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UNIVERSITI TEKNOLOGI PETRONAS

EVALUATION OF PHYSICAL FINGER INPUT PROPERTIES FOR PRECISE TARGET SELECTION

By

AHSANULLAH

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfillment of the requirements for the degree stated.

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EVALUATION OF PHYSICAL FINGER INPUT PROPERTIES FOR PRECISE TARGET SELECTION

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AHSANULLAH

A Thesis

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PERAK

NOVEMBER 2011

DECLARATION OF THESIS

Title of thesis	Evaluation of Physical Finger Input Properties for Precise Target Selection

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Date :	Date :

DEDICATION

I dedicate this research work to my beloved ***parent*****s**, ***brothers, teachers***, and ***friends*** who have always been a great moral and practical support in my life.

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ABSTRACT

The multi-touch tabletop display provides a collaborative workspace for multiple users around a table. Users can perform direct and natural multi-touch interaction to select target elements using their bare fingers. However, physical size of fingertip varies from one person to another which generally introduces a fat finger problem. Consequently, it creates the imprecise selection of small size target elements during direct multi-touch input.

In this respect, an attempt is made to evaluate the physical finger input properties, i.e. contact area and shape in the context of imprecise selection. The research methodology is proposed which consists of various phases, i.e. development of the multi-touch tabletop display, experimental designs, and a survey. The developed tabletop display allows users to perform multi-touch interaction using their fingers. It is used to investigate the physical input properties and the specification of the fingers' angle of approach for multi-touch interaction.

In the first experiment, physical finger input properties have been investigated and the outcome suggests that there is a difference in the individuals' fingertip contact area and shapes. Additionally, a study related to the specification of the finger's angle of approach when interacting with a tabletop display has been conducted. It shows that the majority of users preferred interacting with the tabletop display using the oblique finger touch method rather than vertical. It provides a suitable foundation for the evaluation of physical finger input properties on a large scale.

In the second experiment, only the physical input properties of the index finger have been evaluated and the results reveal that there is a difference in the individuals' fingertip contact areas and shapes among different groups. It is validated through statistical analysis that there is significant difference in the contact areas for different groups. This study reveals to us the variation in the individuals' fingertip contact areas

and shapes which may increase imprecise selection. Moreover, the results of this study recommend different sizes and shapes of target elements. In this respect, the appropriate design and configuration of these elements on sensitive displays can lead to a more precise selection in direct multi-touch input.

ABSTRAK

Paparan multi-sesentuh permukaan meja menyediakan ruang kerja bagi beberapa pengguna bekerja bersama-sama di sekitar meja tersebut. Pengguna boleh menyentuh secara langsung dan berinteraksi seperti lazimnya dengan pelbagai cara untuk memilih elemen sasaran menggunakan jari mereka. Walau bagaimanapun, saiz fizikal hujung jari berbeza dari seseorang ke seseorang yang umumnya menjerumus kepada masalah jari yang besar. Oleh itu, ia menyebabkan pemilihan sasaran elemen saiz kecil yang tidak tepat pada input langsung multi-sesentuh.

Dalam hal ini, usaha telah dibuat untuk menilai ciri-ciri fizikal jari, iaitu kawasan sentuhan dan bentuk jari dalam konteks pemilihan tidak tepat. Kaedah penyelidikan yang dicadangkan yang terdiri daripada pelbagai fasa iaitu paparan multi-sesentuh permukaan meja, reka bentuk uji kaji, dan kaji selidik. Paparan permukaan meja membolehkan pengguna melakukan pelbagai sentuhan menggunakan jari mereka. Ia digunakan untuk menentukan sifat-sifat fizikal dan spesifikasi sudut jari untuk interaksi secara berbilang sentuh.

Dalam eksperimen pertama, sifat fizikal jari telah ditentukan dan keputusan menunjukkan bahawa terdapat perbezaan di kawasan sentuhan hujung jari dan bentuk sentuhan hujung jari tersebut. Selain itu, kajian yang berkaitan dengan spesifikasi sudut jari apabila berinteraksi dengan paparan permukaan meja telah dijalankan. Ia menunjukkan bahawa majoriti pengguna suka untuk berinteraksi dengan paparan permukaan meja dengan menggunakan sentuhan jari secara menyerong dan bukannya menegak. Ia menyediakan asas yang sesuai untuk penilaian ciri-ciri fizikal jari secara meluas.

Dalam eksperimen kedua, hanya ciri-ciri fizikal jari telunjuk telah dinilai. Keputusan menunjukkan bahawa terdapat perbezaan di kawasan sentuhan hujung jari dan bentuk sentuhan hujung jari di kalangan kategori jari yang berbeza. Ia disahkan melalui analisis statistik bahawa terdapat perbezaan yang signifikan dalam kawasan yang disentuh bagi kumpulan yang berbeza. Kajian ini mendedahkan bahawa perubahan di kawasan hujung jari individu dan bentuk sentuhan hujung jari boleh menyebabkan pilihan yang tidak tepat lebih kerap berlaku. Selain itu, keputusan kajian ini mencadangkan saiz dan bentuk sasaran. Dalam hal ini, reka bentuk yang sesuai dan konfigurasi elemen pada paparan yang sensitif boleh membawa kepada pilihan yang lebih tepat dalam input langsung multi-sesentuh.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

API: Application Programming Interface

ATM: Automated Teller Machine

ANOVA: Analysis of Variance

CMOS: Complementary Metal Oxide Semiconductor

CCD: Charge Couple Device

CCTV: Closed Circuit Television

CLI: Command Line Interface

C.P.U: Central Processing Unit

CRT: Cathode Ray Tube

CNN: Cable News Networks

DLP: Digital Light Processing

DOF: Degree Of Freedom

DI: Diffuse Illumination

FTIR: Frustrated Total Internal Reflection

GUI: Graphical User Interface

GPS: Global Positioning System

IR LEDs: Infrared Light Emitting Diodes

I/O: Input/Output

IRs: Infrared Illuminators

LCD: Liquid Crystal Display

MSM: Mean Square Model

MERL: Mitsubishi Electric Research Laboratory

NUI: Natural User Interface

PDA: Personal Digital Assistant

SAW: Surface Acoustic Wave

SPSS: Statistical Package for Social Sciences

SSM: Sum of the Square Model

SLAP: Silicone iLluminated Active Peripherals

TIR: Total Internal Reflection

2D: Two Dimensional

TouchLib: Touch Library

3D: Three Dimensional

TUIO: Tangible User Interface Object

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter provides a brief introduction to multi-touch display technologies, their background, importance, challenges and related issues in the aspect of interaction techniques. The problem statement is formulated based on literature review. The motivation for undertaking this research is explained in this chapter and the methodology is briefly described. Finally, the thesis format is given at the end of this chapter.

1.2 Background of Study

The invention of the computer and its association with hardware interfaces (e.g. keyboard and mouse) and software interfaces (e.g. Command Line Interface and Graphical User Interface) has assisted users for accessing digital information in many ways (Hinckley, 2002; Sharp, Rogers, & Preece, 2007). The development in the field of Human Computer Interaction (HCI) has not only produced quality interaction using existing interfaces in the last few decades, but it has also focused on advanced interface technologies. However, it is observed that traditional input devices offer indirect and unnatural methods of interaction to users which restrict their capacity of interaction with the computer (Forlines, Wigdor, Shen, & Balakrishnan, 2007). The limitations of existing interfaces and the changes in user requirements have always demand for novel interface technologies to be produced. As a consequence, many researchers have attempted to design and develop multimodal, intelligent, direct and natural rather than the regular, unimodal and indirect user interfaces (Karray, Alemzadeh, Saleh, & Arab, 2008).

The research trend in the area of multi-touch screen/displays started in the early 1980's at IBM, Bell Labs, University of Toronto. Basically, multi-touch sensitive displays are physical input devices that allow users to perform multi-points of interaction directly using multiple fingers (Hrvoje Benko, Wilson, & Baudisch, 2006; B. Buxton, 2011; J. Y. Han, 2005). The first multi-touch system called the flexible machine interface was developed by Mehta (Mehta, 1982) while studying for his master's degree at the University of Toronto. The system allowed users to perform a multi-point interaction at the same time. Following this, a Soft Machine was introduced by (Nakatani & Rohrlich, 1983) and the properties of the touch screen based user interfaces were discussed comprehensively.

Over the years, various multi-touch displays have been designed and developed using different technologies, i.e. resistive, surface acoustic wave (saw), capacitive, and computer vision (B. Buxton, 2011; Izadi, Hodges, Butler, Rrustemi, & Buxton, 2007; Moeller & Kerne, 2010). Related to system design and development, each technology has its own advantages and disadvantages from the perspective of architecture, functionality, scalability and cost. The detailed description and comparison of these display technologies are given in the second chapter of this thesis. Usually, the resistive and surface acoustic wave based displays are found in small sizes whereas, the capacitive and computer vision based displays are found in both sizes, i.e. small and large (Dietz & Leigh, 2001; J. Y. Han, 2005; Rekimoto, 2002).

Recently, the development of multi-touch tabletop displays using different technologies has laid the foundation for designing the Natural User Interface (NUI). The NUI is considered as a next major development in computing and user interfaces as previously GUI provided extraordinary interaction capabilities as compare to CLI (Seow, et al., 2009). In connection to this, tabletop displays facilitate the direct, multi-model and natural methods of multi-touch interaction to users (B. Buxton, 2011; Shen, 2006; Shen, et al., 2006; Shen, et al., 2009). The development in hardware and software interfaces, over the years, along with the methods of interaction, is shown in Figure 1.1.

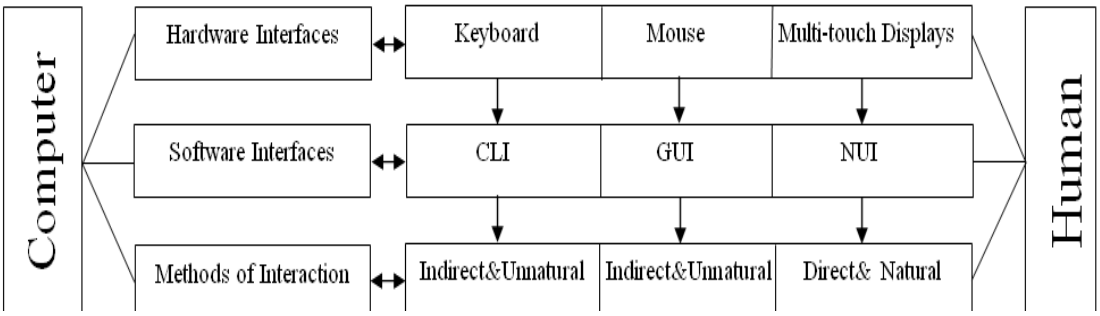


Figure 1.1: Overview of interface technologies and methods of interaction

1.3 Multi-touch Tabletop Display Technologies

The continuous development in the capacitive and computer vision technologies encouraged researchers to produce the digital tables/ interactive displays of different sizes. Recently, these technologies are widely used to design and develop different types of multi-touch tabletop displays. However, the tabletop displays developed using the capacitive technology, uses a matrix of capacitive sensors inside a medium of surfaces. This matrix of sensors enables displays to detect users multi-touch input; the most popular examples of these displays are DiamondTouch ((Dietz & Leigh, 2001; Rekimoto, 2002).

Multi-touch tabletop displays are also developed using computer vision based technologies that use image processing techniques and cameras to detect and track a user’s multi-touch input. Cameras are configured and calibrated in different ways according to the size and position of the display. There are two main types of vision based multi-touch displays, i.e. purely vision based and optical and vision based (Rong, Feng, & Pengfei, 2010). In purely vision based displays, cameras are employed for detecting the visual gesture of hands and fingers as multi-touch input; computer vision techniques are used for tracking this input. The most common examples of purely vision based displays are Everywhere (Pinhanez, et al., 2003) and PlayAnywhere (Wilson, 2005). These systems are also known as visual tracking systems

On the other hand, the development of vision and optical based tabletop displays depends on computer vision techniques, cameras and the optical phenomenon of infrared light. Infrared light sources, i.e. infrared light emitting diodes (IR LEDs), are assembled in front of the edges of the system's surface. These light sources emit light inside the surface medium into a pattern called the Total Internal Reflection (TIR). The sensitivity of the system's surface depends on the Frustrated Total Internal Reflection (FTIR) technique, and also on the optical surface architecture (J. Y. Han, 2005). When a user interacts with the optical surface using his/her bare fingers, the infrared light frustrates and creates bright fingertip images called fingertip blobs. The configured and calibrated infrared cameras detect these fingertip blobs and send them to the Central Processing Unit (C.P.U) to be processed using computer vision techniques. The most common examples of these displays are the Low cost multi-touch system and Perceptive pixels (J. Y. Han, 2005).

The capacitive and vision based multi-touch tabletop surfaces are opaque in nature, thus the Digital Light Processing Projector (DLP) is always used for displaying digital contents onto their surfaces. There are two main common techniques used for developing capacitive and vision based systems, i.e. bottom-up and top-down approaches. In the bottom-up approach, the cameras and projector are used beneath a multi-touch surface. Whereas, using the top-down approach, the cameras and projector are used above or in front of a multi-touch surface.

1.4 The Importance of Multi-touch Tabletop Displays

Traditionally, humans use the physical tables in homes, offices and design centers as well as many other places for different purposes. Consider the use of a table in an office, it provides a convenient physical setting for a single or multiple users to examine physical documents, to draw maps on papers and navigate the maps, and to perform many other activities. However, users are also used to examine digital documents using the desktop/laptop computer, mobile devices, and projected displays (Shen, et al., 2006).

The discovery of multi-touch tabletop displays also provides a collaborative workspace and multiple users sit in front of each other around the table. The tabletop display provides a high visualization of 2D/3D digital information and users can select and manipulate target elements using their bare fingers directly. Users can also perform collaborative multi-touch interaction to examine the digital documents directly and naturally (B. Buxton, 2011; Dietz & Leigh, 2001; J. Y. Han, 2005; Rekimoto, 2002; Shen, et al., 2006). These displays introduce the concept of social computing, and increase the integral value of discussions and meetings around the table (Chen, Nien, & Wu, 2009; Haller, et al., 2009; Shen, 2006).

However, it is predicted that these displays will free us from traditional input devices, i.e. keyboard and mouse (Fuller, 2008), in the near future, in the way that the mouse minimized the usage of the keyboard in the past (Brown, 2008). An example of the direct and natural multi-touch interaction using a tabletop display is shown in the following figure 1.2.

Figure 1.2: Multi-touch interaction with a multi-touch tabletop display

A survey was conducted by (H Benko, Morris, Bernheim Brush, & Wilson, 2009) for identifying the importance of tabletop displays in the context of use pattern. It was reported that, 36% of the users utilized these displays for viewing entertainment media activities, 31% for collaborative activities, 17% for the visualization of applications and 5% for accomplishing productivity tasks. It was also reported that tabletop displays possessed the potential of facilitating novice users for accessing the digital information frequently in a collaborative manner.

Consider the potential of tabletop displays, these can be used for multiple purposes in different domains, e.g. medical image analysis in healthcare (Gross, et al., 2009), interactive learning in academic institutes (AlAgha, Hatch, Ma, & Burd, 2010; Minyoung, Yongjoo, & Kyoung Shin, 2009; Yu, Zhang, Ren, Zhao, & Zhu, 2010) and public information at museums, restaurants and airports (Correia, Mota, Nóbrega, Silva, & Almeida, 2010).

1.5 Challenges and Issues Using Multi-touch Tabletop Displays

The multi-touch tabletop displays are emerging rapidly, presenting new challenges to researchers and designers for addressing various issues. These issues can be classified into three main areas, i.e. screen-based, user-based and input-based challenges. Screen-based challenges pertain to size, shape and affordance of displays. User-based challenges relate to ergonomics, individual differences and accessibility. Finally, input-based challenges concern multi-touch support, and gesture and pattern recognition (Bachl, Tomitsch, Wimmer, & Grechenig, 2010; Ryall, Forlines, Shen, Morris, & Everitt, 2006; Shen, 2006).

Resolving all these challenges and issues is essential in order to enrich the direct and natural multi-touch interaction on sensitive displays. However, user-based issues have received greater attention in the aspect of precise and frequent selection of target elements using the bare fingers.

1.6 Finger Input Properties

Using multi-touch tabletop displays, users are able to use multiple fingers for accessing target elements directly. Therefore, user-based challenges are directly related to the physical characteristics of human fingers and their input properties. The input properties of fingers have been studied by researchers in order to explore their potential for and optimum use in multi-touch interactions (Feng, Xiangshi, & Zhen, 2008; Wang, Cao, Ren, & Irani, 2009; Wang & Ren, 2009).

By medical and anatomical analysis, it has been identified that the human hand possesses 23 degrees of freedom (DOF) and has complex mechanisms (Anderson, 1992). Inherently, it's this DOF which allows humans to pick up, hold and manipulate physical objects in a real environment. Consequently, humans can also use their fingers for interacting with multi-touch displays as well as one finger being used as a pointing device (Albinsson & Zhai, 2003). Fingers possess different input capabilities as shown in Figure 1.3, and can be used for performing several tasks using unimanual and bimanual multi-touch interaction frequently and accurately (Wang, et al., 2009; Wang & Ren, 2009).

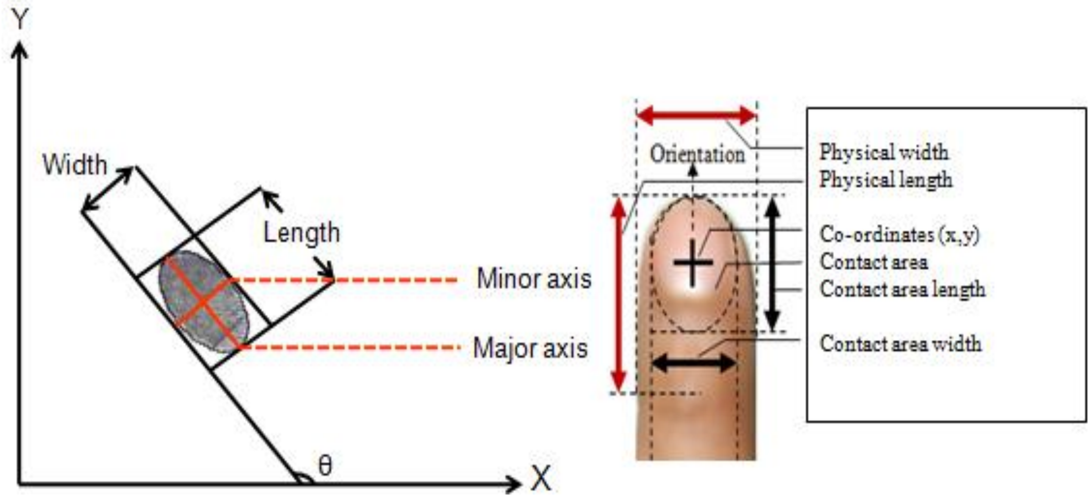


Figure 1.3: Finger input properties (Wang & Ren, 2009)

Thus, it has been described as "*In wide variety of tasks, continuous graphical interaction using several fingers allows the communication of information to a computer faster and more fluently than the single point graphical interaction*"(Malik, 2007) The concurrent use of multiple fingers by many users on a collaborative workspace lead to a more effective performance of complex tasks (Jiao, Deng, & Wang, 2010; Kin, Agrawala, & DeRose, 2009; Malik, 2007).

