob, which needs to be further explored in the future.

On the other hand, the subjective assessment following the knob experiments (via 14 questions in 7 different categories) showed that the subjects strongly preferred the haptic knobs over the virtual one in almost all categories (Fig. 6.10). The results are encouraging and suggest that adding haptic feedback to a virtual knob improves interaction quality, user experience, and also the confidence of the user. For example, it appears that feeling the detents while rotating the knob does not help much in terms of task performance, but allows users to receive a confirmation, which appears to improve their personal interaction experience and confidence.

Chapter 7

CONTRIBUTIONS AND FUTURE DIRECTIONS

This thesis presents the design of a novel multimodal tabletop that effectively combines visual and haptic modalities to provide an interactive experience to a user. The user conveys her/his intention of interaction via hand gestures [28], and HapTable recognizes these static and dynamic gestures in real time to display haptic feedback. The main contribution for this thesis could be summarized as follows:

- *Rich haptic feedback in normal and tangential direction* : HapTable is able to provide vibrotactile haptic feedback in normal direction, and frictional haptic feedback in tangential direction. To our knowledge, HapTable is the first tabletop that combines multiple haptic technologies and enables the usage of both at the same time or individually depending on the application.
- *Localized vibrotactile haptic feedback* : HapTable is able to provide localized vibrotactile haptic feedback using our proposed method. For example, it can create a flow effect underneath a stationary hand. To our knowledge, it is the first system to provide a localized feedback on a large, non hand-held surface.
- *Gesture-based haptic feedback* : HapTable provides haptic feedback based on the gesture performed. For example, one can rotate a knob on its surface and receive appropriate haptic feedback. To do this, the developer needs to select the suitable haptic feedback method and haptic signal.
- *One of a kind integration* : HapTable is one-of-a-kind integrated platform. While designing HapTable, we carefully considered how different gesture recognition, haptic, and display technologies can co-exist and provide feedback in a

timely manner to enhance the interaction.

We demonstrated the haptic feedback capabilities of our table via two example applications along with detailed user studies; one for static and one for dynamic gestures. However, HapTable is not restricted to only those gestures and can be potentially used to display haptic feedback for a variety of other hand gestures, with applications in information and data visualization, games, entertainment, and education.

As an example for an interaction triggered by a static gesture, we displayed directional vibrotactile haptic feedback to the index fingers of both hands and the single hand of the subjects. Using the piezo patches attached to the edges of the tabletop surface, we successfully created a travelling vibrotactile flow under their fingers and beneath their hand in all four directions. We are not aware of any earlier study investigating vibrotactile flow on large-size touch screens. Using the methods presented in this paper, it is possible to display localized and directional vibrotactile haptic feedback on our tabletop surface. Our future studies will investigate the potential applications of this technology in data visualization, education, and gaming. For example, in climate visualization, we imagine that a user can put their hand(s) on the tabletop surface to feel the direction of wind forces, virtually overlaid on some other graphical climate data. Considering the fact that climate data is complex and multi-dimensional, which overloads the visual channel, communicating some climate information, such as the wind forces, through haptic channel may alleviate the perceptual and cognitive load on the user, as suggested in [59]. Similarly, in an educational setting, a user could better appreciate granularity of different materials such as sand, pebbles, beads, and seeds by shaking a virtual cup containing its granules to feel their vibrations, rather than just observing their behavior visually.

As an example for dynamic gestures, we haptically rendered a virtual knob on the table surface using the principles of electrostatic actuation. We investigated the potential benefits of frictional haptic feedback on task performance and user experience in selecting an item from a pull-down menu by rotating the knob. We are not aware of any earlier studies on electrostatic haptic rendering of a virtual knob on a

touch surface. This required recognition of rotation gesture, tracking of individual finger positions, and displaying frictional forces to the user accordingly, all in real time. A knob is just one type of virtual control used in user interfaces and our future studies will investigate the haptic versions of the others such as a slider, switch, and keyboard. For example, a haptic slider can be rendered by modulating the friction between the user's finger and the surface as in the case of the haptic knob, while a key press can be simulated by localized vibrotactile effects using piezo patches. Once these controls are tested through user studies and designed as haptic widgets, they can be customized and integrated into various applications as a part of user interface.

In the applications mentioned above and the other potential ones, the challenge is to find the most effective mapping between the user hand gestures and the haptic effects. In fact, surface haptics is a new area of research and even the more fundamental relations between the voltage signals applied to the actuators and our haptic sensing and perception are not completely known yet. Without fully understanding those relations, developing an effective mapping between a gesture and haptic effect is highly challenging. HapTable contributes to this effort by providing a unified platform to create and evaluate various haptic effects using two surface haptic technologies individually or in a combined manner. In our study, we explored the former approach, but the latter may lead to richer effects due to its multi-modal nature. For example, the detents of the knob in our user study could be displayed by vibrotactile feedback to signal sector crossings, while frictional forces, displayed by electrovibration, can be used to control knob's rotation. With the aim of understanding the mapping between gestures and appropriate haptic feedback, future work can focus on creating and evaluating haptic stimuli for different gestures and virtual controls on HapTable.