Keeping in mind the importance of finger input properties, there are four main finger properties which are explored, i.e. position, motion, physical, and event property. The event property is used commonly for performing target selection tasks (Wang & Ren, 2009). The position property consists of x and y co-ordinate values with respect to the major and minor axis of the fingertip. It is used for accomplishing a precise interaction with touch screens (W. Buxton, Hill, & Rowley, 1985; Lee, Buxton, & Smith, 1985). The physical property consists of the size and shape of the contact area, orientation and pressure. The size of the fingertip is also used for achieving precise selections (Hrvoje Benko, et al., 2006); however, this property has not been tested extensively. Recently, the physical property has received much attention in the context of imprecise selection and is highly recommended for a more extensive evaluation (Wang & Ren, 2009).

1.7 Imprecise Selection Problem

It is found through different studies that the larger size finger creates the imprecise selection of smaller size target elements in direct multi-touch input on sensitive displays (Albinsson & Zhai, 2003; Bachl, et al., 2010; Hrvoje Benko, et al., 2006; Esenther & Ryall, 2006; Forlines, et al., 2007; Olwal, Feiner, & Heyman, 2008; Potter, Weldon, & Shneiderman, 1988; Ryall, et al., 2006; Vogel & Baudisch, 2007; Voida, Tobiasz, Stromer, Isenberg, & Carpendale, 2009; Wang, et al., 2009; Wang & Ren, 2009; Daniel Wigdor, Forlines, Baudisch, Barnwell, & Shen, 2007; Daniel Wigdor, et al., 2006; D. Wigdor, Perm, Ryall, Esenther, & Chia, 2007; Daniel Wigdor, et al., 2009; Wu & Balakrishnan, 2003). The example of the imprecise selection problem is illustrated in Figure 1.4.

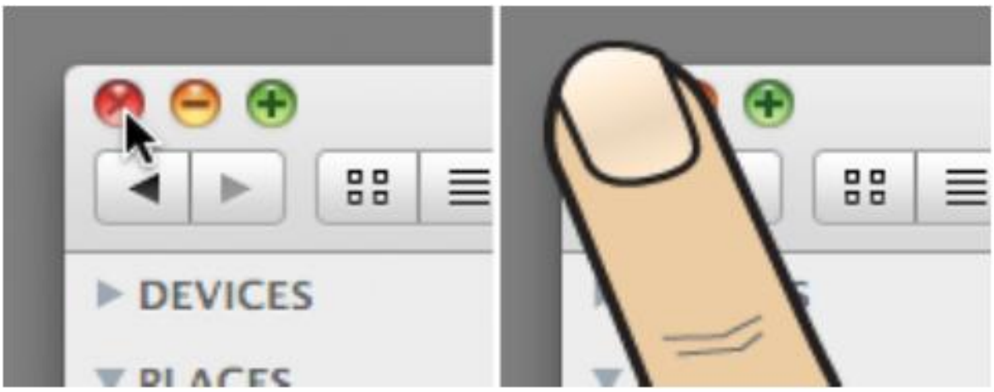


Figure 1.4: Imprecise selection problem (Bachl et al., 2010)

Due to the imprecise selection, users get frustrated as they experience unexpected behavior in many situations. For example, when the target elements are closely located, it is almost impossible to prevent the users' fingertips from occupying two or more elements simultaneously. Thus, it becomes an inconvenience for a user when attempts to select the desired element without receiving any appropriate feedback. There is the possibility of an unexpected response or no response at all for the users during their interactions (Ryall, et al., 2006; Shen, et al., 2006; Wu, Shen, Ryall, Forlines, & Balakrishnan, 2006).

Moreover, tabletop displays provide a collaborative workspace to multiple users in which they perform unimanual and bimanual methods of interaction. These methods involve the multiple configurations of fingers such as position and orientation during interaction (Moscovich, 2007). So, such an arrangement of multiple fingers on sensitive displays may create imprecise selection of target elements in a collaborative multi-touch interaction. Consequently, the imprecise selection using bare fingers either related to standalone or real time applications may lead to serious problems.

1.8 Motivation of the Study

The multi-touch display introduces a new paradigm of interaction in the field of human computer interaction. In this regard, many interaction techniques have been proposed to achieve a precise selection of target elements, i.e. direct touch (Potter, et al., 1988), on-screen widgets (Albinsson & Zhai, 2003), target zoom-in (Blanch, Guiard, & Beaudouin-Lafon, 2004; Olwal, et al., 2008), and cursor-offset (Hrvoje Benko, et al., 2006; Potter, et al., 1988; Vogel & Baudisch, 2007). These techniques have contributed significantly in many ways, such as to zoom-in target objects before selection and use of the cursor-offset above the fingertip. The detailed description of these techniques is given in the second chapter of this thesis.

However, these techniques still lacking in providing high precise selection with the appropriate feedback in direct multi-touch input (Wang & Ren, 2009; Daniel Wigdor, et al., 2007; Daniel Wigdor, et al., 2006). By reviewing these techniques, it is observed that the precise selection is not required only for target elements but some other questions also raised in our mind, i.e. “How to perform text input precisely and frequently using bare fingers on small or large size sensitive displays?”, “How to select text that is written in different languages precisely using fingers?”, “How to draw the maps and figures precisely using bare fingers as normally sketched through mouse pointer on the desktop monitor?”

Realizing the importance of finger input properties in the context of imprecise selection, some studies have been conducted to explore and evaluate these properties accordingly (Hrvoje Benko, et al., 2006; Feng, et al., 2008; Forlines, et al., 2007; Wang, et al., 2009; Wang & Ren, 2009; Wilson, Izadi, Hilliges, Garcia-Mendoza, & Kirk, 2008; Xiang, Wilson, Balakrishnan, Hinckley, & Hudson, 2008). The outcome of those studies indicates that precise selection can be improved by means of a suitable design of target elements and users interface design. The detailed description of the finger input properties is presented in second chapter of this thesis. Some of the studies also recommended that users’ fingertip’s contact area and the shape to be explored extensively to overcome the imprecise selection (Wang, et al., 2009; Wang & Ren, 2009; Wu & Balakrishnan, 2003). Keeping in mind the importance of sensitive displays, precise selection, and finger input properties, we are motivated to evaluate the physical finger input properties in the context of imprecise selection accordingly. This study may enrich the precise selection of target elements during direct multi-touch interaction.

1.9 Research Questions and Hypothesis

In order to improve the precise selection of target elements using bare fingers directly, this research study will attempt to answer the following research questions.

1. Is there any variation in the individuals’ fingertips occupied contact area and shape?

   1.1 How much individuals’ fingertips occupy the contact area during interaction?

1.2 Does the individuals' finger's angle of approach impact on the variation of occupied contact areas and shapes?

2. Is there any significant difference among individuals' fingertips occupied contact areas?

3. How to design and develop an experimental setup (tabletop display) for evaluation of physical finger input properties?

However, keeping in view the second research question of this study, a null hypothesis is formulated as described.

H_0: There is no significant difference between the individuals' fingertip contact areas.

This hypothesis may help in confirming that weather there is significant difference among individuals fingertips contact areas or not. If there is significant difference then null hypothesis will be rejected, otherwise accepted.

1.10 Research Objectives

In general, the prime objective of this study is to review multi-touch display technologies, precise selection techniques and finger input properties in the context of imprecise selection. It provides an opportunity to understand their basic concepts and relative strengths and weaknesses. Based on the literature review, this study has been carried out to achieve two main objectives which are as follows.

1. To evaluate the physical finger input properties, i.e. contact area and shape along with the finger's angle of approach.

2. To propose an architecture for the development of multi-touch tabletop display.

1.11 Research Methodology

The research design has been developed in multiple phases that work towards meeting the research objectives of this study. In the first phase, a multi-touch tabletop display is developed based on the proposed architecture; it is then used to investigate the physical finger input properties. In the second phase, an experiment is conducted in order investigate the individuals' fingertip's contact areas and shapes. In the third phase, the survey based study is conducted related to specifications of the finger's angle of approach. In this respect, a close-ended questionnaire is formulated and distributed among the participants to collect data accordingly. The fourth phase is specifically focused to evaluate to individuals *index fingertip'* contact areas and shapes on a large scale.

1.12 Thesis Format

This thesis begins with an introduction to the background of multi-touch display technologies and related issues. In the Second Chapter, multi-touch display technologies are reviewed, and their issues are discussed in the context of architecture, functionality, scalability and cost. In addition, various precise selection techniques and finger input properties are reviewed in the context of imprecise selection. In the Third Chapter, the research design is described which consists of various methods that have been used for data collection and analysis to confirm the answers to the research questions as well as the subsequent hypothesis. In the Fourth Chapter, the design and development of the multi-touch tabletop display is discussed which helps in understanding its architecture and functionality. In the Fifth Chapter, the results are presented and discussed in the context of the problem statement, accordingly. In the Sixth Chapter, the conclusion and some recommendations of this study are described.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Reviews of related work are presented in this chapter which consists of three main sections. In the first section, the existing sensitive display technologies are comprehensively reviewed in order to identify their merits and demerits in terms of their architecture, functionality, scalability and cost. This enables us to recognize the appropriate technology to utilize for the development of a multi-touch tabletop display. In the second section, precise selection techniques are reviewed which provide a basic understanding of selecting target elements using fingers, and their related issues. In the third section, finger input properties are studied in order to know their usefulness with interactive displays, and to identify which properties are specifically involved in causing the imprecise selection.

2.2 Touch Enabling Technologies

Over the years, different types of sensitive displays have been designed and developed using various technologies, i.e. resistive, surface acoustic wave, capacitive and computer vision. Many of the existing displays allow single user multi-touch interaction, but have limited multi-user multi-touch interaction capabilities. For example, a small size Apple iPhone ("http://www.apple.com/iphone/," Apple Inc, 2010) display developed using capacitive technology offers single user multi-touch interaction. On the other hand, a large size multi-touch tabletop display called DiamondTouch (Dietz & Leigh, 2001), also developed using capacitive technology which allows multi-user multi-touch interaction. There are also many large size multi-touch tabletop displays developed using computer vision technologies that allow multi-user multi-touch interaction. The Microsoft Surface is a common example of these display technologies that support multi-user multi-touch interaction around a table.

Recently, a comparative study of touch enabling technologies has been conducted by (Mudit & Anand, 2010) in order to understand their merits and demerits. Different studies have also been conducted in academic and corporate organizations in order to explore various multi-touch interaction techniques (Hrvoje Benko, et al., 2006; Kim, Kim, & Lee, 2007; Wu & Balakrishnan, 2003) and finger input properties (Wang & Ren, 2009) using different technologies. Keeping in mind the problem statement of this study, these touch enabling technologies are further reviewed to identify their advantages and disadvantages in terms of their architecture, functionality, scalability and cost. These factors play an important role in the design and development of these displays. Therefore, it is important to find an appropriate technology for the development of a multi-touch tabletop display which can be used for evaluation of finger input properties

2.2.1 Resistive Touch Technology

Resistive displays are fabricated with two conductive layers, coated with an indium tin oxide material and an insulating layer with spaces embedded between the conducting layers. The architecture of the resistive display and the resistive display device are shown in Figure 2.1. The front layer is a flexible hard coated covering whereas the back layer is a glass substrate. Resistance based displays or touchpads are pressure sensitive. When a user interacts with the display using a stylus, finger or nail, the conducted layers communicate to each other, and generate an electric field in the x and y co-ordinates. The generated electric field is measured by a controller and passed to an operating system for further processing (Downs, 2005; Mudit & Anand, 2010; Schöning, et al., 2008).

The resistive displays are commonly used in retail Point-Of-Sale (POS), medical monitoring devices and portable/handheld products, e.g. Nintendo DS and Personal Digital Assistant (Downs, 2005; Schöning, et al., 2008) . In addition, a music controller called “Lemur” is a common example of a resistance based multi-touchpad that detects multi-touch input delivered by fingers (JazzMutant, 2003).

Figure 2.1: Architecture of resistive display (left) (Schöning, et al., 2008) and resistive display device (right) (Lutherz, 2011)

From literature review, it is perceived that the resistive technology is suitable for developing small size, portable displays as well as touchpads at low cost. The resistive displays detect a single user’s multi-touch input, but there is ambiguity in processing the input. These displays are generally unable to provide clear images; moreover, they are easily damaged by sharp items, e.g. a knife (Downs, 2005; Mudit & Anand, 2010; Schöning, et al., 2008). Furthermore, their high visualization of 2D and 3D digital information as well as the number of unique function keys they can possess is very limited due to their small size. For instance, a resistance based PDA offers a virtual keyboard on display and possesses limited functional keys. This may be inadequate from a user's perspective, who might expect additional function keys with high visualization of digital information (Sharp, et al., 2007).

2.2.2 Surface Acoustic Wave Touch Technology

Surface Acoustic Wave (SAW) based displays are developed using two transducers (transmitting and receiving), configured on both the x and y edges of a glass surface. Another important component called the reflector is also deployed inside the edges of the glass substrate plate. The surface acoustic wave display and architecture are shown in Figure 2.2.

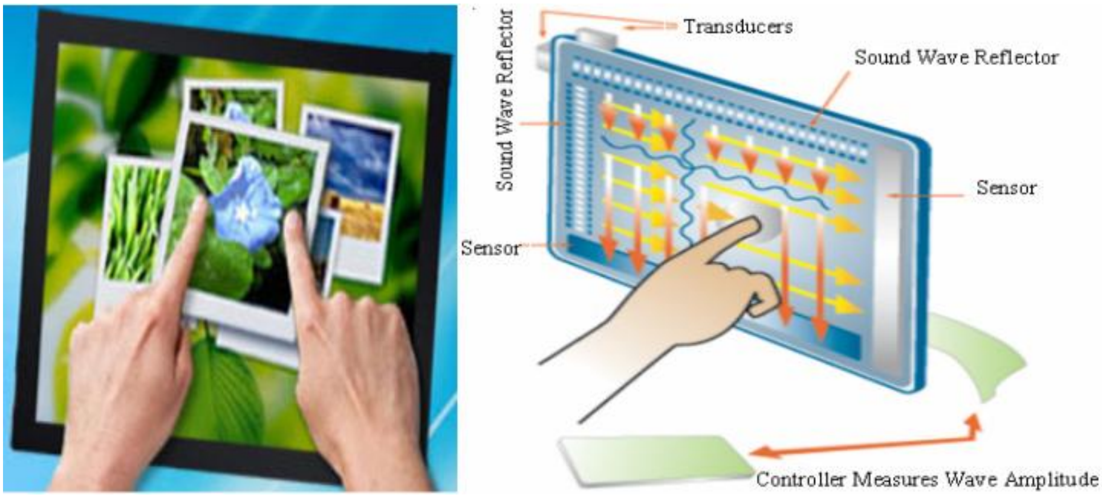


Figure 2.2: SAW display device (left) and the architecture of SAW display (right) (Leadingtouch technology Co., 2010)

The operating principle of these displays depends on the generation of acoustic waves in the x and y co-ordinates inside the faceplate. The microcontroller drives electrical signals to the transmitting transducer which changes these signals into ultrasonic waves, and then releases them to the reflectors. These waves are refracted to the receiving transducers by the reflectors. The receiving transducers alter the received ultrasonic waves into electrical signals, and then pass the signals to the microcontroller. When a user interacts with the display using his/her finger, waves are generated and computed in a unit of time interval, and it causes touch events to be detected accordingly (Holzinger, 2003; Mudit & Anand, 2010).

SAW displays are commonly configured in Cathode Ray Tubes (CRT) and Liquid Crystal Display (LCD) monitors. These displays offer better image quality than resistive displays, and allow for single user multi-touch interaction using the bare fingers.

These are recommended for diverse applications in different domains which include banks, medical facilities, sales kiosks and educational facilities (Mudit & Anand, 2010). However, these displays are not completely sealable, and their technology is also less encouraging for the development of large size tabletop displays due to their inflexible architecture. Moreover, these displays are expensive and can be affected adversely by the large quantity of dust, grease and water as is often found in an open environment (Mudit & Anand, 2010; Schöning, et al., 2008). These contaminant elements absorb waves easily and establish a ground for dead zones on the displays. These displays are always being touched by fingers, and therefore, limit the detection of a hard stylus (Holzinger, 2003).

2.2.3 Capacitive Touch Technology

The first multi-touch tablet was developed by (Lee, et al., 1985) using a matrix of 64x32 capacitive sensors based on an interpolating scheme inside an interactive surface. The invention of the multi-touch tablet laid the foundation for the development of a variety of multi-touchpads. Basically, multi-touchpads are non unified input devices in which a user’s hands and fingers do not overlay the displays and the user is unable to touch target elements directly (B. Buxton, 2011). The FingerWorks, TouchStream, iGesture and Tactex Controls are common examples of multi-touchpads, introduced by the corporate companies (Fingerworks, 1998; Taxtex, 1998). Specifically, the product FingerWorks was developed based on an idea which was introduced by (Westerman & Wayne, 1999). However, these multi-touchpads are capable of detecting the single user’s multi-touch input driven through the user’s fingers, but possess a limited capacity for providing a display with multi-user multi-touch interaction (B. Buxton, 2011).

However, the first transparent multi-touch display was developed by (Boie, 1984) at Bell Laboratory using a matrix of capacitive sensors in rows and columns inside a panel. It supported single user multi-touch interaction for selection of target elements using fingers. After many years, the tabletop display called DiamondTouch was introduced by (Dietz & Leigh, 2001) at Mitsubishi Electric Research Laboratory (MERL) using capacitive antennas/sensors in rows and columns inside an interactive surface. The DiamondTouch display and its architecture are shown in Figure 2.3.

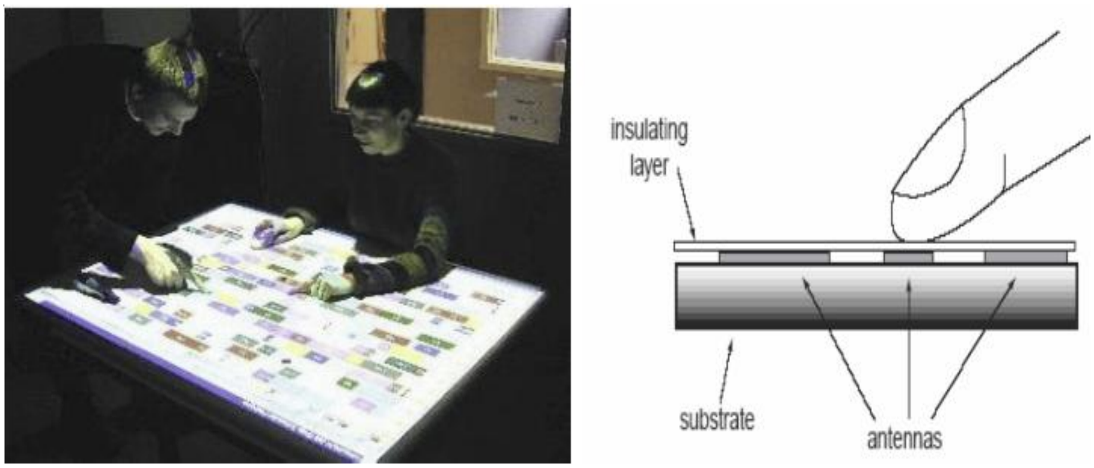


Figure 2.3: DiamondTouch display (left) and its architecture (right) (Dietz & Leigh, 2001)

The display allows multiple users to sit together in front of each other on chairs around a table and perform multi-touch interaction simultaneously. A special receiver unit is attached to the chairs by which users are capacitively coupled with it. When users interact with the system surface using their bare fingers, input signals are sent through the users' bodies to the receiver units. This system is capable of identifying which part of the system's surface is currently being touched and by which user. The system's surface is opaque in nature, thus the DLP projector is calibrated and mounted above the surface for displaying the digital information.

Later on, to enrich the concept of multi-touch interaction another tabletop display was introduced called SmartSkin (Rekimoto, 2002). The system's surface is composed of a dense matrix of capacitive sensors (e.g. transmitting and receiving antennas) in rows and columns. The transmitting antennas are configured vertically, and the receiving antennas are arranged horizontally. The reason for using the dense matrix of antennas is to increase sensitivity of the system's surface. The SmartSkin display and its architecture are shown in Figure 2.4.

When a user touches the sensitive surface using the fingertip, the input signal is generated to the transmitting sensors, and the receiving sensors obtain that signal. By computing the input signal, the finger touch event is detected by the system. The SmartSkin display is capable of detecting the shape and position of hands and fingers, thereby allowing simultaneous multi-user multi-touch interaction.

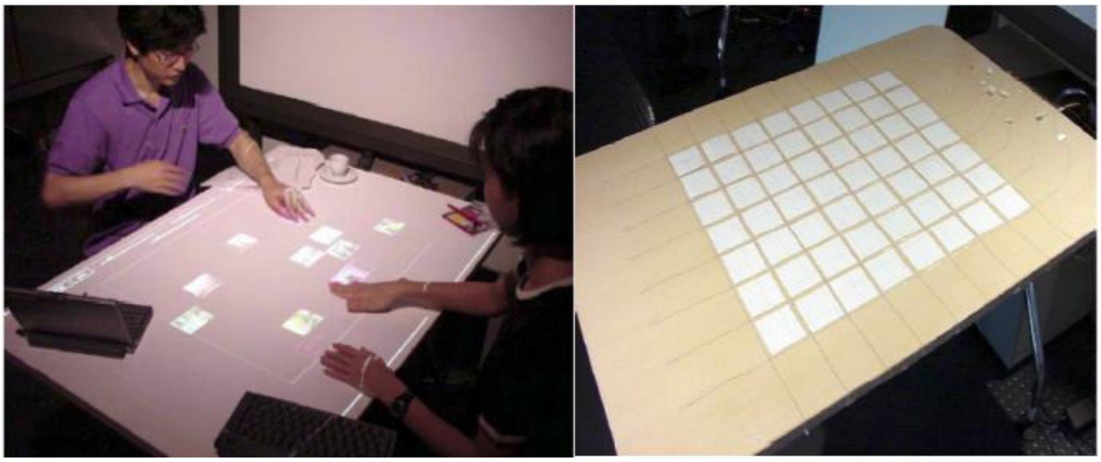


Figure 2.4: SmartSkin Display (left) and its architecture (right) (Rekimoto, 2002)

The interactive surface of this system is also opaque in nature; therefore the DLP projector is configured and calibrated above the surface for displaying the digital information. The SmartSkin measures two dimensional finger touch input, in which it is difficult to identify and differentiate the position of the hands and fingers precisely during proximity interaction. It is also difficult to measure the distance between the fingers and the interactive surface precisely during proximity interaction (Rekimoto, 2002). A more recent system is the small size Apple iPhone introduced by ("http://www.apple.com/iphone/," Apple Inc, 2010) which is based on capacitive sensor technology. It is also capable of detecting single user's multi-touch input but limited in providing a collaborative workspace to multiple users for multi-touch interaction.

2.2.4 Computer Vision Based Technologies

The need for computers with greater computational power, but at a reduced cost has encouraged researchers to develop multi-touch displays at low cost using computer vision techniques rather than resistive, SAW and capacitive technologies. The vision based displays are capable of detecting multi-touch input at a high speed. These displays are classified into two main categories according to their architecture and techniques, i.e. purely vision based and optical, and vision based systems (Moscovich, 2007; Rong, et al., 2010). In purely vision based systems, cameras are positioned in order to detect the gesture of a user's fingers, and tracking of the gesture is done through computer vision techniques. These displays can be developed anywhere without any dedicated physical surface (Rong, et al., 2010). These systems allow users to perform indirect multi-touch interaction for direct manipulation of target elements. Indirect multi-touch interaction means that users are not able to place their hands and fingers directly on the digital contents. Thus, these displays are also known as visual tracking systems (Malik & Laszlo, 2004; Rong, et al., 2010).

2.2.4.1 Purely Vision Based Multi-touch Displays

One of the earliest purely vision based multi-touch display called VIDEOPLACE, was developed by (Krueger, Gionfriddo, & Hinrichsen, 1985) using computer vision techniques. After many years, another multi-touch tabletop display was introduced called EnhancedDesk (Nakanishi, Sato, & Koike, 2002). Basically, it is an enhanced version of the DigitalDesk developed by Wellner (Wellner, 1993). In this system, a couple of cameras are mounted above the desk surface, and their faces are directed downwards to visualize the gesture of the user's hands and fingers. An LCD projector is deployed and calibrated above the surface of the desk to project the digital information. The multi-touch input is detected by the system using the gesture of the multiple fingers. Users can select and manipulate both physical and displayed virtual target elements.

The development of flexible components and the potential of computer vision techniques have encouraged researchers to develop multi-touch displays that can be placed anywhere due to their flexible architecture. The common example of these displays are Everywhere and PlayAnywhere. The Everywhere system was developed by (Pinhanez, et al., 2003) using a pan-tilt zoom camera, mirror and portable LCD projector featuring a motorized focus and zoom. However, the PlayAnywhere (Wilson, 2005) system was developed using an infrared camera that was mounted above the surface along with an infrared illuminator. The infrared illuminator brightens the surface area and the camera visualizes it precisely. A short distance projector is also mounted in front of the interactive surface for displaying the digital information. While interacting with the surface, the gestures of the multiple fingers are illuminated and their shadows are generated on the surface. These shadows are detected by a camera and processed by using shadow based computer vision techniques. The accuracy of the shadows depends on the distance between the fingers and system's surface.

The PlayAnywhere system is capable of detecting the real touch and proximity input of users on the interactive surface. The drawback of this system is that it allows only limited multi-touch input of multiple fingers and lacks in its ability to offer the concurrent multi-touch input of multiple users. Also, these displays lack visual feedback precision in simultaneously detecting and tracking the multi-finger input (Malik & Laszlo, 2004; Wilson, 2005). The PlayAnywhere display and its architecture are shown in Figure 2.5.

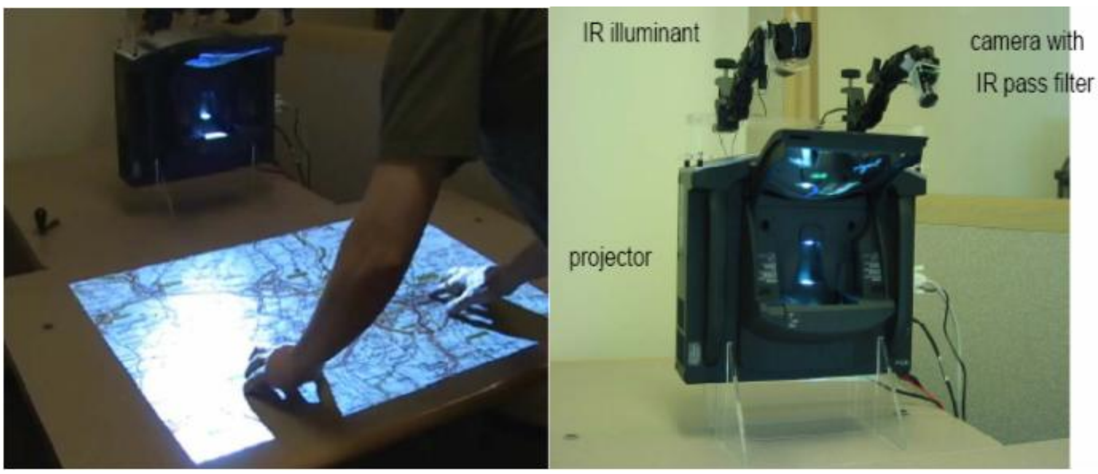


Figure 2.5: PlayAnywhere display (left) and its architecture (right)(Wilson, 2005)

2.2.4.2 Optical and Vision Based Multi-touch Displays

The first multi-touch display called Flexible Machine Interface was developed by (Mehta, 1982) using the optical phenomenon of light inside a frosted-glass surface and computer vision techniques. After that, the HoloWall display was developed by (Matsushita & Rekimoto, 1997) using the diffuse illumination technique in which infrared light emitting diodes (IR LEDs) are used behind a glass surface. These LEDs illuminate the glass surface and help in creating fingertip blobs during interaction. A rear projection sheet is attached behind the glass surface to display the digital content by the projector. The infrared camera along with the projector is configured and calibrated at the bottom of the glass surface. When the user interacts with system's surface using multiple fingers, then the infrared light is reflected back, and is detected by the camera as an input image. These input signals are processed using image processing techniques by the computer system.

Following the design principles of the HoloWall, another system called TouchLight was introduced by (Wilson, 2004) in which holographic projection material is used behind a semi transparent acrylic surface. An infrared illuminator rather than IR LEDs is used at the back of the surface to illuminate the whole acrylic sheet. The two infrared cameras are deployed and calibrated behind the system's surface to detect the gestures of the multiple fingers. The TouchLight display and its architecture are shown in Figure 2.6.

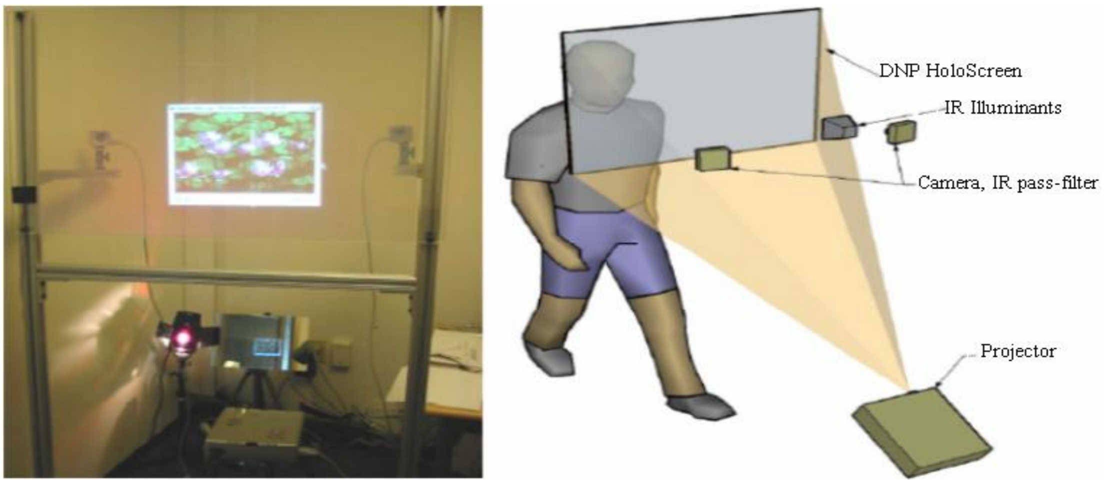


Figure 2.6: TouchLight display (left) and its architecture (right) (Wilson, 2004)

When a user interacts with the surface, then the infrared light is reflected back and detected by the cameras. Along with the cameras, the projector is used to display the digital information on the interactive surface. A microphone is attached with the display which provides audio feedback during tapping with the fingertips. The TouchLight system is more effective than HoloWall in the context of detecting multi-touch input precisely, but it occupies more space (Wilson, 2004).

Later on, a low cost multi-touch system which senses through Frustrated Total Internal Reflection (FTIR) was introduced by (J. Y. Han, 2005). FTIR is a novel optical sensing technique in which a set of IR LEDs is configured for the emission of infrared light in front of the edges of a crystal clear acrylic sheet. When light is emitted and encounters the edges of the sheet, it undergoes its medium and constitutes Total Internal Reflection (TIR). Basically, TIR is an optical phenomenon in which a ray of light strikes a medium boundary at an angle larger than the critical angle, in relation to the normal, to the surface. When a user interacts with the optical surface using the bare fingers, then infrared light is frustrated inside the medium of the surface, and creates image patterns called fingertip blobs. An infrared camera is configured and calibrated beneath the system's surface to capture the user's fingertip blobs as multi-touch input. The multi-touch display and its architecture are shown in Figure 2.7.

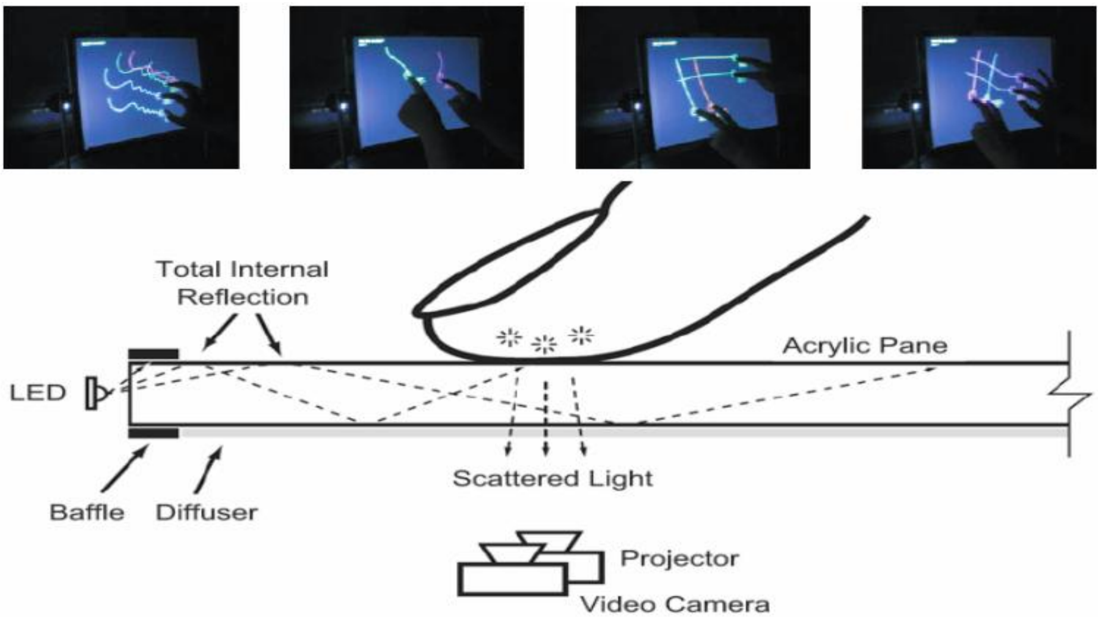


Figure 2.7: Multi-touch display (above) and its architecture (below) (J. Y. Han, 2005)

The multi-touch input is sent by the camera to the computer system for further processing. A diffuser is used on the rear side of the acrylic sheet for projecting digital information through the projector. The FTIR based multi-touch system enables multiple users to perform direct and natural multi-touch interaction to select and manipulate target elements simultaneously.

However, the system is developed using a camera and projector thus it occupies a particular amount of space like TouchLight and HoloWall, and other capacitive displays. The system remains vulnerable to harsh lighting conditions and is lacking in the area of detecting proximity touch. Later on, another multi-touch display called Perceptive pixel interactive media wall was introduced and commercialized by (Han, 2007), and uses the FTIR sensing technique. This system has been used by the renowned media news channel, Cable News Networks (CNN). The Perceptive pixel's interactive media wall display is shown in Figure 2.8.

Figure 2.8: Perceptive pixel's interactive media wall display with multi-touch interaction (Han, 2006)

The discovery of the FTIR sensing technique laid the foundation and became the driving force for the design and development of wall size and tabletop displays at low cost. It has increased the commercial aspect, and also encouraged researchers to develop a variety of multi-touch displays to explore the challenges related to the interaction techniques, user interface design and user experiences (Bachl, et al., 2010; Hrvoje Benko, et al., 2006; Cuypers, Schneider, Taelman, Luyten, & Bekaert, 2008; Dohse, Dohse, Still, & Parkhurst, 2008; Feng, et al., 2008; Gross, Fetter, & Liebsch, 2008; Hofer, Naeff, & Kunz, 2009; Jiao, et al., 2010; Kim, et al., 2007; Moeller & Kerne, 2010; Wang, et al., 2009; Wang & Ren, 2009).

Keeping in mind the commercial and research aspects, the Microsoft Company introduced the multi-touch tabletop display named Microsoft Surface (Microsoft Inc, 2007). This system is designed and developed using the Diffuse Illumination (DI) technique, rather than the FTIR technique. In this system, an acrylic sheet is used as an interactive surface and a diffuser layer is attached from the rear side of the surface for displaying digital information. Infrared Illuminators (IRs) beneath the acrylic sheet are used for illumination. For detecting the multi-touch input, infrared cameras are calibrated and configured under the system's surface. When a user interacts with the digital surface using his/her fingertips, infrared light is reflected back to the camera rather than frustrated as in the FTIR sensing technique. The cameras detect the multi-touch input as fingertip blobs and send them to the computer system for further processing. A short throw distance digital projector is configured at rear side of the surface for displaying digital information on the interactive surface. The Microsoft Surface and its architecture are shown in Figure 2.9.

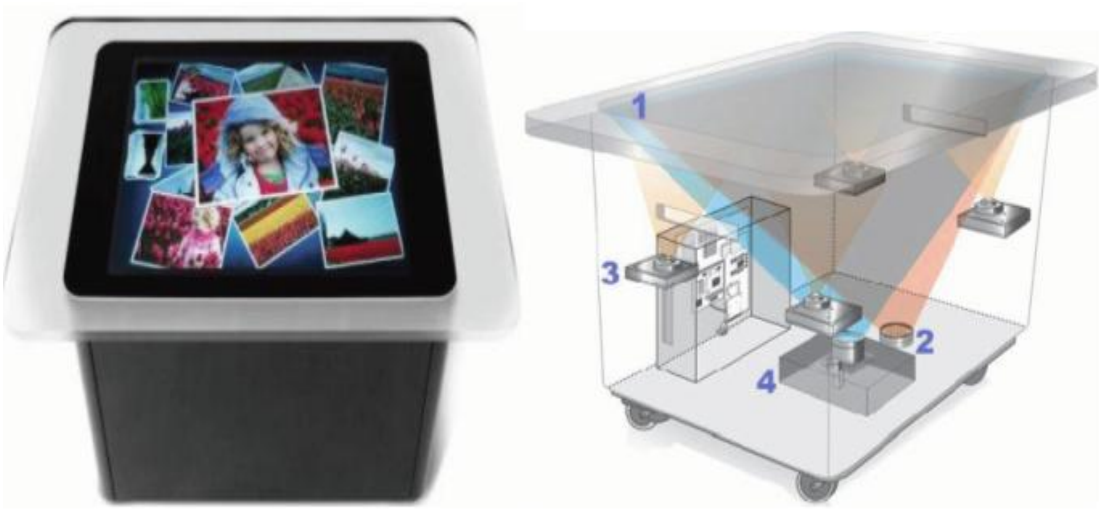


Figure 2.9: MS surface (left) and its architecture (right) (Microsoft Inc, 2007)

However, it has been found through studies that capacitance, FTIR and DI based tabletop display technologies use bulky hardware components that introduce portability issues. Consequently, it is difficult to shift these displays from one place to another (Izadi, et al., 2007). In order to overcome the portability issues, another system called ThinSight was introduced by (Izadi, et al., 2007), using a grid of retro-reflective optosensors behind the LCD panel rather than employing cameras and a projector. The ThinSight display and its architecture are shown in Figure 2.10.