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Appendix A

SURFACE MOTION DETECTION TECHNOLOGIES

A.1 Surface motion detection technologies

This appendix provides a review of current motion detection technologies and present our insights on how they can be used for haptic research. Our requirements for the preferred motion technology for HapTable were following:

- should not occlude visual display,
- should not interfere with surface haptic feedback mechanisms,
- should provide us enough information on hand posture for recognition.

With these requirements in mind, we classified available detection technologies under three main groups: pressure-requiring, capacitance-based, and optics-based technologies.

A.2 Pressure-requiring technologies

Technologies that require user to apply certain level of pressure on the surface of the touch screen is grouped under this category. These screens are compatible with electromechanical haptic actuation, since applying pressure may degrade but will not affect the sensation of a physical deformation. However, they are not suitable for electrostatic haptic actuation because their underlying technology is capacitance-based.

A.2.1 Resistive touch

Being one of the earliest touch technologies, resistive touch screens require users to press firmly on its surface to recognize finger location (Fig. A.1). These screens are low- cost and durable, and can sense touch by any tool, including gloved hand and stylus. However, resistive touch screens are able to detect upto three fingers and mainly used for pressing, and not for dragging due to pressure requirement. They are commonly used in airplane and bank ATMs (Automated Teller Machines). This technology cannot provide distinguishable hand posture images, and cannot recognize gestures

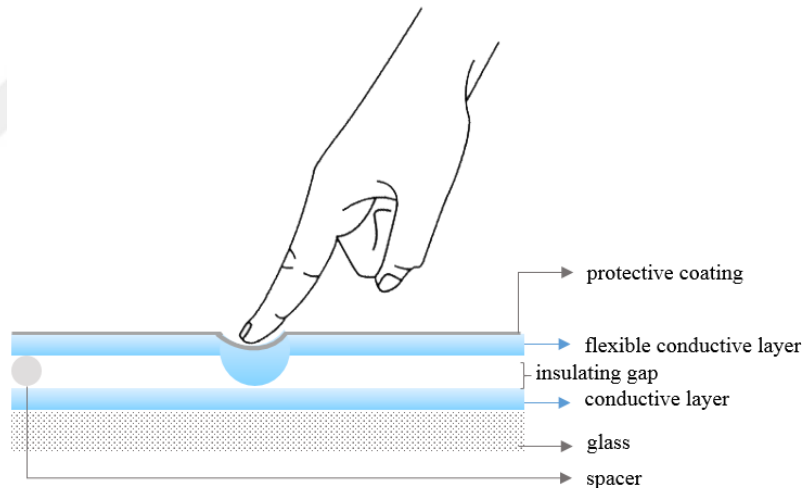


Figure A.1: Resistive touch screen technology consists of two conductive layers, with an insulating gap with spacers in between. When user applies pressure, the two conductive layers become closer and produce a change in the capacitance value. By looking at this value, these screens can detect a finger press.

A.2.2 FlexiTouch

Tekscan FlexiForce Pressure Mapping System is a flexible layer that can be put on any surface [[47]]. Similar to resistive touch screens, user needs to press firmly so that

controller can provide the pressure map of the hand as shown in Fig. A.2. Although it may be possible to recognize gestures, electrostatic-based haptic actuation will interfere with FlexiForce because pressing firmly on electrostatic screen diminishes perceiving the haptic effect. Moreover, since these screens are very flexible, it will diminish the effect of piezo haptics, too.

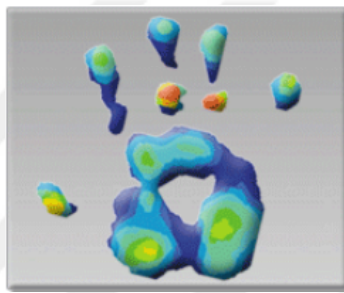


Figure A.2: Output of a FlexiForce pressure mapping system for a hand press. Colors indicate the amount of pressure.

A.3 Capacitance-based technologies

Capacitance-based technologies interfere with electrostatic actuation technologies because both systems are based on capacitance principle. When we place an electrostatic haptic feedback layer on a capacitive screen, voltage applied to haptic feedback layer is perceived as a touch input by the capacitive touch screen.

We believe that one solution for this problem is to use a controller than can switch between detecting a hand motion and providing haptic feedback at a high frequency. With this pre-determined switch frequency, users will not realize the absence of haptic feedback. Moreover, if a high resolution projected capacitive screen used, it might be possible to understand the hand gesture by looking at the capacitance value at each x and y intersection.

A.3.1 Surface Capacitive Touch

When user touches a surface capacitive screen with a capacitive instrument, such as finger or stylus, the amount of current at that touch position changes. By looking at the amount of change, the controller can precisely understand the touch position (Fig. A.3).