Each retro-reflective optosensor consists of two elements, i.e. emitter and detector. The emitter emits infrared light for lighting up the panel; when the user interacts with the panel using his/her fingers then light is reflected back to the detector. The configuration of emitters and detectors in rows and columns behind the LCD panel enables the system to detect the multi-touch input. The potential of this novel optical sensing technique has enabled researchers to build a thin form factor display. It can be used in offices and homes just like personal computers.

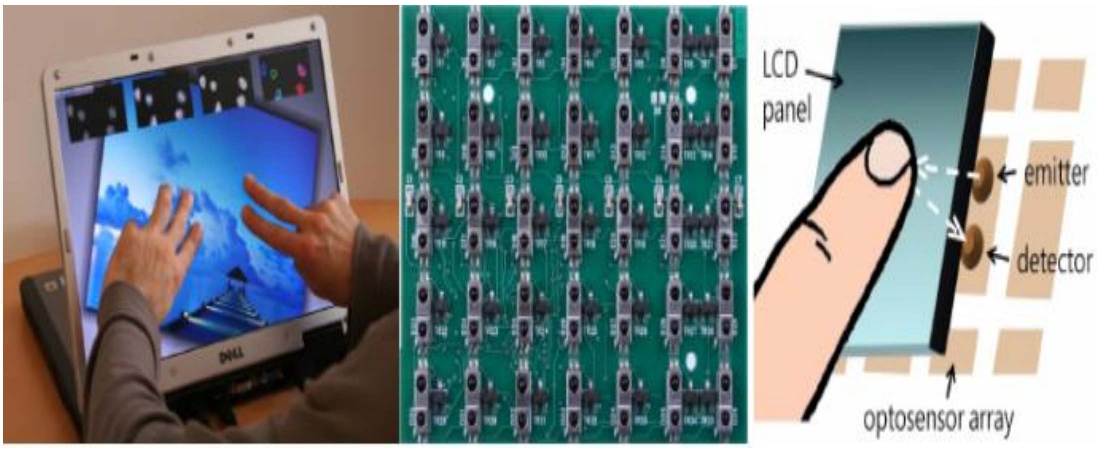


Figure 2.10: ThinSight display (left) and its architecture (left) (Izadi, et al., 2007)

The ThinSight system has an advantage over camera and projector based multi-touch systems due to its compatibility and fully integrated displays. However, this system does not provide a collaborative workspace for multiple users; it is also unable to detect the multi-touch input accurately due to its low resolution (Izadi, et al., 2007).

In order to improve the detection accuracy of multi-touch input, (Hofer, et al., 2009) introduced the FLATIR multi-touch system using the FTIR sensing technique.

The system architecture is based on three panels, i.e. an acrylic sheet, LCD panel and IR sensor board. These panels are integrated in a particular sequence, primarily, an acrylic sheet is configured with IR LEDs around its clean edges and the LCD panel is placed on its backside. Finally, a matrix of IR sensors is deployed from the rear side of the LCD panel. The FLATIR multi-touch display and its architecture are shown in Figure 2.11.

When a user interacts with the display, then infrared light is frustrated and scattered down to the matrix of IR sensors; these sensors detect the input simultaneously. The FLATIR system is compatible and integrated like ThinSight. Both systems support multi-touch input but do not provide a collaborative multi-user multi-touch interaction. In addition, the adverse effect of ambient light on the displays degrades the multi-touch input detection (Moeller and Kerne, 2010).

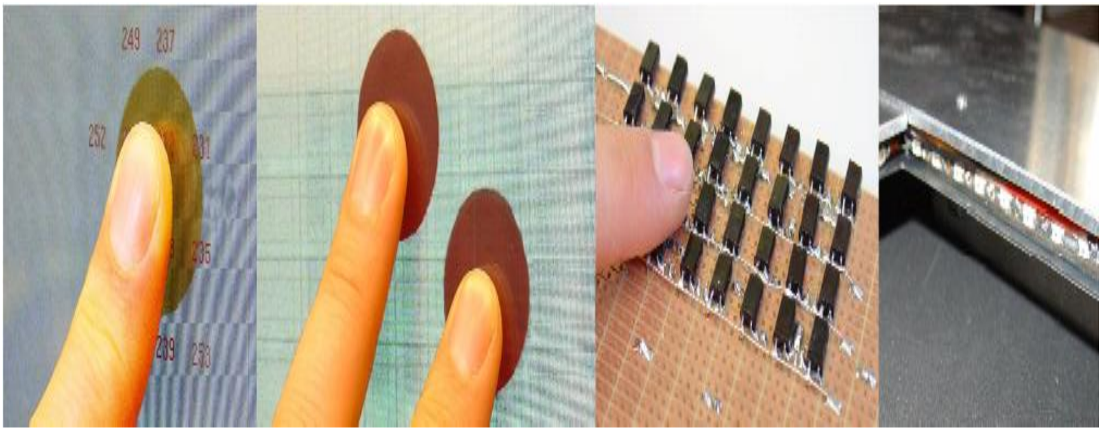


Figure 2.11: FLATIR display (left) and its architecture (right) (Hofer, et al., 2009)

Recently, another multi-touch system called Scanning FTIR was developed by (Moeller & Kerne, 2010) using the FTIR sensing technique. In this system, the infrared light sources are configured in front of two edges of an acrylic sheet, and infrared sensors are also configured in their complementary sides. When these light sources emit the light, total internal reflection is generated inside the surface medium. The LCD panel is integrated behind the acrylic surface in order to display the digital information. The architecture of the Scanning FTIR display is shown in Figure 2.12.

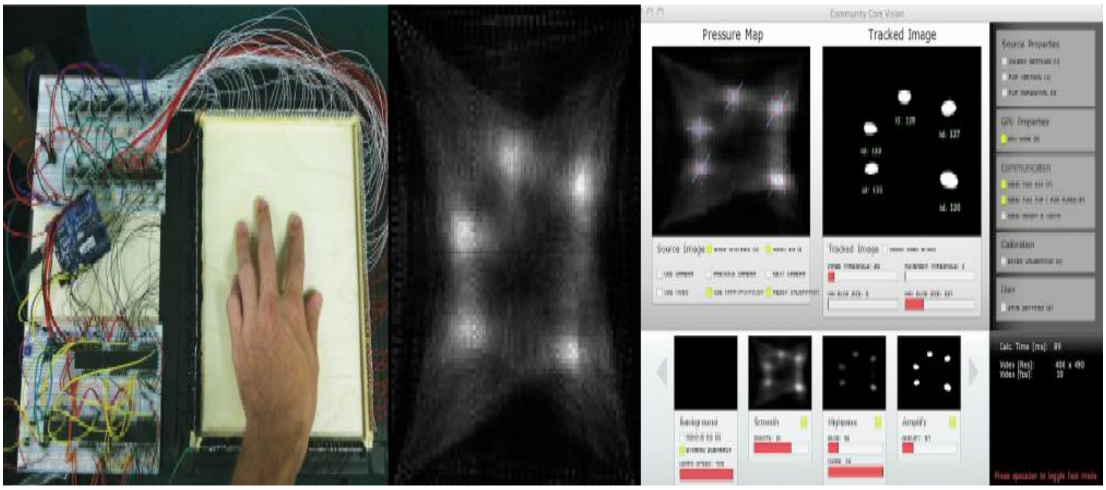


Figure 2.12: Architecture of the Scanning FTIR display (left) and fingertip calibration (right) (Moeller & Kerne, 2010)

When a user interacts with the display using the fingertips, infrared rays are generated and detected by the sensors as input signals. This system is capable of detecting input at the center of the surface effectively, but not at the edges of the surface due to an insufficient amount of light. Even though this system supports multi-touch interaction, it has limitations in regards to assisting multi-users with the multi-touch interaction.

2.3 Comparison Touch Enabling Technologies

From the review of related work, it is learned that different touch technologies are used for the development of different displays, both of small and large sizes. Each technology has its own merits and demerits in terms of architecture, functionality, scalability and cost. Although resistive and SAW touch technologies do support the development of small size displays at low cost; the construction of these displays is rather difficult without industrial support due to their complex architecture.

Even though display technologies existing today do provide single user multi-touch interaction, however, they have limitations in providing a collaborative workspace for multi-user multi-touch interaction. At present, the resistive displays are only capable of being interactive with a stylus or nail, but are difficult to interact with using the bare fingers. Whereas, SAW displays are able to detect bare fingers but are limited in detecting a hard stylus; moreover, these displays are highly affected by ambient light. The multi-touch input is detected by means of measuring an electric field so these technologies provide neither the image pattern of the fingertip contact area nor its measurement.

The capacitive and computer vision based display technologies have encouraged researchers, engineers and developers in regards to exploring the development of small and large size displays. However, the capacitance based displays or touchpads are difficult to design and construct without industrial infrastructure, and thus involve high cost. In contrast, optical and vision based displays are easier and cheaper to construct due to their simple architecture as compared to resistive, SAW and capacitive displays.

From the literature survey, it is found that the FTIR sensing technique is simple in regards to architecture, inexpensive and more scalable than other touch display technologies. For these reasons, it has been widely used by (Hrvoje Benko, et al., 2006; Cuypers, et al., 2008; Dohse, et al., 2008; Feng, et al., 2008; Gross, et al., 2008; J. Y. Han, 2005; Kim, et al., 2007; Wang & Ren, 2009) and many others for developing different multi-touch tabletop displays to explore various interaction techniques at the academic level.

The FTIR sensing technique supports the development of tabletop displays using the bottom-up and top-down approach as well as development of even wall size displays. The capacitive tabletop and purely vision based systems use the top-down approach in configuring the projector for displaying digital content which introduces an occlusion and portability problem. As the user’s hands and fingers break the projected images during multi-user multi-touch interaction, the FTIR based multi-touch tabletop displays using the bottom-up approach help to avoid occlusion and reduce portability issues.

It has also been found through studies, that the FTIR sensing technique can provide complete image patterns of the user’s fingertips in high resolution during multi-touch interaction. It shows the potential of measuring the user’s fingertips occupying the contact area, and helps in identifying the fingertip shape and orientation during interaction. Moreover, it has been widely used for evaluation of finger input properties in order to overcome imprecise selection (Feng, et al., 2008; Wang, et al., 2009; Wang & Ren, 2009). A summary of different touch display technologies and their comparisons have been compiled from the literature survey and are shown in Table 2.1.

The FTIR based tabletop displays also provide multi-user multi-touch interaction in a collaborative workspace. Owing to the potential of this technology, it is decided to select the FTIR technique for the development of our multi-touch tabletop display to evaluate finger input properties

Table 2.1: Comparison of touch enabling technologies

Comparison of Touch Screen Technologies				
Technologies	Resistive	SAW	Capacitive	Optical and Computer Vision (FTIR)
Architecture & Development				
Design Complexity	High	High	High	Low
Construction complexity	High	High	High	Low
Influence of ambient light	Low	High	Low	Low
Functionality				
Finger touch detection	Yes	Yes	Yes	Yes
Allow single user	Yes	Yes	Yes	Yes
Allow single touch	Yes	Yes	Yes	Yes
Allow multiple users	No	No	Yes	Yes
Allow multi-touch	No	No	Yes	Yes
Fingertips contact area detection	No	No	Average	Strong
Nail detection	Yes	Unknown	No	No
Stylus or Pen detection	Yes	No	No	No
Fiducial markers detection	No	No	No	No
Scalability	Low	Low	Low	High
Cost	Medium	Medium	High	Low

2.4 Precise Selection Techniques

The human finger is used as the pointing device (Albinsson & Zhai, 2003) for interacting with multi-touch sensitive displays to access digital information. Utilizing the input capabilities of fingers, various interaction techniques are introduced that facilitate users in selecting and manipulating target elements. Using these techniques, the index finger is commonly used for single target element selection and multiple fingers are used where the selection of simultaneous multiple elements are desired (Jangwoon, Jaewan, HyungKwan, & Chilwoo, 2007; Kim, et al., 2007; Kin, et al., 2009).

However, the physical size of fingertip varies from person to person (Wu & Balakrishnan, 2003), that generally leads to a fat finger problem. It creates imprecise selection of target elements. To resolve this issue, different software (e.g. cursor-offset) and hardware (e.g. LucidTouch) based approaches have been introduced (Albinsson & Zhai, 2003; Hrvoje Benko, et al., 2006; Blanch, et al., 2004; Esenther & Ryall, 2006; Olwal, et al., 2008; Potter, et al., 1988; Vogel & Baudisch, 2007). These approaches are reviewed and discussed comprehensively in the following sub-sections.

2.4.1 Cursor-offset

In this technique, a crosshair cursor is created above the fingertip at a particular distance during interaction, and its position ensures that the desired target is selected exactly. When the user's fingertip is take-off from the display then the touch event is activated completely. This technique facilitates users in selecting target elements directly using their bare fingers, but accuracy is lacking when small target objects are selected. Moreover, the users' fingers may occupy more space than the exact target point on the display, thus more concentration is needed to select small targets. The cursor-offset technique is observed as the slowest technique in the context of response during selection (Albinsson & Zhai, 2003; Olwal, et al., 2008).

In order to ensure direct touch input with legacy applications, some researchers proposed the mouse emulation technique called Fluid DTMouse (Esenther & Ryall, 2006) as shown in Figure 2.13.

Figure 2.13: The fluid DTMouse technique (Esenther & Ryall, 2006)

In this technique, the cursor is associated with the pointing finger during interaction with the display, and the desired target element is selected when the finger is released. In order to select small size target elements precisely, the users utilize the thumb and middle finger to control the cursor at the exact target element, and then the index finger is applied for tapping. When the index finger is take-off then the target element is selected. This technique contributes towards precise selection but it is inconvenient to use when an element is placed in the corner of a display; furthermore, it consumes more time by engaging two fingers to locate the exact position of the target element.

Other techniques that have also been introduced for achieving high precision are the Dual Finger selection techniques in which two fingers are involved. These techniques are named as Dual Finger Offset, Dual Finger Midpoint, Dual Finger Stretch, Dual Finger X-Menu and Dual Finger Slider (Hrvoje Benko, et al., 2006).

Using these techniques, the first contact is made by the primary finger (index finger of the right hand) and the second contact is made by the secondary finger (index finger of the left hand) to select the target elements. The Dual Finger Offset technique with the fixed cursor offset contributes to resolving the issue of occlusion to some extent, but lacks the ability to offer a more precise selection due to instability in the cursor speed. The Dual Finger Midpoint technique with variable cursor offset improves stability in the cursor speed which helps in accomplishing precision. The example of Dual Finger Midpoint and X-Menu techniques are shown in Figure 2.14.

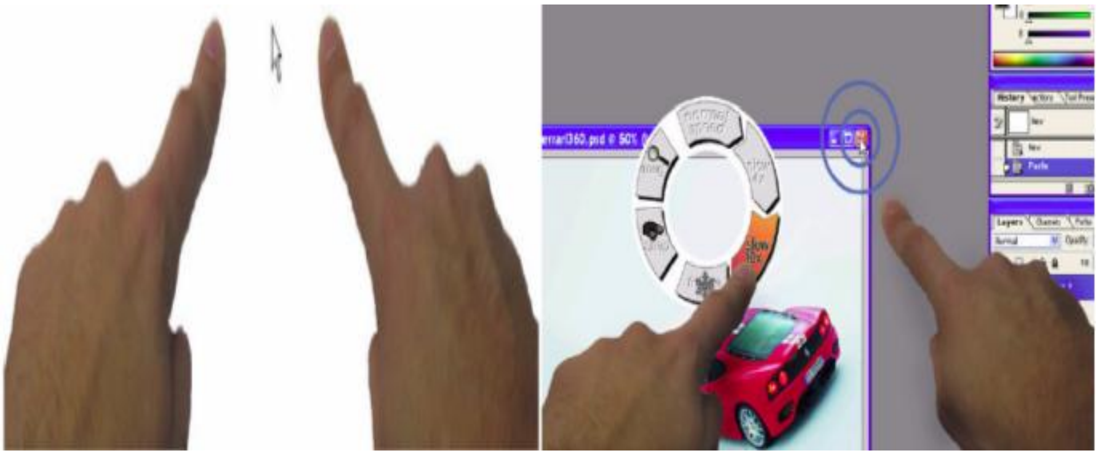


Figure 2.14: Dual finger midpoint and X-Menu technique (Hrvoje Benko, et al., 2006)

However, this technique limits precise selection of target elements that are placed in corners of the display (Hrvoje Benko, et al., 2006). For improving the precision, a Dual Finger Stretch technique is introduced in which the target element is equally expanded and decreased in all directions by keeping the movement of the secondary finger close and far. The single target element is selected precisely, but zooming in all directions without any specific limit may occupy more space on small size displays. The Dual Finger Stretch technique is shown in Figure 2.15.

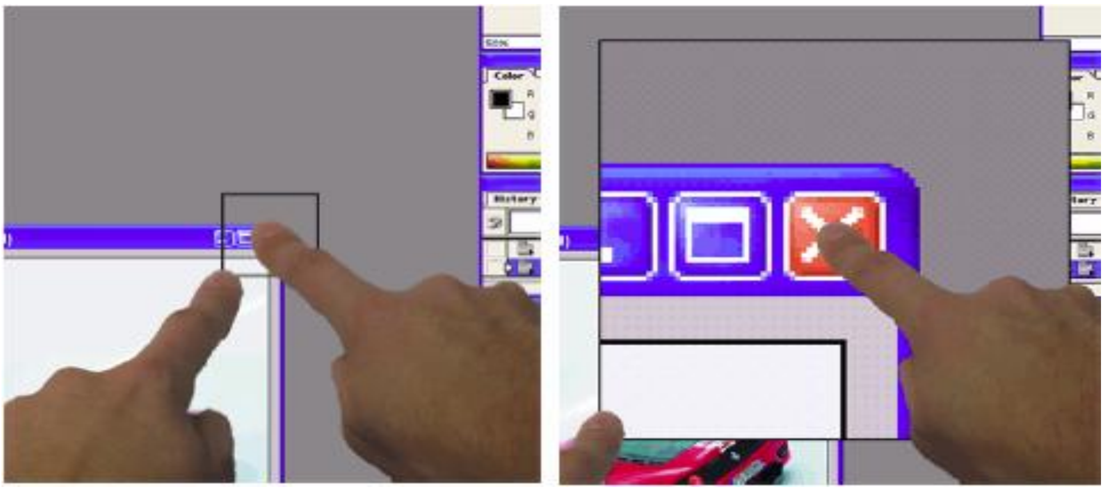


Figure 2.15: Dual finger stretch technique (Hrvoje Benko, et al., 2006)

Another Dual Finger X-Menu technique is introduced that consists of six different widgets, i.e. normal, slow 4x, slow 10x, freeze and snap, and magnify. Using the X-Menu, users are required to crossover a particular area of the menu in order to activate it without lifting up the finger. These X-Menu controls enable users to select target elements precisely. In order to enrich the precision, a Dual Finger Slider technique is introduced that specifies the reduction of the cursor speed by the distance between the fingers. By moving both fingers closer to each other, the cursor speed is reduced; it is increased when the fingers are moved away from each other. By specifying the cursor speed through two fingers, precise selection is improved (Hrvoje Benko, et al., 2006).

By reviewing the Dual Finger techniques, it is observed that the Dual Finger Stretch technique performed better than the other techniques during the selection of small size target elements. It allows users to zoom-in the target elements first in all directions prior to the selection and offers high precision. However, this technique loses the contextual view of small pixel size elements as reported by (Albinsson & Zhai, 2003). These techniques offer one offset cursor for the selection of a single target element by involving at least two fingers. Thus, it would be difficult to frequently select target elements on small size or hand held displays; it also limits simultaneous selection of multiple target elements.