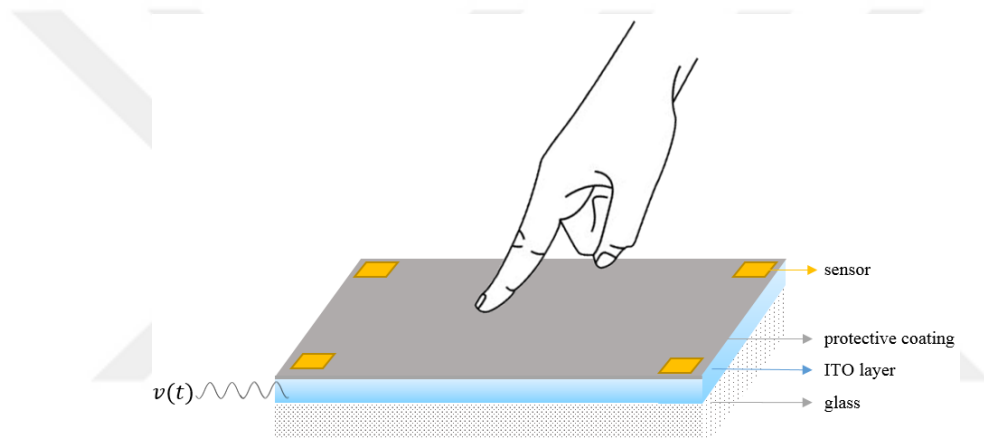


Figure A.3: Layers of a surface-capacitive screen.

Surface capacitive screens interfere with electrostatic haptic actuation, because both technologies work based on same capacitance principle. Moreover, surface capacitive screens are able to detect a single point on screen, and therefore, controller cannot provide us an image of hand posture.

A.3.2 Projected Capacitive Touch

Similar to surface capacitive touch screen, projected capacitive touch screens also work based on the capacitance principle and are incompatible with electrostatic actuation method. However, unlike surface capacitive screens, a grid of sensors on conductive layers (instead of four sensors at corners) detects the change in the capacitance at the intersections of rows and columns. Therefore, project capacitive screens provide more accurate touch location.

Depending on the controller, projected capacitive touch screens can detect relative and non-relative motions. However, there is still work needed to be done to understand the mapping between the capacitance change and hand postures in order to convert data provided by projected capacitive screens into hand postures. By developing new controllers, multi-pad, grid, and diamond patterned projected capacitive screens may be used both as a hand motion detection and haptic screen.

A.4 Optics-based technologies

Optics-based solutions use either infrared or laser light to detect motion through cameras. However, electromechanical based haptic actuation methods physically deform the surface to provide haptic feedback and laser light based systems are affected by this deformation. Therefore, we will focus on infrared light based setups. In general, infrared- based systems have infrared light sources illuminating the surface, while infrared light sensors detect the absence or presence, or the intensity of infrared light.

A.4.1 Infrared Touch Screens

Matrix-based infrared (IR) touch screens are the most common technology among IR- based touch screens. Two adjacent edges of this rectangular screen have IR light emitting diodes (LEDs) and the remaining two edges have infrared light detectors that sense the light coming from the corresponding edge. When a finger obstructs the infrared light, light detectors in both edges can easily detect the location where the light is absent; i.e. the location of the finger.

The advantage of this optical touch screen technology is that it can be used with any surface haptic technology since it is mounted on the borders of the screen, rather than covering the screen surface. However, natural hand motions can not be recognized due to the matrix structure of the LEDs and light detectors. As shown in Fig. A.4a, each infrared LED in yellow bezels corresponds to an infrared sensor in blue bezel. The corresponding sensor detects the absence or existence of light. Therefore, it forms a matrix structure on screen. When a hand touches as in Fig. A.4b, image

perceived by controller will be similar to Fig. A.4c. In this image, we cannot understand whether this was a hand with fingers spread or not. Therefore, resolution of a matrix IR screen is limited by the sensor width. Moreover, such screens cannot track two fingers rotating.

More precise hand motion detection can be achieved using different arrangements of light detectors such as BaantoTM. By placing two 90° field of view cameras on two adjacent corners and two 170° field of view camera in between, they can provide a better image of hand motions by detecting absence of infrared light coming from remaining three edges [51]. Yet, difference between fingers separated from each other and fingers held together still cannot be detected accurately.

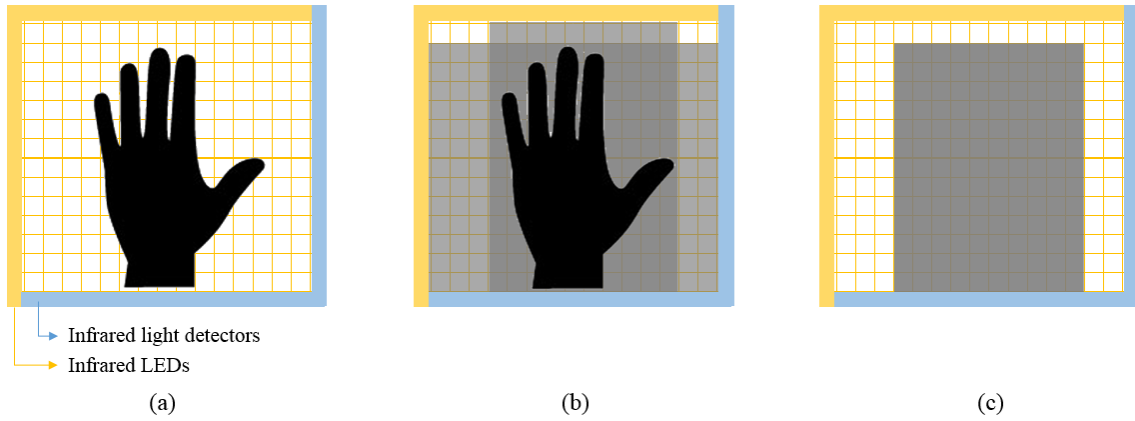


Figure A.4: Matrix infrared touch screen: (a)structure, (b)hand occluding light for detection, and (c)object in contact perceived by controller.