In order to achieve frequent and accurate interaction, multi-touchpad and multi-finger cursor techniques are introduced and named as multi-finger hand cursor, similarity cursor and adjustable area cursor. The multi-touchpad is a relative positioning device, consisting of tactile buttons. It is coordinated with the frame of the user’s hand according to the appropriate size of the display. By pressing specific tactile buttons, the user can create multi-cursors on the surface through multi-fingers to control more than one element at a time. The multi-finger cursor technique is shown in Figure 2.16.

The multi-finger approach provides frequent interaction, but there is a possibility of ambiguity in identifying which cursor belongs to which hand’s finger. By using these techniques, it is difficult to move fingers independently in all directions because each finger’s movement depends on another. Furthermore, the variation in hands and their fingers’ motion at a particular scale may create ambiguity in the interaction. In this respect, it is difficult to utilize the potential of multiple fingers in a controlled manner (Moscovich & Hughes, 2006).

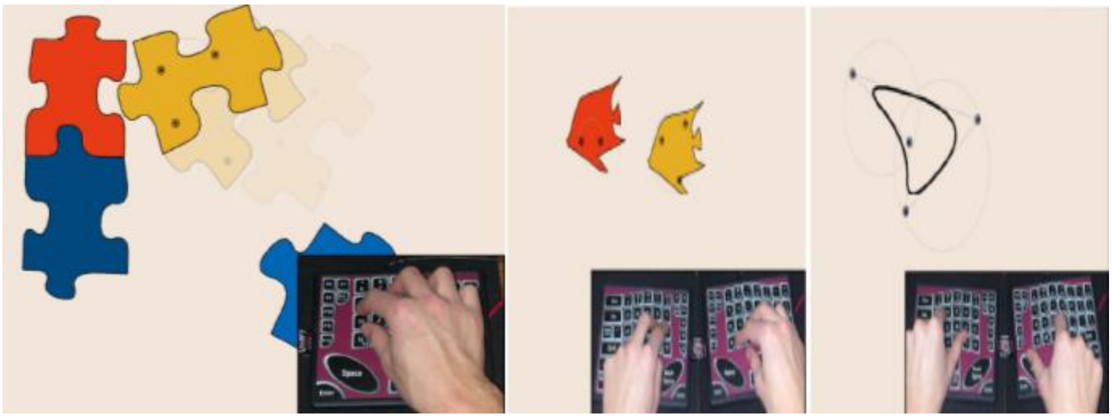


Figure 2.16: Multi-finger cursor technique (Moscovich & Hughes, 2006)

Using offset cursor techniques, the cursor is dragged towards the target element carefully, and then the finger is lifted off for precise selection. Thus, the phenomena of this interaction may increase the access time as compared to direct touch. The user cannot aim to touch the target element directly at the first instance, and may even have to pay close attention for generation of the offset cursor above the fingertip in real time. There is no visual feedback thus the user cannot rely on the predictable offset cursor only. In addition, a constant distance of the offset cursor above the fingertip, and its direction limit the access of target elements at the bottom edge of the display (Vogel & Baudisch, 2007).

The Shift technique was introduced by (Vogel & Baudisch, 2007) in which an offset callout function is activated during interaction. When the desired element is selected directly under the fingertip, then its copy is shown on the display for function activation. It reveals the replica of the area occluded by the fingertip and offset cursor at a non occluded part of the display. The callout function can be placed anywhere on the display and does not disturb the user during the selection of target elements. The Shift technique is shown in Figure 2.17.

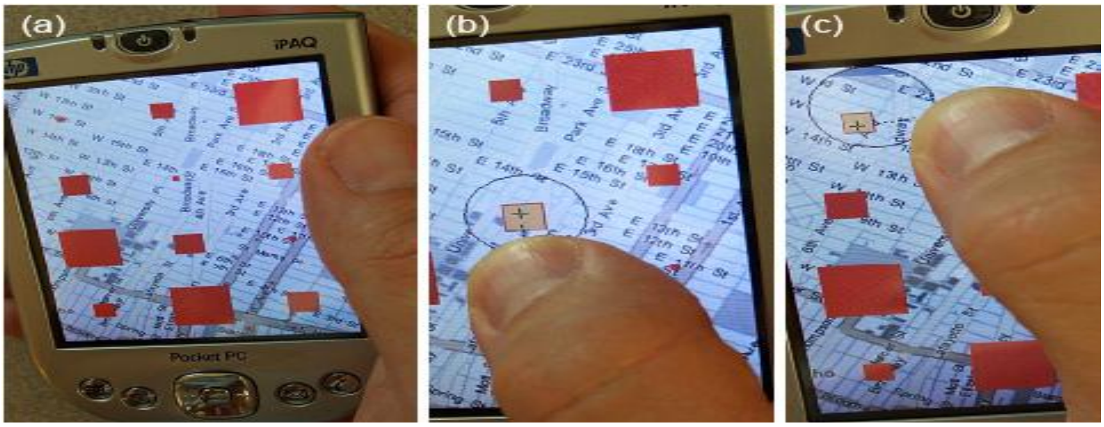


Figure 2.17:The Shift technique with callout function that is activated only when a user aims to select small target elements (Vogel & Baudisch, 2007)

It provides direct touch with visual feedback and decreases the user's frustration during interaction. It can be useful for single target selection using hand held devices but does not allow selection of multiple target elements using multiple fingers.

2.4.2 On-Screen Widgets

In order to overcome imprecise selection of small target elements, on-screen widgets were introduced (Albinsson & Zhai, 2003). These widgets enable users to zoom-in small target elements by tapping with their fingertip directly rather than using the cursor offset. Using the zooming technique that is shown in Figure 2.18, the small target element is enlarged first and then selected by the fingertip.

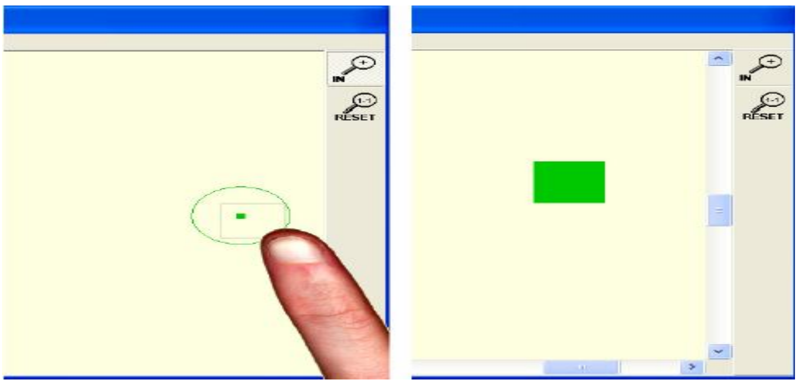


Figure 2.18: The target element selection using zoom-in technique (Albinsson & Zhai, 2003)

This approach involves discrete steps to select only a single target element which degrades the user's performance in terms of time. In addition, the zoom-in technique using widgets loses the contextual view of the small size target elements that leads to a bad user experience.

The Rub-pointing technique was introduced by (Olwal, et al., 2008) in which target elements are zoomed in and out through rubbing the pointing finger on the display. As shown in Figure 2.19, the rubbing gesture of the fingertip enables users to rub the target element to zoom-in with the primary finger and tap it with the secondary finger for its selection. The rub-pointing technique increases the precise selection of small targets. It allows users to perform concurrent steps to carry out tasks by applying two fingers at the same time. This technique is lacking in performing the zoom-out operation and increases the space. For carrying out tasks in a continuous manner, the Ripple technique was introduced in which visual feedback is provided by generating ripples during the target element selection (Daniel Wigdor, et al., 2009).

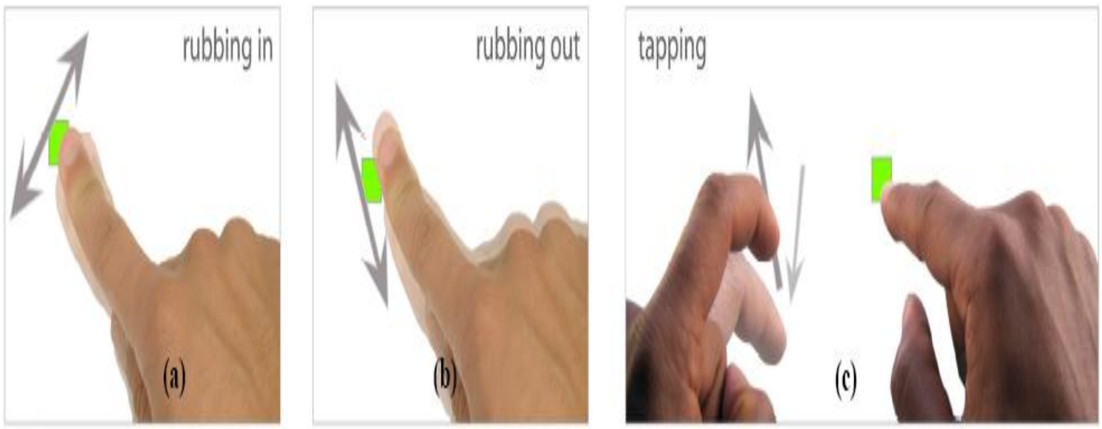


Figure 2.19: Rub-pointing technique with zoom-in and out and tapping functions (Olwal, et al., 2008)

This technique facilitates users in selecting target elements directly without using on-screen widgets and the offset cursor. It strengthens the direct and multi-touch interaction with visual feedback.

2.4.3 Hardware Based Solutions

From the review of related work, it is identified that the position of the offset cursor above the fingertip and on-screen widgets contribute towards achieving precise selection. Nevertheless, hardware based solutions have also been proposed to overcome the imprecision problem; elements are selected using a stylus rather than fingertips. This approach facilitates users in selecting small target elements precisely in many situations, but prevents the direct and natural touch of using the bare finger. The stylus is a much sharper pointer than the fingertip and is affiliated with the issue of hand tremors (Hrvoje Benko, et al., 2006; Ren & Moriya, 2000). To provide a precise selection using the bare fingers, an alternative hardware based solution was proposed by (Daniel Wigdor, et al., 2006), in which users can interact with the display from its front and rear sides.

Interacting with the display from its rear side reduces the occlusion effect but creates another type of occlusion. For example, users cannot see their fingers on the rear side of the display which presents some difficulty when trying to approach the exact target at a particular distance (Daniel Wigdor, et al., 2007), as well as including the possibility of collision between different users' hands and fingers during interaction. In addition, it may also introduce various ergonomic issues. The example of a multi-touch display with interaction under the table is shown in Figure 2.20.

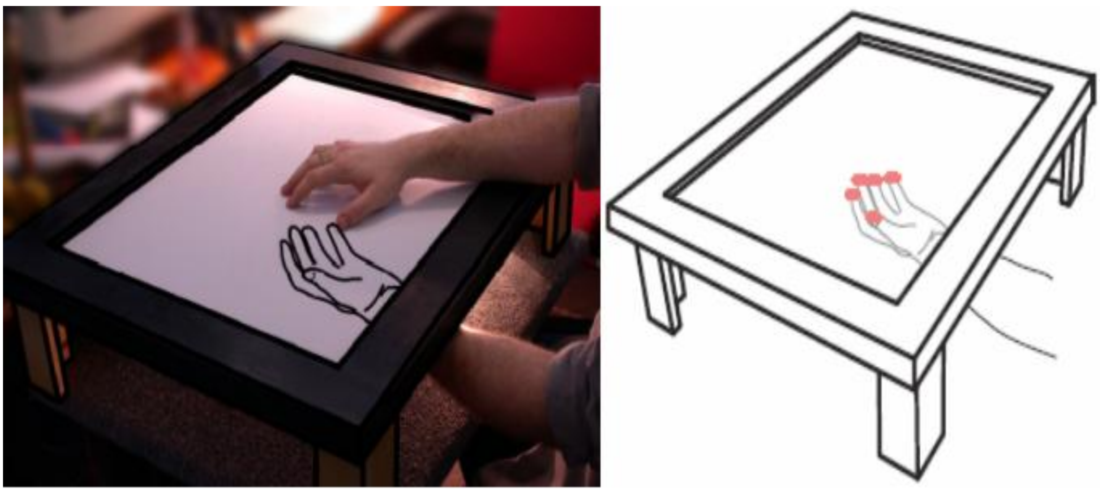


Figure 2.20: Multi-touch display with interaction under the table (Daniel Wigdor, et al., 2006)

Rear interaction with the display opens a new trend of interaction; a mobile device called LucidTouch was introduced by (Daniel Wigdor, et al., 2007). The LucidTouch device with the pseudo-transparency technique is shown in Figure 2.21.

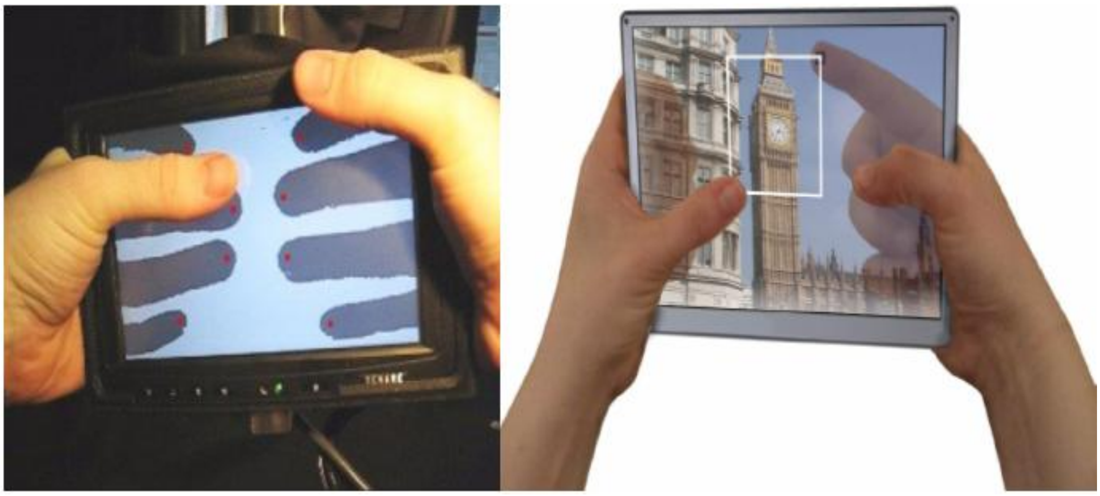


Figure 2.21: LucidTouch device with the pseudo-transparency technique (Daniel Wigdor, et al., 2007)

The user keeps the device in the palms of both hands and interacts with the target elements using the bare fingers from its back side. A pseudo-transparency technique was introduced which enables the user to perform multi-touch interaction. The user can see the gesture and posture of his /her fingers on the front side of the display device, and this feature allows him/her to point on the target elements at exact the location. The pseudo-transparency technique is augmented with vision track touch cursors and provides lucid touch. When the fingers are hovering behind the display, a red cursor is shown but it changes to blue when the user touches the display.

It improves precise selection by reducing occlusion and providing visual feedback. The LucidTouch mobile device detects multi-touch input, but the potential of all the fingers cannot be utilized since the device needs to be held by both hands.

Using the traditional text entry and pointing input devices users get visual, auditory and tangible feedback during interaction. Users can target and select the target elements precisely on the monitor display. Whereas, interacting with intuitive displays using fingers does not allow frequent and precise selection with visual feedback.

Quite recently, the SLAP widgets known as slide, knobs and keyboard with visual markers were introduced that provide visual and tangible feedback on the display during interaction (Weiss, et al., 2009). The SLAP widgets are shown in Figure 2.22.

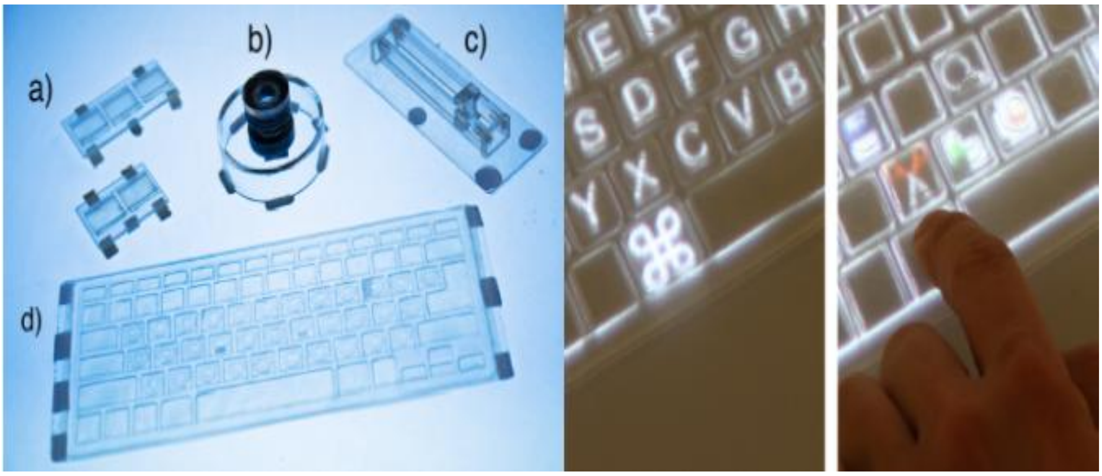


Figure 2.22: The SLAP widgets (Weiss, et al., 2009)

These widgets are transparent, made up of silicone rubber and visual markers are written on their bottom side. These visual markers register when the widgets are manually placed on the display. Using these widgets, users can manipulate the target elements effectively, and also key-in text input in the same way as using a traditional keyboard. These widgets are significant for providing visual and tangible feedback that enhances precise selection, but their physical characteristics limit the natural style of interaction. These widgets are static in nature; thus they are incompatible with resistive, capacitive and SAW based displays. It would be difficult to place these widgets on small size displays and interact with them accordingly.

From the review of related work, it can be concluded that above techniques contribute in achieving the precision accordingly. It has been found through studies that size of target elements was undertaken based on assumptions to achieve the precision. However, some researcher has determined the size of user's fingertip but there was not an argument based on extensive study relating to the fingertip size. Meanwhile, the above hardware and software approaches lacks in providing high precise selection with visual feedback in direct multi-touch input. In this respect, users expect more precise and frequent selection of target elements according to their natural input capabilities.

2.5 Finger Input Properties

In general, humans possess dynamic capabilities to perform different activities using their hands and fingers in daily life. Usually, interacting with the computer humans also use their hands and fingers to access digital information using different ways. Similarly, interacting with multi-touch sensitive displays, humans also use their hands and fingers to select and manipulate target elements directly. Considering the importance and potential of these hands and fingers, some studies have been conducted to explore their input properties and use them according to their capabilities in multi-touch interaction (Albinsson & Zhai, 2003; Hrvoje Benko, et al., 2006; Hall, Cunningham, Roache, & Cox, 1988; Kim, et al., 2007; Ramos, Boulos, & Balakrishnan, 2004; Wilson, et al., 2008; Xiang, et al., 2008).

It is identified that use of multiple fingers simultaneously may assist in performing complex tasks easily dealing with multi-touch tabletop displays. Because, these multi-touch displays facilitate users to make use of their hands and fingers to perform one and two handed interaction according to their abilities. The example of one and two handed multi-touch interaction is shown in Figure 2.23.