A.4.2 Frustrated Total Internal Reflection

In Frustrated Total Internal Reflection (FTIR), infrared light is directed into the acrylic surface used as the visual display. When user touches to acrylic surface, the light reaches to the contact point is reflected. This causes an intense infrared light at the contact point, which is detected by the cameras below [13]. The visual display is achieved through a projector below the surface.

Although it provides a sufficient hand posture image for gesture recognition, we need a compliant surface on top of the acrylic that may interfere with both electrostatic and electromechanical haptic actuation. Another drawback is that when we provide electromechanical vibration by creating a physical deformation on acrylic surface, the detection mechanism may fail due to light scattering in the acrylic surface.

A.4.3 Rear Diffused Illumination

In Rear Diffused Illumination (Rear DI), infrared light is directed to touch surface from below. When user touches the surface, the light is reflected back and camera below the surface are able to capture the reflected light brighter. The top layer, which is a diffuser for a projector, is used for both even illumination of tabletop and to project the display. This technology was used for building Microsoft Surface 1.0 [54].

The advantage of this system is that it allows us to track objects and to capture hand motions. Moreover, it will not interfere with any haptic actuation method because surface illumination will not be affected by surface deformations. However, for accurate tracking, system requires an even illumination on the surface. To get an even illumination, wide-angle infrared lights are used for this purpose.

A.4.4 In-Cell Light-Sensing Touch

This technology is commercially available in Samsung SUR40. It uses an LCD monitor for visual display instead of a projector, and it does not require infrared cameras. The infrared light and light detectors are embedded in the LCD cell [54].

With this touch technology, we are able to see the hand motion in a higher resolution, and we do not need a thick table to contain the computer, infrared lights and cameras. Since it is an optics-based system, it does not interfere with any haptic technology.

Appendix B

EXAMPLES FOR HAND MOTION TAXONOMY

B.1 Examples for Hand Motion Taxonomy

In Chapter 4, we have presented a taxonomy for hand motions and explained each class in detail. In order to guide our applications and haptic and motion research in future, we have searched verbs in WordNet and assigned each to the related taxonomy class [49].

Table B.1 contains verb list for relative motions. Empty cell refers to the cell above. Likewise, table B.2 has the same structure, and provides verbs for non-relative motions.

Table B.1: Examples for relative (dynamic) hand motion categories

Taxonomy Level		Motion Verbs
Level 2	Level 3	
Manipulative	1-Hand,	draw, smudge, scratch, remove, polish, cut, tense
	1-Finger	(a rope fixed at two points), turn on the switch
	1-Hand,	rotate, flip a coin, stretch, extend, direct, lead
	2-Finger	
	1-Hand,	rotate, flip a coin, stretch, extend, direct, leadshape
	Multiple-Fingers	clay, blend, turn, pour
	1-Hand,	flatten, iron, smoothen, shape, compress, deform,
	Palm involved	kneading rubbing
Continued on next page, relative motions		

Table B.1 – continued from previous page, relative motion

Taxonomy Level		Motion Verbs
Level 2	Level 3	
Exploratory	2-Hand, 1-Finger	squeeze, stretch, move
	2-Hand, 2-Finger	elongate, turn upside down, reverse, tear, rip
	2-Hand, Multiple-Fingers	twist, contract
	2-Hand, Palm involved	flatten, using rolling pin (for dough), thicken
	1-Hand, 1-Finger	move back and forth(texture), push/pull (weight, hardness), contour-following
	1-Hand, 2-Finger	squeeze (hardness), turn, rotate(exact shape), twirl
	1-Hand, Multiple-Fingers	move (3D shape), open a cap (function), crush, crumble, gyrate (function)
	1-Hand, Palm involved	move back and forth (texture)
	2-Hand, 1-Finger	stretch, squeeze (elasticity)
	2-Hand, 2-Finger	lift, raise (weight)
	2-Hand, Multiple-Fingers	explore, rotate (functionality)
	2-Hand, Palm involved	resurface, slide towards opposite directions
Continued on next page, relative motions		

Table B.1 – continued from previous page, relative motion

Taxonomy Level		Motion Verbs
Level 2	Level 3	
Gestural	1-Hand, 1-Finger	lasso selection, slither [slide down along a surface], accelerate
	1-Hand, 2-Finger	zip, walk, run
	1-Hand, Multiple-Fingers	throw, slap, bound, seek, search through, look for
	1-Hand, Palm involved	grasping, using a handle, wave
	2-Hand, 1-Finger	crash, group, merge
	2-Hand, 2-Finger	copy, duplicate, resurface (a hidden item)
	2-Hand, Multiple-Fingers	compare, tell apart
	2-Hand, Palm involved	gather, group, pile