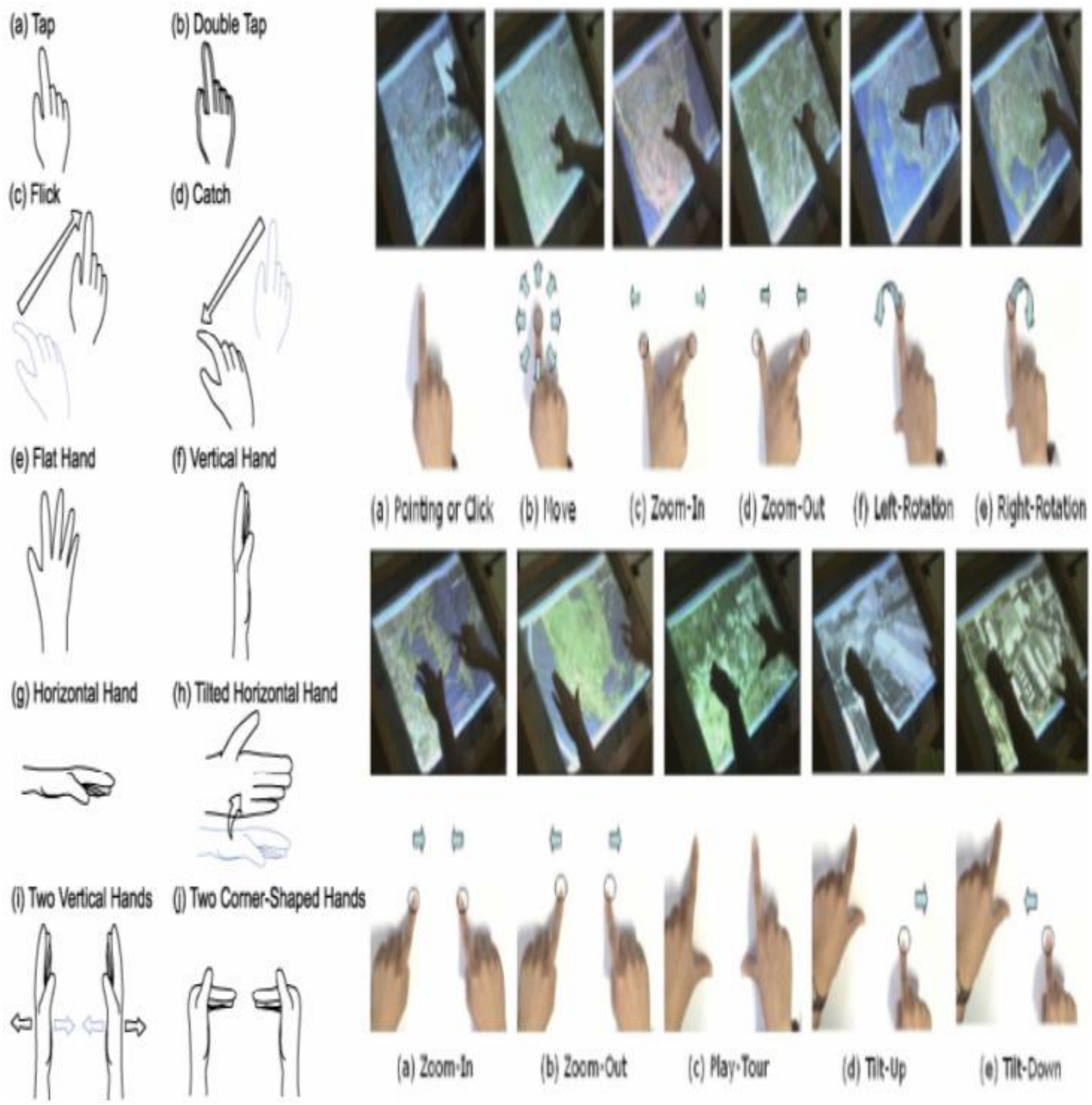


Figure 2.23:One and two handed multi-touch interaction with interactive displays (Kim, et al., 2007; Wu & Balakrishnan, 2003)

By medical and anatomical analysis, it is observed that the human hand has 23 degrees of freedom (DOF) (Anderson, 1992). It means that a user can move his hand in 23 possible directions in a free space. Keeping in mind potential of this DOF and importance of precise selection of target elements, recently an empirical study has been conducted to explore finger input properties. In which, the four main properties were identified, i.e. position, physical, motion and event properties (Wang & Ren, 2009).

Each property has its own characteristics that can be utilized to interact with multi-touch displays. The classification of these properties are shown in Table 2.2 and briefly discussed in the following sub-sections.

Table 2.2: Classification of human finger input properties (Wang & Ren, 2009)

Input Property	Finger Property
Position Property	Co-ordinate values (x, y)
Motion Property	Velocity
	Acceleration
Physical Property	Size of Contact Area
	Shape of Contact Area
	Orientation
	Pressure
Event Property	Tap
	Flick

2.5.1 Position Property

The precise selection techniques that use finger input properties for the selection of target elements are discussed briefly in sub-section 3.2.1. The finger position property is described in terms of x and y coordinates. It has been used by (W. Buxton, et al., 1985; Potter, et al., 1988) using take-off techniques. The index fingertip was used to investigate the precise selection of elements, and it was mentioned that precision depends on the size of the target element. The input accuracy varies as the size of the target elements changes (Hall, et al., 1988). This study was conducted for the index finger only, and the rest of the fingers were not investigated.

2.5.2 Motion Property

The motion property is an important finger input property which is used when a user moves his fingers on the interactive display to select and manipulate target elements.

It has two main characteristics, i.e. velocity and acceleration, which are utilized to zoom-in, zoom-out and drag and drop target elements in many directions (Kim, et al., 2007). The gesture of the fingers is recognized through a protocol called Tangible User Interface Object (TUIO). Basically, it was proposed by (Kaltenbrunner, Bovermann, Bencina, & Costanz, 2005) for tangible interaction, and is also useful for interacting with virtual target elements. The motion property can be used extensively to interact with virtual target elements using visual tracking systems.

2.5.3 Physical Property

The physical property of fingers is also an important finger input property with different characteristics, i.e. size of contact area, shape of contact area, orientation and pressure (Wang & Ren, 2009). The resistive mobile sensitive displays detect the finger input when pressure is applied by the fingers. The pressure and torque capabilities of the finger were studied and examined by (Herot & Weinzapfel, 1978) to achieve the accuracy in the direct touch input. In this study, five interaction techniques were proposed, in which a user can manipulate and rotate target elements by keeping control of the cursor's position and speed.

The pressure widgets were proposed by (Ramos, et al., 2004) to further investigate the finger pressure property. A pressure widget tries to select target elements in a discrete form of interaction using a stylus with variable pressure exerted by the finger. A partial and full visual feedback is provided to the user during the selection of the target elements.

(Hrvoje Benko, et al., 2006) proposed the use of the fingertip contact area and pressure to activate a click event through the phenomena of rocking and pressing on the multi-touch display. The posture of the finger plays an important role for selecting and manipulating target elements precisely. In this context, two types of generic finger postures are identified, i.e. vertical and oblique touches (Forlines, et al., 2007). The identification of these postures helps in determining the impact of the fingertip contact area on precise selection of small size target elements. Moreover, the finger's shape property is also used and investigated by researchers to select target elements

(Wilson, et al., 2008; Xiang, et al., 2008). When users interact with displays using their fingertips, the shapes of their contact points are formed in different sizes. The formation of their shapes and sizes depends on the physical size of the users' fingers, posture and applied force during interaction. Following the nature of these shapes, virtual objects are selected on the interactive displays.

In the past, the orientation property was not extensively used for direct touch input because it was observed that only the fingertip contact point and its shape can be detected. However, recently developed intuitive displays are able to detect the orientation of fingertips during interaction. A small scale study has been conducted to explore the orientation property and its potential for target manipulation (Wang, et al., 2009; Wang & Ren, 2009). This property of fingers is related to the DOF of hands and fingers that allows users to manipulate target elements in many directions. In addition, the appropriate utilization of the finger orientation property also depends on the size, shape and orientation of the interactive display.

It is observed that, many target elements are touched by a fingertip using mobile touch screens, specially using virtual keyboard. In this respect, how to design a touch screen widgets that react the fingertip's contact area? Realizing the importance of fingertips contact area in selecting the touch screen widgets precisely, another study is conducted in which Sliding Widgets have been proposed. Although, these widgets improve the precise selection on many touch screen but lack in providing the accuracy for resistive touch screens. A significant force is required to interact with resistive touch screens (Moscovich, 2009b).

This study opened many ways to focus on the design of touch screen buttons in the aspect of speed and accuracy. It is questioned that how designers can decrease extra cognitive effort that is done during selecting of targets elements. It reported that fingertip contact area selection is important on its own, but it is also very important to learn and understand that how it affects on users perception related to target elements width or how users observe contact area. In addition, it is significant to know size of buttons and their configuration on screen in terms of spacing (Moscovich, 2009b).

After that, realizing the importance of precise touch input, recently another study is conducted in which a generalized perceived input point model is proposed. It is studied that an offset between the centre of fingertip contact area and target element do not only depend on their x and y co-ordinates but also depend on the wider context of touch interaction. It represents the offsets for the postures of individuals' fingers and users. It is attempted to know that what exact location a finger is touching. This study contributes in increasing the touch accuracy through respective offsets that are determined in both model touch per-posture and per-user accordingly. However, this study suggests that users are different and fingertip contact area is determining factor in today's touch technology. In addition, it is also identified that the more understanding is required regarding the users' mental model of touch (Holz & Baudisch, 2010, 2011).

These physical characteristics play an important role in designing and developing a suitable size, shape, and configuration of target elements in context of precise selection in direct multi-touch input.

2.5.4 Event Property

The event property has been explored and used for the selection of target elements by sending input through a cursor. It consists of two main characteristics, i.e. tap and flick. The tapping technique is commonly used to simulate the cursor in different precise interaction techniques, but it lacks the ability to select elements at the corners and bottom of interactive displays. Whereas, the super flick technique is proposed for sliding target elements across the display similar to sliding physical objects in the real world (Reetz, Gutwin, Stach, Nacenta, & Subramanian, 2006). In this technique, the gesture of a pen reflects the direction of the place to which the target element is to be moved. The sliding element stops moving at a particular location of the display when the effect of the applied stroke slows down.

From the comprehensive literature review, it is observed that the precise selection of target elements is achieved through different techniques. The position and event finger input properties are widely used in these techniques. However, each technique has its own pros and cons, and there is a lack of precise selection in direct touch input. Users expect effective and accurate multi-touch interaction with visual feedback on interactive displays. The recent development in multi-touch display technology and the existing interaction techniques have encouraged researchers to explore the rest of the finger input properties.

A study conducted by (Wang & Ren, 2009) demonstrates the impact of finger input properties on precise selection and user interface design. Subsequently, recommendation was given for further investigation of finger input properties on a large scale. Specifically, the fingertip contact area, shape and orientation are important to investigate accordingly. It may contribute toward high precise selections in direct multi-touch input.

2.6 Summary

In the first section of this chapter, the four main touch enabling technologies are reviewed, i.e. resistive, Surface Acoustic Wave (SAW), capacitive and optical computer vision. These valuable technologies possess various advantages and disadvantages from the point of view of architecture, functionality, scalability and cost. These pros and cons have pointed to selecting the appropriate technology for developing a multi-touch tabletop display at low cost for evaluation of finger input properties.

In the second section of this chapter, the precise selection techniques are studied, i.e. cursor-offset, on-screen widgets and hardware based techniques. These software and hardware based approaches provided different methods of selecting target elements. These techniques involve human finger input properties for selecting target elements but the use of these properties has led to various issues as well. The limitations of these techniques have highlighted the necessity for evaluation of finger input properties.

In the third section of this chapter, keeping in mind the issue of imprecise selection, the finger input properties are studied which are associated with physical characteristics of fingers, i.e. physical length and width, position and orientation. It is observed that these physical characteristics are involved directly in creating the imprecise selection of target elements, thus are recommended for evaluation accordingly.

In the next chapter, the research design that is undertaken for developing a new multi-touch tabletop display and evaluation of finger input properties is presented.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview

This chapter introduces to a research methodology that has been planned to evaluate the physical finger input properties in the context of imprecise selection of target elements. It attempts to answer the basic question i.e. “How the research activities are organized and undertaken to evaluate physical finger input properties”?

This scientific enquiry consists of four major phases; in the first phase, a multi-touch tabletop display is developed using the FTIR sensing technique. In the second phase, an experiment is conducted to investigate the physical finger input properties using the developed multi-touch tabletop display. It assisted in collecting data samples related to physical finger input properties. In the third phase, a survey based study is conducted to specify the finger’s angle of approach for interacting with tabletop display. A close-ended questionnaire is formulated and distributed among participants for the data collection. In the fourth part, another experimental is conducted for evaluating the physical input properties of the *index finger* only. For conducting this study, paper sheets and inkpad are used to collect the fingertip imprinted data samples.

3.2 Development of Multi-touch Tabletop Display

Since, different touch enabling technologies have been reviewed in the second chapter to find an appropriate and low cost multi-touch sensing technique for the development of a tabletop display. It has been studied through literature that the Frustrated Total Internal Reflection (FTIR) sensing technique is suitable in regards to architecture, functionality, scalability and cost (J. Y. Han, 2005). In addition, it is explored that the FTIR based displays are widely used for the exploration and empirical evaluation of finger input properties (Hrvoje Benko, et al., 2006; Feng, et al., 2008; Wang, et al., 2009; Wang & Ren, 2009). These displays are also used for exploring and analyzing multi-touch interaction techniques to improve precise selection of target elements (Hrvoje Benko, et al., 2006; Kim, et al., 2007). Thus, the FTIR sensing technique is selected for the development of the multi-touch tabletop display. In the phase one, the whole design and development process consists of various steps that are shown in Figure 3.1. Each step has its own importance and is described in following sub-sections.

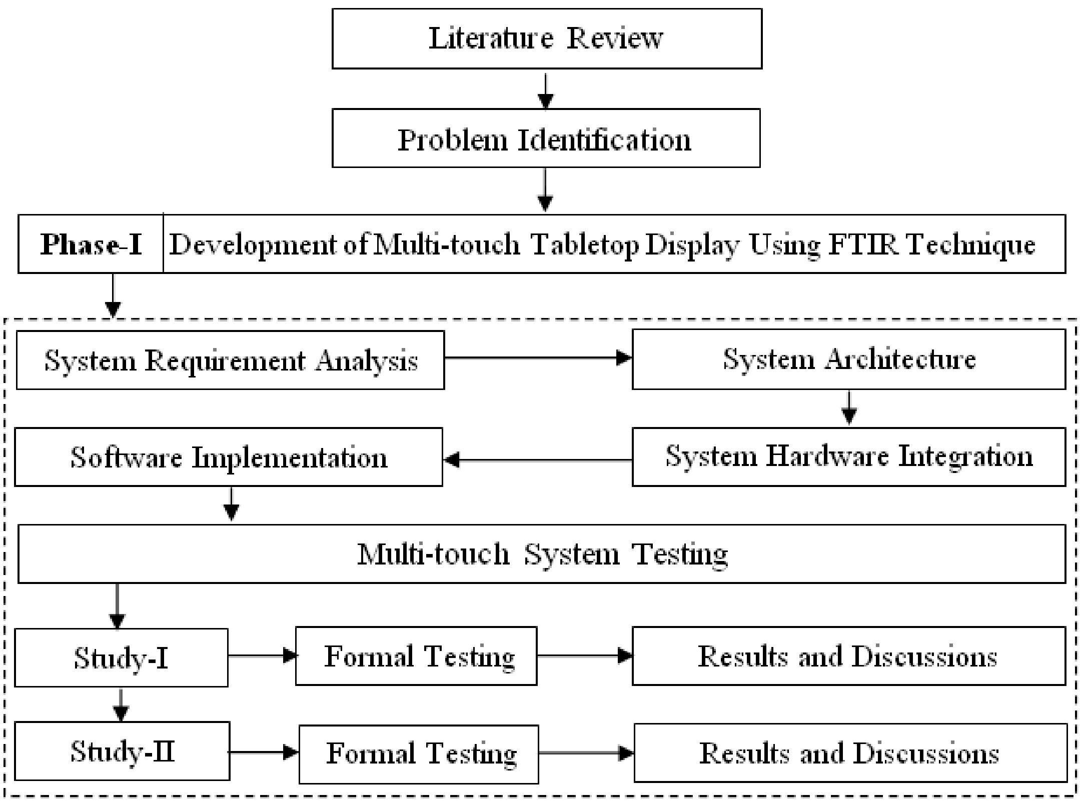


Figure 3.1: Overall research flow of diagram for the development of multi-touch tabletop display

3.2.1 System Requirement

Before developing the multi-touch tabletop display, related works have been reviewed in the context of hardware and software requirements. The requirements have been analyzed and gathered. This approach helped in collecting the suitable components accordingly for the development of tabletop display. Consequently, it played an important role in producing the reliable testbed to be used for conducting the planned experiments.

3.2.2 System Architecture

Since, every physical or software system would have required the architecture for its implementation accordingly. Similarly, for the development of the FTIR based multi-touch tabletop display, architecture has been proposed. It has helped in developing the system and assisting in understanding its structural and functional phenomena. Basically, the multi-touch tabletop display's architecture has been divided into four main segments according to the specific hardware components, i.e. a Unified Multi-touch Interface, Infrared Camera, Central Processing Unit (C.P.U) and Digital Light Processing (DLP) Projector. Following the proposed architecture, these hardware components have been organized, interconnected and calibrated according to their specifications in the system.

3.2.3 System Hardware Integration

In order to construct the system, a clean and controlled environment is required thus the Usability Laboratory at Universiti Teknologi PETRONAS is selected respectively. A rectangular transparent acrylic sheet is selected for the development of the unified multi-touch interface. A transparent silicone rubber sheet is overlaid carefully on the acrylic sheet then, a rear projection screen sheet is superimposed on the silicone rubber sheet accordingly. Infrared Light Emitting Diodes (IR LEDs) are configured in front of all the edges of the acrylic sheet using a U-profile aluminum frame. This phenomenon helped in producing an optical surface that to be used as a multi-touch input interface. A rectangular L-profile wooden frame is developed in which the optical surface is framed properly. In order to develop the tabletop multi-touch display, the bottom-up approach is used thus, a wooden table is constructed in which the optical surface is assembled and its electrical components (IR LEDs) are connected to computer system.

Since, an optical surface is based on the infrared light, so for an infrared camera is required to detect multi-touch input signals. Thus, a normal web camera is modified to make it an infrared camera, by replacing the infrared blocking filter carefully in front of its image sensor. The infrared camera is placed under the optical surface inside the table and connected to the computer system. In addition, a short-throw distance Digital Light Processing (DLP) projector is also placed near the camera and connected to the computer system. This whole process enabled us to develop the multi-touch tabletop display.

3.2.4 Software Implementation

For making the system fully functional, the open source multi-touch software called TouchLib (NUI, 2009) is implemented in the computer system. It enabled us to calibrate an optical surface according to its x and y co-ordinates to make it multi-touch interface. Additionally, infrared camera and projector are calibrated carefully according to the x and y co-ordinates of the multi-touch interface. This setup enables the system to detect and track the users' multi-touch input using their bare fingers.

3.2.5 Multi-touch System Testing

In order to accomplish a stable experimental setup for the investigation of physical finger input properties, the developed multi-touch system is tested through formal test approach. This testing approach helps in improving a developed systems related to the different issues raised during its development and also after testing its functionality. During the formal testing of a multi-touch system, it is attempted to know weather is it detecting multi-touch input or not and is it suitable for the investigation of physical finger input properties.