Table B.2: Examples for non-relative (static) hand motion categories

Taxonomy Level		Motion Verbs
Level 2	Level 3	
Manipulative	1-Hand, 1-Finger	erase, tilt, slant, disturbing a flow, blot, stain, poke
	1-Hand, 2-Finger	deform, indent
	1-Hand, Multiple-Fingers	bend, whirl, spin (by tapping), cut
	1-Hand, Palm involved	push, compress (spring)
	2-Hand, 1-Finger	deform
	2-Hand, 2-Finger	stick (the item on a surface), attach
	2-Hand, Multiple-Fingers	drill (holes)
	2-Hand, Palm involved	divert, block, ban
	1-Hand, 1-Finger	explore (rough texture), tap, dip (viscosity)
	1-Hand, 2-Finger	knocking (hardness, material)
Exploratory	1-Hand, Multiple-Fingers	touch (temperature), rest
Continued on next page, relative motions		

Table B.2 – continued from previous page, non-relative motion

Taxonomy Level		Non-relative Motion Verbs
Level 2	Level 3	
Gestural	1-Hand, Palm involved	compare (texture, tempera- ture)
	2-Hand, 1-Finger	lift, unhide
	2-Hand, 2-Finger	chop (by one hand, while other keeps the object in-place, hardness)
	2-Hand, Multiple-Fingers	hold (global shape)
	2-Hand, Palm involved	pushing a button, tapping, waiting, spot, point, thumb up, thumb down
	1-Hand, 1-Finger	showing number, peace, cir-cumvolve, pick, select, mark
	1-Hand, 2-Finger	dash [strike/smash violently], strike
	1-Hand, Multiple-Fingers	stamp, accept, authenticate, push, straighten, smoothen, channelize, catch
	1-Hand, Palm involved	
	2-Hand, 1-Finger	constrain
	2-Hand, 2-Finger	resurface
	2-Hand, Multiple-Fingers	protect, hide, reading Braille, play keys

Continued on next page, relative motions

Table B.2 – continued from previous page, non-relative motion

Taxonomy Level		Non-relative Motion Verbs
Level 2	Level 3	
	2-Hand, Palm involved	hold, fix, push, agree, offer (a present)

Appendix C

PARAMETERS USED IN THE HUMAN STUDIES

C.1 Parameters used in Flow Experiment

Pair	distance (cm)	Point L active, R passive			Point R active, L passive		
		f_1	Δd_1	p_1	f_2	Δd_2	p_2
		(Hz)	(μm)		(Hz)	(μm)	
F	8.49	471.0	0.27	P_B	578.0	1.32	P_{ALL}
1	8.49	595.5	1.42	P_{ALL}	236.5	0.39	P_D
2	12	129.0	0.10	P_D	426.5	0.28	P_{ALL}
3	26.83	538.0	0.70	P_A	586.0	0.88	P_{ALL}
4	49.48	428.0	1.61	P_{ALL}	187.5	0.74	P_{ALL}

Table C.1: The distance between the test points for each pair, actuation frequencies (f_1, f_2), the piezo patches used for actuation (p_1, p_2), and the displacement differences between the test points ($\Delta d_1, \Delta d_2$) are given in the table on the right. The excitation voltage for each pair is $100V_{pp}$.

Region	Direction	First half	Second half		
		of the signal	of the signal		
		f_1 (Hz)	p_1	f_2 (Hz)	p_2
R_1	LR	194.0	P_C	263.0	P_A
R_1	UD	341.0	P_D	238.0	P_D
R_2	LR	355.0	P_D	461.0	P_A
R_2	UD	238.0	P_D	354.0	P_D
R_3	LR	589.0	P_C	538.0	P_C
R_3	UD	249.0	P_B	495.0	P_D
R_4	LR	464.0	P_A	355.0	P_D
R_4	UD	471.0	P_D	415.0	P_D

Table C.2: Actuation frequencies (f_1 , f_2) and the piezo patches used for actuation (p_1 , p_2) are given for the flow experiments using the hand region. The excitation voltage for each pair was adjusted by human sensitivity curve.

C.2 Parameters used in Knob Experiment

Sensory Condition	Voltage		Haptic Stimuli
	V	n/a	
HD	100 V _{pp}	n/a	• 1 msec square wave at sector crossing
HD+CF	100 V _{pp}	n/a	• 1 msec square wave at sector crossing • 180Hz sine wave between sector crossings
HD+VF	100 V _{pp}	n/a	• 1 msec square wave at sector crossing • 60 to 180Hz sine wave between sector crossings, depending on the rotational velocity

Table C.3: Haptic stimuli rules for four different sensory conditions tested in knob experiments.

Appendix D

INSTRUCTIONS USED IN THE HUMAN STUDIES

D.1 User Instructions for Flow Experiment

D.1.1 User Instructions for Flow Experiment Between Two Fingers

Thank you for volunteering to participate in this user study. Please read through the information sheet, and ask any questions that you may have before the experiment begins and during trial session. The experimenter will not answer any questions afterwards.

Before beginning the experiment, please note that we will not collect or publish any information that may reveal your identity. You are free to withdraw from the study at any time and without giving any reason for withdrawal.

The goal of this experiment is to recognize the direction of the flow taking place between two index fingers of each hand as soon as possible. We will present a pre-determined location to place your fingers. After your fingers are placed, system will recognize them and provide haptic stimuli from one finger to another. The experiment takes upto 15 minutes.

Prior to the experiment, experimenter will help you to prepare for the experiment using the following procedure:

- Experimenter will take measurement of your finger size.
- Experimenter will clean your finger tips using ethanol.
- Experimenter will provide noise-cancelling headphones, playing white-noise to

block any audio cues coming from the system. Please put the headphones on, and adjust them accordingly.