Considering this factors, the two different studies (Study-I and Study-II) have been undertaken by undergraduate students in their final year projects at Usability Laboratory, Universiti Teknologi PETRONAS. These small studies assist in providing a stable experimental setup. In the project of study-I, an undergraduate student have been assisted in developing a drawing application then it has been implemented on the multi-touch tabletop display. After that, it is attempted to identify users' preference of interaction in the context of *easy to use* as compared to an optical mouse.

In this small study, thirty volunteer participants have been involved for the data collection. These participants have been randomly selected, interviewed, and instructed properly in order to perform some tasks e.g. scrolling, drag and drop the target objects using the optical mouse and fingers. When users completed the defined tasks then a close-ended questionnaire has been distributed among the participants to obtain their feedback.

The outcome of this study-I supported in identifying the issues related to system functionality and stability for the investigation of finger input properties that are discussed in fourth chapter of this thesis. Considering the outcome of this study, it is attempted to improve our baby system. When it has been improved accordingly then again another study is conducted for testing its functionality and stability. In the project of study-II, it is attempted to demonstrate the proof-of-concept of using the multi-touch tabletop display for the video surveillance system. The main objective of this project was to develop a video surveillance application and enable more than one user to perform moving, scaling, and rotating actions on the multi-touch tabletop display. In this respect, an undergraduate student has been fully assisted during the development of the application and in obtaining the users feedback accordingly.

For seeking the feedback of a video surveillance application using the multi-touch tabletop display, eleven volunteer participants have been invited and interviewed. All participants were randomly selected and they have been briefed on the research background, problem statement, objectives, and the basic setup of multi-touch tabletop display. In addition, it is instructed to users that they can interact with the application. After that, they are given 15 minutes to interact with the video surveillance application on the multi-touch tabletop display. Lastly, a close-ended questionnaire is distributed personally among the participants to collect the feedback

3.3 Evaluation of Physical Finger Input Properties

In order to evaluate the physical finger input properties, an experimental design is proposed that consist of two experiments and one survey studies. Since, it is described in the section 3.1 that an overall research flow of this study is categorized in four main phases. In the first phase, the multi-touch tabletop display is developed and the rest of two experiments and one survey based study is conducted in other three phases. The overall flow of research methodology related to evaluation of physical finger input properties is illustrated in the Figure 3.2.

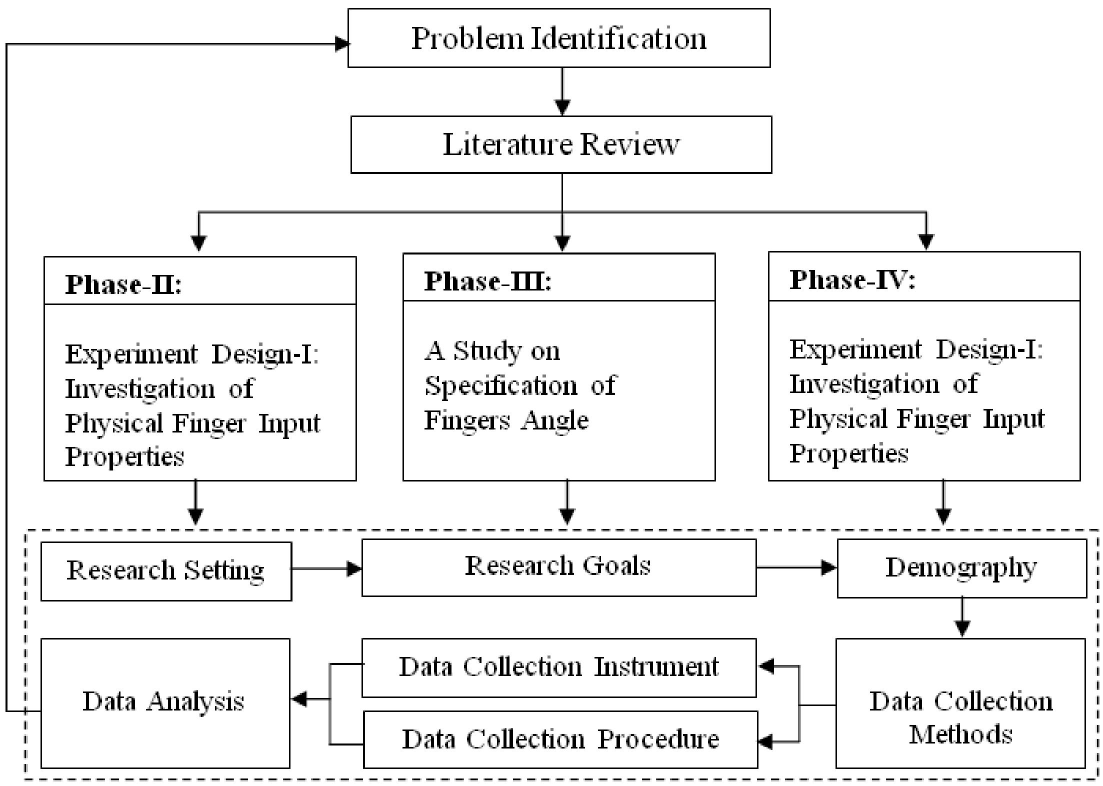


Figure 3.2: Overall flow of research methodology

3.4 Experiment Design-I: Investigation of Physical Finger Input Properties

For the evaluation of physical input properties, the experimental design is proposed that consists of various steps, i.e. research setting, goals, demography, and data collection methods and data analysis. Each step plays an important role in conducting the experiment. These steps are described as follows.

3.4.1 Research Setting

This research study has been conducted in the Usability Laboratory at the Department of Computer and Information Sciences, Universiti Teknologi PETRONAS. It is well established that this setting accommodates a comfortable and controlled environment that ensures physical and psychological comfort for the participants. It helps in maintaining the privacy and confidentiality of the data during the data collection process.

3.4.2 Research Goals

Humans use their fingers to select and manipulate target elements on multi-touch displays. It is found that the size of the fingertips vary from person to person that generally leads to the problem of fat fingers. It is found that the fingertips introduce the imprecise selection of small size target elements in direct multi-touch input. Thus, this study is aimed at investigating the users’ physical input properties that may help in solving the imprecise selection.

3.4.3 Demography

For conducting the experiment, twenty volunteer participants are involved ranging in age from 25-35 years old. All participants were randomly selected and were right handed postgraduate students at Universiti Teknologi PETRONAS. They were instructed briefly before performing the selected tasks for reliable data collection.

3.4.4 Data Collection

In order to collect data, a random sampling technique is used in which each data sample is collected randomly. It is a common technique, normally used in various scientific studies (Jackson, 2008). Additionally, all data samples have been collected under a direct personal observation. Usually, this approach is used for the laboratory experiments and localized scientific enquiries to collect data from individuals completely and accurately. However, it consumes more time and budget when data is to be collected on a large scale in a particular project (Agarwal & Khurana 2009; Kumar, 2002). The data collection approach of this study consists of two main phases, i.e. data collection instrument and data collection procedure. These are described in the following sub-sections.

3.4.4.1 Data Collection Instrument

The developed multi-touch tabletop display is used as a testbed for collecting fingertip data samples. Prior to conducting the experiment, the multi-touch display is calibrated carefully through multi-touch software to ensure a reliable data collection.

3.4.4.2 Data Collection Procedure

Prior to collecting the data, the multi-touch system is introduced to all the participants and they are allowed to access two applications, i.e. photo and ripples using their bare fingers. In this way, participants become familiar with the system's functionality and multi-touch interaction. In general, it is observed that users utilized different methods of interaction with multi-touch displays for performing various tasks such as selection and manipulation of target elements. Despite that, researchers have specified the two interaction methods be used, i.e. vertical and oblique touch (Forlines, et al., 2007; Wu & Balakrishnan, 2003). This specification of interaction methods provides an abstraction to achieve accurate and frequent multi-touch interaction.

Considering the importance of both interaction methods, these have been used to collect the users' fingertip data samples for this investigation. It helps in to identifying that how these methods may affect precise selection of small target elements in direct touch input. Keeping in mind the scope of this study, most of the data samples have been collected using the oblique touch method. In order to collect data samples, primarily each participant is instructed on how to properly interact with the display using the oblique touch. When a user lands-on his right hand's five fingertips for interacting with the horizontal display, then the oblique touch is maintained by him. By keeping the fingertip positions on the display, the fingertip contact areas (fingertip blobs) are detected by the system after that the user takes-off his fingers accordingly. Each trial is completed by every user in approximately 30 seconds. Subsequently, the data samples of the fingertips' occupied contact areas are collected (in the form of fingertip blobs) and saved for further analysis. The total number of trials is 300 (20 participants x 5 fingers x 3 repetitions).

3.4.5 Data Analysis

In order to investigate the data samples of the users' fingertip contact areas and shapes, image processing methods, i.e. imread, canny, and binary area are used accordingly. These image processing methods help in computing the fingertip contact areas by summing up their pixels and assist in identifying their shapes. The obtained data is organized for further analysis which is done by a Statistical Package for Social Sciences (SPSS). In which, descriptive statistics is applied to identify the variation in the obtained data through a standard deviation and mean. Additionally, data is illustrated through a bar graph which represents its overall distribution. The detailed description, analysis and discussion of obtained results are given in the fifth chapter of this thesis.

3.5 A Study on Specification of Fingers Angle

During the first experiment, it is observed that the users use various gestures and postures of their hands and fingers to select target elements on the multi-touch tabletop display. Naturally, users' hands and fingers possess a number of joints that produce a certain degree of freedom. This freedom allows them to move their fingers in many directions on the display. Users can interact with tabletop display using two main touch gestures such as oblique and vertical. Using oblique touch method, users maintain different angles of approach i.e. 85°, 75°, 65°, 55°, 45°, 35°, 25° and 15° degrees on multi-touch tabletop display. Whereas, using vertical touch method, users maintain 90° degree angle of approach. These two methods of interaction using index finger are shown in figure 3.3.

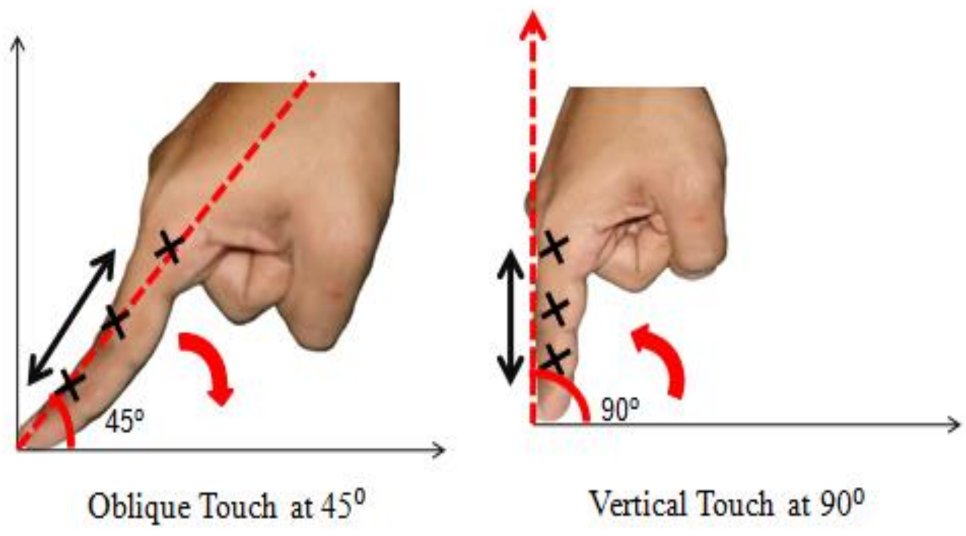


Figure 3.3: Oblique and vertical finger touch methods

In which oblique touch method is illustrated at 45° degree and vertical touch method is represented at 90° degree of angles. Whereas, black crosses at the fingers shows their joints respectively. This scenario suggests that due to presence of enough degree of freedom in users' fingers lead to the various angles of approach of during multi-touch interaction. This variation in the finger's angle with respect to the orientation of the displays may introduce different issues e.g. ergonomic issues, fingertips may occupy variable spaces rather than occupying the exact target point which in turn may increase the error rate in selecting target elements.

However, it has not been studied here what the merits and demerits of these interaction methods are in the context of imprecise selection and ergonomic issues or how these can be used accordingly. Thus, it is questionable as to which angle of approach is preferred by the users for precise and frequent multi-touch interaction on tabletop displays.

The literature review and personal observations have convinced us to specify the finger's angle of approach in order to evaluate physical finger input properties in the context of imprecise selection. In connection with this, a survey based research is planned for data collection that consists of different steps, i.e. research setting, goals, demography, data collection and data analysis. These steps have been described as follows.

3.5.1 Research Setting

In order to conduct this research study, the Usability Laboratory at the Department of Computer and Information Sciences, Universiti Teknologi PETRONAS is selected. Similarly, it establishes a comfortable and controlled environment for the participants which subsequently assist in collecting data properly.

3.5.2 Research Goals

The main aim of this survey based study is to specify the finger's angle of approach of users in context of their preference of multi-touch interaction with multi-touch tabletop display. Additionally, an attempt is made to know the users' prior experience of using sensitive input devices. This study assists in evaluating the physical input properties in the context of imprecise selection. The outcome of this study may help in proposing a suitable size, shape, and configuration of target elements for sensitive displays. Eventually, it may enrich precise and frequent selection of target elements in direct multi-touch input.

3.5.3 Demography

In order to conduct this study, similar twenty volunteer participants are involved as engaged in the first experiments ranging in age from 25-35 years old. All participants randomly selected and were right handed postgraduate students at Universiti Teknologi PETRONAS. They were instructed briefly before performing the selected tasks in order to collect data reliably

3.5.4 Data Collection

A survey based approach is used in order to collect data accordingly. This technique is widely used in social and scientific studies. However, the data collection method consists of two main phases, i.e. data collection instrument and data collection procedure. These have been described in the following sub-sections.

3.5.4.1 Data Collection Instrument

A close-ended questionnaire (Appendix A) is formulated accordingly and used it as instrument for the data collection. It consists of two main questions, one is related to users' preference of finger's angle of approach and other is related to users' prior experience of using the sensitive input devices. In this questionnaire, the number of alternative options is given to respondents to select them respectively. It is written in simple English language that provides clarity and ease of understanding for the respondents. However, this questionnaire is widely used to collect data in social and scientific studies. The main advantage of using this is that, it provides an opportunity to respondents to select the number of given options rather than writing a specific statement (Jackson, 2008).

3.5.4.2 Data Collection Procedure

Prior to conducting this study, comfortable chairs were provided to the participants in the laboratory. They were interviewed in order to create a relaxed and friendly environment while introducing them to the research objectives of the study and its importance. A notice of "do not disturb" was placed on the door to maintain solitude and prevent disturbance. After that, they were allowed to perform multi-touch interaction in order to access the photo application using the multi-touch tabletop display. Interaction with the multi-touch tabletop display using the photo application is shown in the following Figure 3.4.

Figure 3.4: Multi-touch interaction with the photo application

This approach provides the users familiarity with the concept of multi-touch interaction using the oblique and vertical touch methods. Subsequently, the questionnaires are printed and personally distributed among all respondents to be completed in a controlled environment. It is requested that the respondents do not write down their names on the questionnaires to ensure confidentiality. All respondents complete the questionnaire in the presence of researchers. This approach helps in preventing the questionnaires from being completed by one other respondent on behalf of another. Finally, the completed questionnaires are collected from each respondent individually.

3.5.5 Data Analysis

The collected data is organized through the Statistical Package for Social Sciences (SPSS) for descriptive statistical analysis. The obtained data is represented through bar graphs in order to know and analyze its distribution accordingly. This study establishes the grounds on which to evaluate physical finger input properties in the context of imprecise selection of target elements. The outcome of this study is described and discussed in the results and discussion chapter.

3.6 Experiment Design-II: Evaluation Physical Finger Input Properties

From the first experiment and second survey based studies, it is observed that users applied multiple fingers simultaneously for accessing the photo application on the multi-touch tabletop display. They performed various tasks such as selection and manipulation of photos in a discrete and continuous manner. It is also observed that users frequently use the oblique touch method for interaction. Additionally, the outcome of a survey based study suggests for evaluating the physical input properties of the index finger by maintaining an approximate 45° angle of approach. Thus, another experiment is planned that consists of various steps, i.e. research setting, goals, demography, data collection methods and data analysis. These steps have been explained as follows.

3.6.1 Research Setting

This research study is conducted in the Usability Laboratory at UTP and local schools and colleges. These different places provided a comfortable space for all participants during the data collection.

3.6.2 Research Goals

In general, unimanual and bimanual methods of interaction support the users in accessing target elements using multiple fingers on the multi-touch tabletop display. It is observed that enough degree of freedom of fingers leverage their input characteristics for performing the complex tasks. Thus, it is important to evaluate the finger input properties of all the fingers in the context of imprecise selection. This extensive evaluation may help in achieving the accurate and frequent multi-touch interaction.

However, it is observed through studied that index finger is commonly used for selection of target elements. Keeping in mind its importance, time limitations and the scope of this study, it is aimed to evaluate the physical input properties of the index finger only on a large scale. This study helps in collecting index fingertips imprinted data samples.

3.6.3 Demography

For conducting this experiment, 150 volunteer participants including students and faculty/staff members were targeted for data collection. They were equally divided into five groups, i.e. 30 participants per group as shown in Table 3.1. The table shows the related details of the participants. In this study, each group of participants is selected based on age because the existing studies (Moscovich, 2009a) (Wang, et al., 2009) (Wang & Ren, 2009) (Daniel Wigdor, et al., 2009) (Holz & Baudisch, 2010) usually determine the age of the selected participants. It indicates that age may significantly impact on the users' fingertip size and shape.

Table 3.1:Participants' Details for Experiment –II

Groups	No. of Participants	Age Range
1	30	8-10
2	30	11-20
3	30	21-30
4	30	31-40
5	30	41-50

3.6.4 Data Collection

In order to collect data, the cross-sectional approach is used in which participants are categorized based on their age. This approach is widely used when researchers are interested to conduct the social and scientific studies based on the individuals' different ages at the same time. After the classification of individuals' age, a convenience sampling technique is adopted to collect data accordingly. Using this technique, it is convenient for researchers to find the participants whenever and wherever accordingly (Jackson, 2008). The data collection approach of this study consists of two main phases, i.e. data collection instrument and procedure. These are described in the following sub-sections.

3.6.4.1 Data Collection Instrument

The investigation of the physical finger input properties during the first experiment illustrates that the sum of the pixel intensity of the users' fingertips varies due to a difference in their fingertip sizes and many other factors. However, it is critically observed that the pixel resolution varies from display to display. There is also difference in the sensitivity of the displays. These factors may affect on the index fingertip data samples. Thus, it is decided to collect imprinted data samples of the index fingertips on paper sheets. In this experiment, the paper sheets have been used for collecting the fingertip data samples instead of using the tabletop display. The main advantage of using paper sheets is obtaining the data of the fingertips in an imprinted form. The data samples have been collected, leading to a permanent size and shape sample without any pixel resolution variation problem.

3.6.4.2 Data Collection Procedure

Prior to the collection of the imprinted fingertips samples, all participants are interviewed to establish a friendly environment and then are asked for their age. After that, all participants are instructed and trained for obtaining data samples properly. A white paper sheet is placed and fixed on a flat surface. Primarily, the index fingertip is tapped on the inkpad by each participant. A tennis ball is placed under the palm of a participant's hand and finally the fingertip is tapped on the white paper sheet. Placing the ball under the palm of each of the participants' hands helps in maintaining the index finger's angle of approach at approximately 45° with respect to the paper sheet. The process that has been used to collect the index fingertips' data samples is illustrated in Figure 3.5.