- Please turn off any electronic devices and remove your accessories (rings, bracelets, watches) prior to the experiment.

D.1.2 User Instructions for Flow Experiment Underneath Hand

Thank you for volunteering to participate in this user study. Please read through the information sheet, and ask any questions that you may have before the experiment begins and during trial session. The experimenter will not answer any questions afterwards.

Before beginning the experiment, please note that we will not collect or publish any information that may reveal your identity. You are free to withdraw from the study at any time and without giving any reason for withdrawal.

The goal of this experiment is to recognize the direction of the flow taking place beneath your hand as soon as possible. We will present a pre-determined location to place your hand. After your hand is placed, system will recognize your hand and provide haptic feedback indicating a direction. This direction can be one of the four following directions shown in Figure D.1. The experiment takes upto 25 minutes.

Prior to the experiment, experimenter will help you to prepare for the experiment using the following procedure:

- Experimenter will take measurement of your hand size.
- Experimenter will clean your hand using ethanol.
- Please place your hand at the designated location D.2. Your fingers should be closed as shown in the figure.
- Experimenter will provide noise-cancelling headphones, playing white-noise to block any audio cues coming from the system. Please put the headphones on,

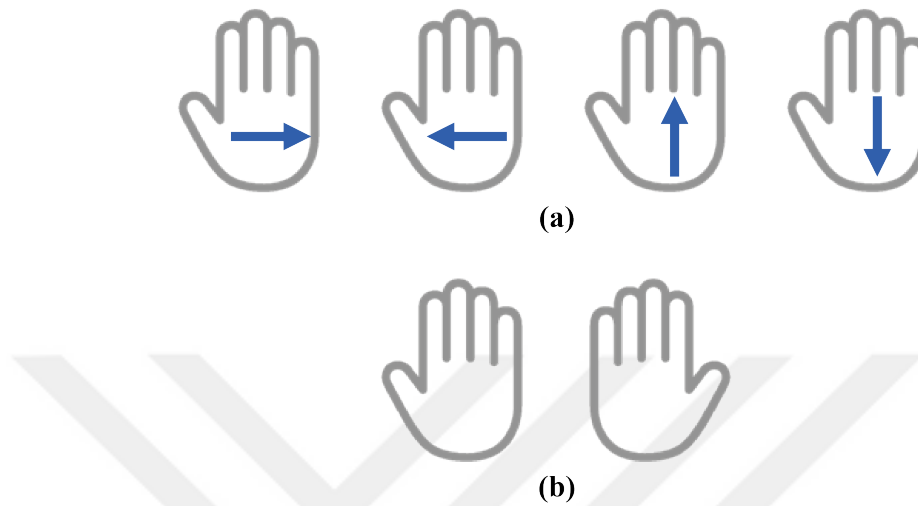


Figure D.1: (a) One of the four flow directions will take place underneath your hand: Left to right, right to left, down to up, and up to down as shown with arrows. (b) Hand image changes for each task, indicating whether you should place your left or right hand.

and adjust them accordingly.

- Please turn off any electronic devices and remove your accessories (rings, bracelets, watches) prior to the experiment.

This experiment consists of two phases : (1) trial session, and (2) actual experiment. The user interface for both phases is the same, as shown in Figure D.2. First, place your hand at the location on the screen Figure D.2a. The text located on top will help you throughout the experiment. After the haptic stimuli ends, you will have two options (Figure D.2b): (1) tap on the arrow direction button that is closest to the flow effect you have experienced, or (2) replay the signal.

The trial session aims to familiarize you with the haptic stimuli and the user interface. In this session, you will be presented with 40 flow effects at one location. During this session, you can replay the stimulus as many times as you wish, you can ask any question to the experimenter, and you can adjust your headphones if necessary. After this session is completed, you can take a break.

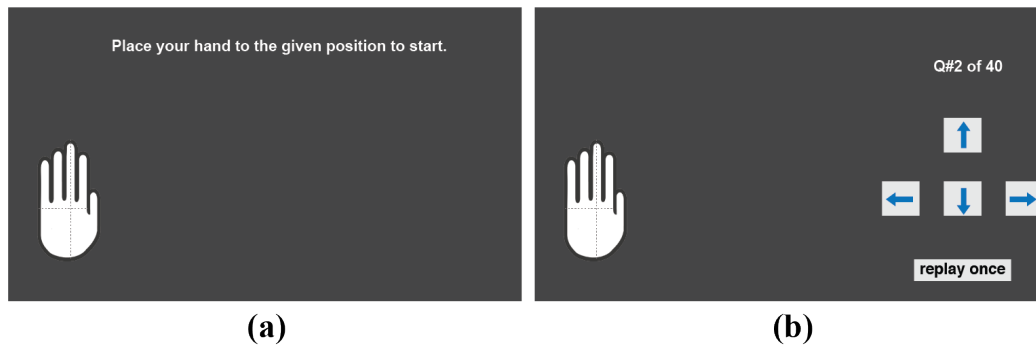


Figure D.2: Screenshot of the experiment at a given time : (a) System will present you a designated location to place your hand. Once you place your hand, system will recognize it and actuate the screen. Once the signal is finished, it will switch to the screen in (b). It will provide you four arrow buttons to select the direction from, and the replay button.

In the actual experiment, 160 flow effects will be presented at four different locations. Please note that you cannot ask any question to the experimenter during this phase. You can replay the given stimuli only once. If you are not sure about the answer, please select the closest one using one of the four arrow buttons shown: If flow has started on the right-side of your hand, and continued towards the left-side, then you should choose “right to left”.

Since hand size varies between participants, the hand shape shown will not be correct for everyone. Please follow the guidelines below to correctly place your hand:

- Align your hand’s vertical axis (middle finger to wrist) to the vertical dotted line.
- The bottom of your hand should align to the bottom of the image.
- Rest your hand at a comfortable position. Make sure that you do not apply pressure towards the touch surface, since this will dampen the vibration.
- Please remove any accessories around your hands and wrists (rings, bracelets, watches) prior to the experiment.

If you have any questions, please ask before the experiment starts. During the experiment, you will not be permitted to ask any questions. The results from this study will be kept for our data analysis. All experimental data will be used anonymously and for research purposes only.



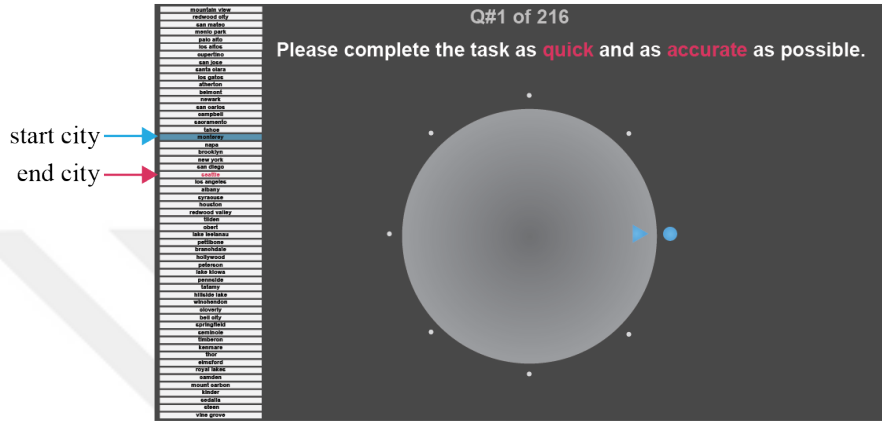
D.2 User Instructions for Knob Experiment

Thank you for volunteering to participate in this user study. Please read through the information sheet, and ask any questions that you may have before the experiment begins and during trial session. The experimenter will not answer any questions afterwards.

Before beginning the experiment, please note that we will not collect or publish any information that may reveal your identity. You are free to withdraw from the study at any time and without giving any reason for withdrawal.

The goal of this experiment is to control a virtual knob to navigate a long menu. The task is to go from one city to another on this menu **as fast and as accurate as possible** by rotating the knob shown on the tabletop display. The experiment will have three phases: (1) pilot experiment, (2) actual experiment, (3) subjective evaluation. The whole experiment will take approximately 40 minutes.

The results from this study will be kept for our data analysis. All experimental data will be used anonymously and for research purposes only.



(a)



(b)

Figure D.3: Screenshots of the experiment user interface at two stages : (a) Before starting rotation : The menu with city names is shown on the left. Blue box indicates the start city, and the red-colored text indicates the end city. The task is to go from start to end city using the knob at the center. If you are left handed, please ask the experimenter to switch the locations for knob and the menu. (b) After completing the task: "target found!" will appear along with a "Next" button. Please press "Next" to proceed to the next trial.

D.2.1 Instructions for Pilot and Actual Experiment

The pilot and actual experiment share the same user interface. You are allowed to ask questions to the experimenter during pilot experiment, but not during the actual experiment.

Prior to the experiment, experimenter will help you to prepare for the experiment using the following procedure:

- Experimenter will clean your index finger using ethanol.
- Experimenter will put a finer cot on the thumb of your dominant hand.
- Your body will be grounded by attaching an antistatic bracelet on your non-dominant hand wrist.
- Experimenter will provide noise-cancelling headphones, playing white-noise to block any audio cues coming from the system. Please put the headphones on, and adjust them accordingly.
- Please turn off any electronic devices and remove your accessories (rings, bracelets, watches) prior to the experiment.

During the pilot experiment, you will work with the experimenter to make you feel comfortable with the rotating gesture. This gesture uses two fingers, thumb and index finger as shown in Figure D.4. Your thumb will be the pivot point, whereas index finger moves in a circular fashion, rotating the knob. The thumb will not move during the gesture, only index finger moves. You can reposition your fingers when necessary. You can lift your hand during the rotation gesture, or move your index figure clock or counter-clock wise as you wish. Once you reach the target city, you will see "Target Found" text on the screen. Please press "Next" button to proceed to the next trial. The pilot experiment has 18 trials, and you are allowed to ask questions to the experimenter. You can take a break between pilot and actual experiment.

Once you complete the pilot experiment, the actual experiment will start. There are 216 trials in the actual experiment, and you are allowed to take break when needed.

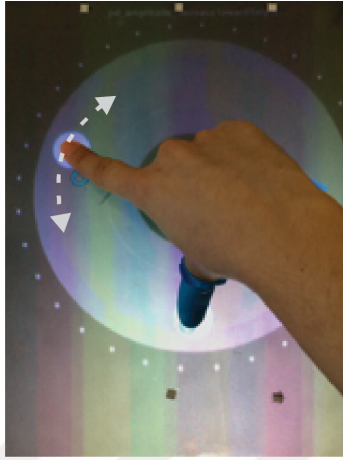


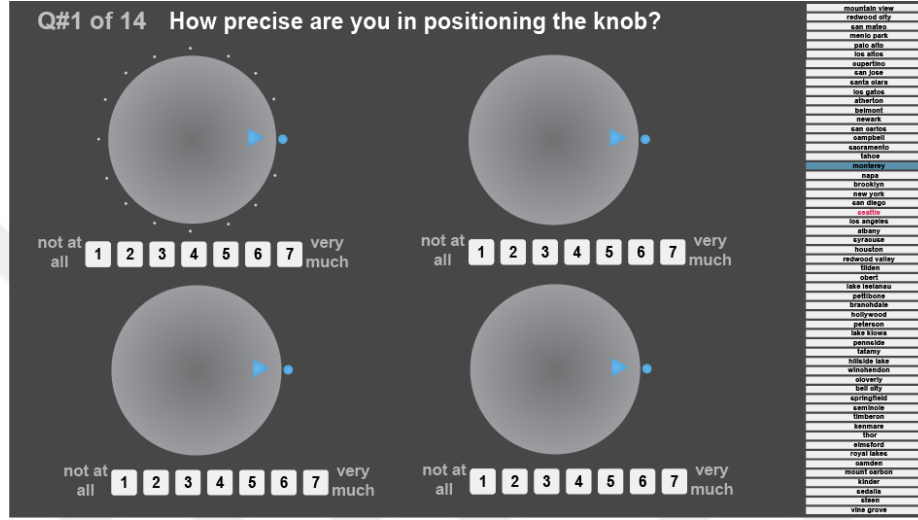
Figure D.4: Experimenter showing the rotation gesture.

However, you are not allowed to talk to the experimenter during this experiment and during the breaks.

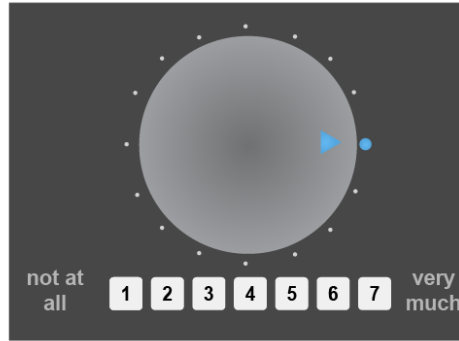
D.2.2 Instructions for Subjective Evaluation

The subjective evaluation phase will present you a subjective question along with the four knobs, each with a different configuration. Beneath each configuration, there will be seven buttons numbered from one to seven, representing the answers for a 7-point Likert scale $??$. Please choose one of the buttons. Once you choose an answer for each configuration, "Next" button will appear at the right-bottom corner. Please proceed to next questions by pressing this button. In total, 14 questions will be presented.

At the end of the subjective evaluation, there will be an informal conversation with the experimenter for additional comments.



(a)



(b)

Figure D.5: (a) Screenshot of the experiment at a given time : On left, you can see four different knobs. You can repeat the task as many times as you want, with any knob shown before your final decision. (b) Each knob with each condition has a button to answer presented question using 7-point Likert scale. In this scale, 1 means "not at all", and 7 means "very much".

Appendix E

QUESTIONNAIRES USED IN THE HUMAN STUDIES

E.1 User background questionnaire for all experiments

Thank you for participating in our user study. Before you leave, please take a few minutes to fill out the following questionnaire. This questionnaire will not be associated with your identity, and will be stored anonymously and only for research purposes.

Sex : F M

Birth Year : 19.....

Dominant Hand : Left Right Ambidexterous

Hand Width : mm

Hand Height : mm

E.2 Questionnaire used in Subjective Evaluation for Knob Study

This questionnaire has been displayed digitally (as shown in Figure D.3), along with four knobs. Each knob represented a different sensory condition, and participants were allowed to try each as long as necessary. Underneath each knob, a collection of buttons for each available score in 7-point Likert scale was presented. Participants are allowed to change any score entered prior to moving on to the next question. Two questions were asked for each metric, and all fourteen questions were randomized in order. Questions asked along with the metric they represented are given in Table E.1.

Metric	Question
Effectiveness	How effective is the knob?
	How useful is the knob?
Ease of use	How easy is it to control the knob?
	How demanding is it to adjust the knob?
Efficiency	How accurate are you in positioning the knob?
(accuracy)	How precise are you in positioning the knob?
Efficiency	How quick are you in performing the task with the knob?
(completion time)	How fast are you in executing the task with knob?
Interaction quality	How natural is your interaction with the knob?
	How intuitive is your interaction with the knob?
Interaction quality	How natural is your interaction with the knob?
	How intuitive is your interaction with the knob?
Attractiveness	How pleasant is your experience with the knob?
	How enjoyable is your interaction with the knob?
Dependability	How supportive is the knob during your interaction?
	How complementary is the knob during your interaction?

Table E.1: The questionnaire displayed digitally on the table surface, along with the four knobs -one for each sensory condition.