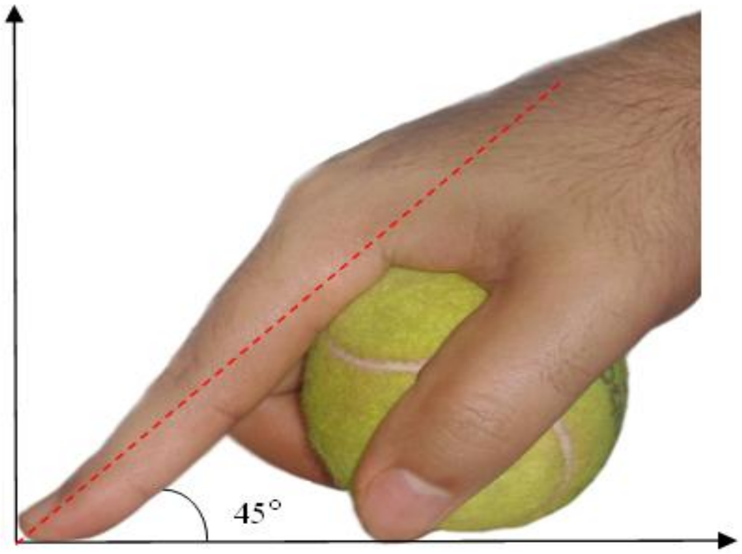


Figure 3.5: Index finger's angle of approach

Each participant spent approximately one minute for fingerprinting, and then the paper sheet is collected personally. The whole data collection process is taken under personal observations which help in collecting the data completely and accurately (Agarwal & Khurana 2009; Kumar, 2002).

3.6.5 Data Analysis

The obtained imprinted images of the index fingertips of different groups are scanned to get an electronic copy of the data samples. After that, each fingertip image is cropped in the MS paint and saved in a file for measuring its total contact area by means of the length and width. The quantified data of all groups is organized using the Statistical Package for Social Sciences (SPSS) for further analysis. In which, descriptive statistics is applied to identify the overall distribution of data samples in each group and measure their standard deviation and means. Additionally, in order to know outliers in data of different group a box plot is generated. Finally to measure the significance difference among the different groups, an inferential statistics is applied accordingly. In which One-Way Analysis of Variance (ANOVA) is used accordingly. The outcome of this study is described and discussed in detail in the results and discussions chapter of this thesis.

3.7 Summary

In order to evaluate the physical finger input properties in the context of imprecise selection of target elements. The research design has been proposed, consisting of four major phases that help in carrying out various research activities. In the first phase, the multi-touch tabletop display is developed using the FTIR sensing technique. The multi-touch tabletop display is meant for a testbed to collect data with the involvement of volunteer participants.

In the second phase, the experimental design is planned for the investigation of the physical finger input properties. In the third phase, a survey based research design is proposed for the specification of the angle of approach that helps in achieving reliable data collection. This research design also consists of the various steps that have been carried out such as the formulation of close-ended questionnaires, research setting, goals, demography, data collection and data analysis. This proposed research methodology helps in evaluating physical finger input properties in the context of imprecise selection of target elements.

In the next chapter, the design and development of the multi-touch tabletop display is discussed.

CHAPTER 4

DESIGN AND DEVELOPMENT OF MULT-TOUCH TABLETOP DISPLAY

4.1 Overview

This chapter introduces the design and development of our multi-touch tabletop display and its outcome in detail. Mainly, it attempts to answer these questions, i.e. "Why the multi-touch tabletop display is developed in this study?", "How it has been developed?" and "Which type of technology and material are used for its development?"

4.2 Multi-touch Framework

Prior to developing any system, a conceptual framework would have been required to understand its structural and functional schemes. In this respect, a general multi-touch framework is proposed for the development of a multi-touch tabletop display as shown in Figure 4.1. It facilitates in understanding a basic structure of multi-touch tabletop display at which different hardware and software components are interconnected accordingly. In addition, it helps in understanding the functionality of each component in a multi-touch system.

However, multi-touch framework consists of the two main layers, i.e. hardware and software. In regards to the hardware layer, it is represented by the multi-touch tabletop display which is the first and foremost layer for users. In order to produce a fully functional interactive display, different applications, multi-touch libraries and system software are installed. When the above software run over this hardware layer with high compatibility then make it possible to produce a fully functional interactive display for users. It is a unified multi-touch input device that accommodates a collaborative workspace for users in order to perform multi-touch input using their bare fingers. Using this interface, multi-touch input is triggered and delivered through the hardware layer to the software layer for further processing in a pipeline.

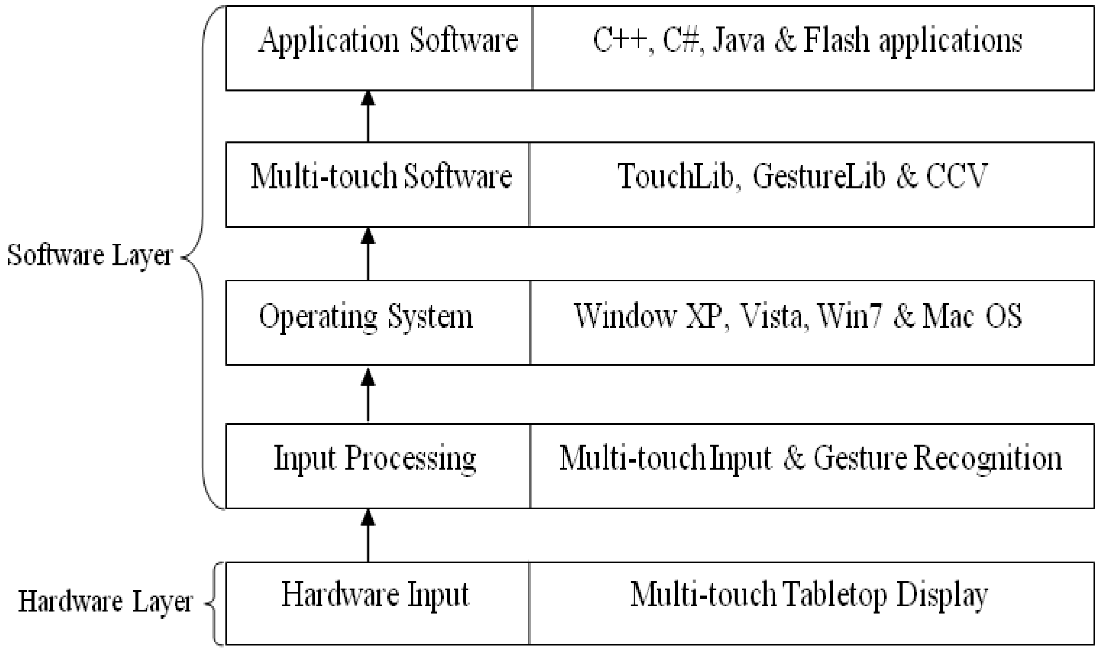


Figure 4.1: A general multi-touch framework

In regards to the software layer, it consists of different types of software (e.g. operating system, multi-touch software and application software) that are integrated and compatible with each other. This layer is responsible for receiving the users' input from the hardware layer for processing accordingly. The input detection and processing mechanism of this layer is based on a particular scheme which has been employed in the multi-touch tabletop display. It has been discussed in third chapter of thesis but it is also better to discuss briefly again here for understanding purpose.

In connection to this, there is a protocol named Tangible User Interface Object (TUIO) was designed and implemented for processing the tangible input on the tabletop display (Kaltenbrunner et al., 2005). Considering the structural and functional specification of this protocol, it has been further improved for detection of multi-touch input. Therefore, it is also implemented in the multi-touch software which enables the system to transmit the information between a controller interface and client application. Basically, it works as a gateway, and it is compatible with different operating systems and applications. This is why both the client applications and the system software adhere to the TUIO protocol accordingly.

Client applications are developed in different languages such as C++, C#, Java, and Flash that always run over the operating system layer. It steers and manages all hardware and software resources. It provides the different services in order to execute those applications and manage the multi-touch input activities which are performed by users on the tabletop display. The main purpose of discussing this multi-touch framework is to illustrate a conceptual schema of interconnected components at different levels. It assists in describing a set of activities which occurs in the multi-touch system and additionally guides in understanding the functionality of each layer at its level.

4.3 Development of Multi-touch Tabletop Display

It is found through studies that different touch enabling technologies have been used for the development of various types of multi-touch displays. Each technology has its own pros and cons in terms of architecture, functionality, scalability, and cost. Considering the cost factor only, Microsoft Surface (Microsoft Inc, 2007) has been commercialized into the market with a price of about RM22, 800. In addition, perceptive pixel's interactive media wall display has also been commercialized with a price of about RM300, 000 (Han, 2007). These commercialized multi-touch displays are so expensive that it limits the purchase of these displays by normal users. Thus, it is difficult to use the potential of these displays technologies by normal users in their life like desktop computers. It is even difficult for many researchers to purchase these displays for research purposes.

In order to meet this challenging issue, related literature has been reviewed accordingly. It is extracted that the FTIR sensing technique is simple in its architecture and can be used for the development of multi-touch tabletop displays at low cost.

Therefore, the motivation is increased towards the design and development of an LCD panel based tabletop display for meeting the objectives of this study. The design and development process of our tabletop display is undertaken in four main phases, i.e. system requirements, architecture, hardware integration and software implementation. These phases play an important role in the system development and are discussed in the following sub-sections.

4.3.1 System Requirements

Before the development of any kind of physical computing system, some hardware and software components would have been required accordingly. Likewise, for the development of this multi-touch tabletop display, different hardware and software components were required; these have been gathered with different specifications through literature review.

The main hardware components are a rectangular transparent acrylic sheet, rear projection material, infrared light emitting diodes, infrared camera with a Complementary Metal Oxide Semiconductor (CMOS) sensor, infrared band pass filter, Liquid Crystal Display (LCD) panel, and the computer system core2 Duo. The main software components are Windows Vista 2007, TouchLibrary V.2.0, application programming interfaces (APIs), and application software.

4.3.2 System Architecture

In order to develop the tabletop display, a general hardware architecture is proposed as shown in Figure 4.2. This architecture provides a schematic view of how different hardware components are interconnected and function within the system. In general, the multi-touch tabletop display is composed of four main hardware components, i.e. Multi-touch I/O Device, Infrared Camera, Central Processing Unit (C.P.U), and an LCD panel.

However, each component, individually, is composed of different hardware pieces and plays an important role in the system's development according to its functionality. Considering the multi-touch I/O device, it is an optical surface which provides a foundation to produce a unified interactive display by integrating the camera, projector and computer. This optical surface is connected virtually to the infrared camera through optical paths as shown above in Figure 4.2.

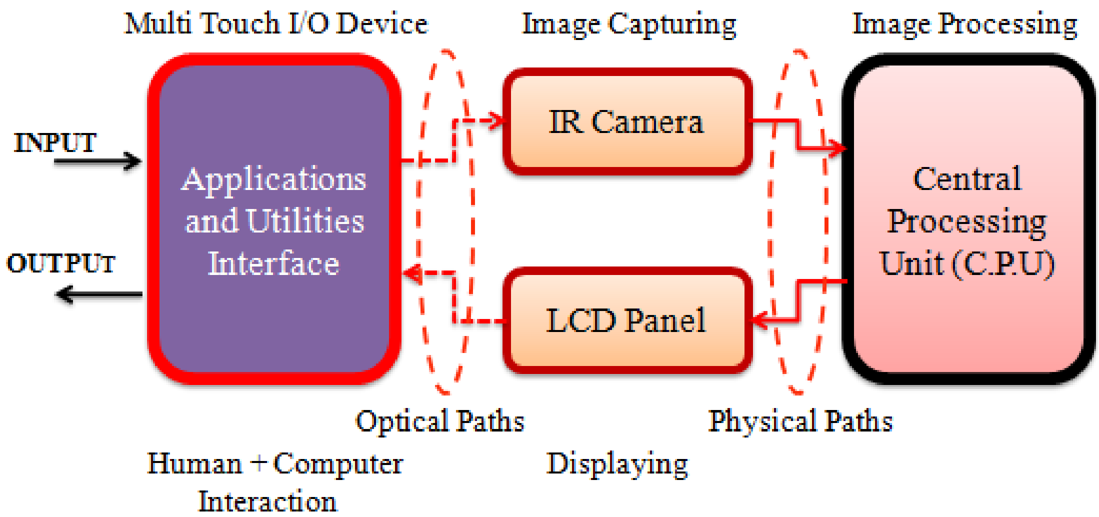


Figure 4.2: Layout of the multi-touch tabletop display architecture

However, the infrared camera is connected to the computer system through physical paths. Camera represents the image capturing process that means user's multi-touch input is based on fingertip images. The camera captures the user's fingertip images created during interaction. Thus, physical paths assist in carrying the detected input images from camera to the computer system for further processing. The computer system is the central hub in multi-touch tabletop display that assists in connecting all hardware components. It is treated as the backbone of the multi-touch tabletop display. It means users driven multi-touch input is processed by the computer system accordingly.

In order to display the digital information, the LCD panel is used, and fabricated behind the multi-touch I/O device. It is connected to the computer system through the physical paths. It helps to project/display the processed input on the multi-touch I/O device. The displayed digital contents/ digital information on this device provide an interactive environment to the users. They can watch digital contents and perform direct multi-touch interaction. Integrating these four main components into a wooden table, a multi-touch tabletop display is produced. It accommodates a collaborative workspace around the table for users where they perform multi-touch interaction. Users access target elements using their bare fingers. Meanwhile, the representation of this general hardware architecture assists in understanding the system design, interconnected components and their functionality at each segment. It provides a roadmap for assembling each hardware component accordingly for the system development as discussed in the following sections.

4.3.3 System Hardware Integration

The different hardware components are required to construct a multi-touch tabletop display, thus, various steps are planned to undertake, i.e. fabrication of the multi-touch I/O device, modification of the camera, and implementation of the LCD panel. These steps help in assembling the hardware components properly during the development process of multi-touch tabletop display. The system hardware integration process is described and discussed in the following sub-sections.

4.3.3.1 Fabrication of Multi-touch I/O Device

The multi-touch I/O device is fabricated using different hardware components, i.e. an acrylic sheet, rear projection film, Infrared Light Emitting Diodes (IR LEDs) and an LCD panel. Each component plays an important role in producing the suitable multi-touch I/O device.

Considering the acrylic sheet, it is transparent and allows for 92% of the infrared light to be transmitted from its medium (ASM, 2003) as shown in Figure 4.3. It has light weight, less toughness, control of the light ray paths, chemical and weather resistance. In addition, it has can be used for indoor and outdoor application due to sustainability of temperature ranges from 170˚ F – 190˚ F degrees. The acrylic sheet is considered as good insulator and has less toughness in its material. Therefore, it is a better choice to use for the development multi-touch tabletop display. Keeping in mind these features, acrylic sheet is widely used by researchers for the development of multi-touch tabletop displays and interactive walls. In contrast to the acrylic sheet, the glass substrate can be used for development of small size touch screens (e.g. mobile phones) but it is difficult to use for the development of large size displays such as tabletop displays, and interactive walls.

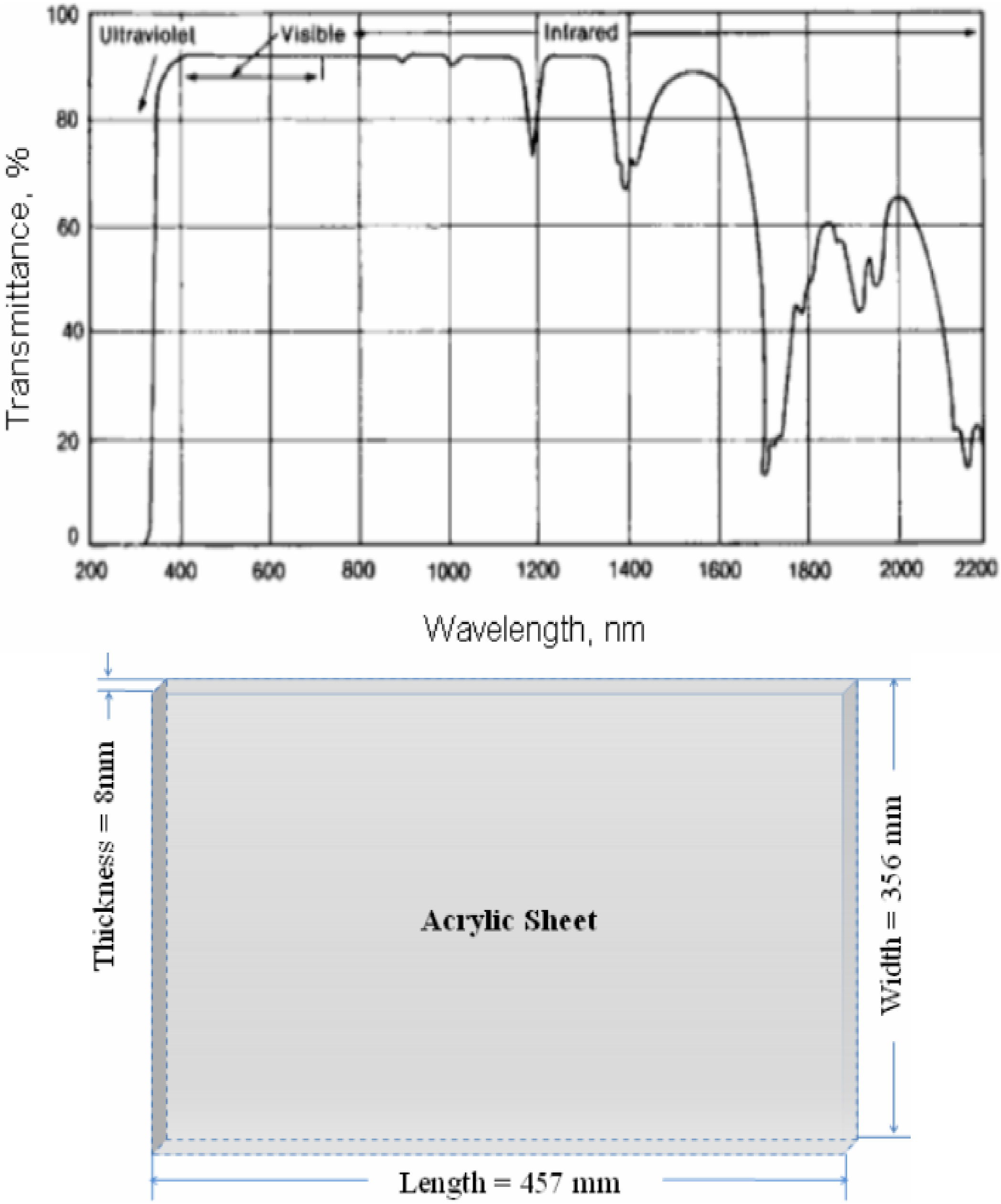


Figure 4.3: Transmission capability of acrylic sheet (top) (ASM, 2003) and its specifications (bottom)

Using the glass substrate, there is possibility of its damage when multiple users work together on a single collaborative display. Users may exert pressure using their hands and fingers in collaborative multi-touch interaction. In this regard, the glass substrate has more toughness in its material as compare to acrylic sheet. It is available in commercial markets with different sizes and specifications. In order develop the multi-touch tabletop display an acrylic sheet is used with specifications of (length 457mm x width 356mm x thickness 8mm) as it is also shown in Figure 4.3.

However, an LCD panel is used in the system for displaying the digital contents on the acrylic sheet but it has not capability of displaying that information. Thus, a rear projection film called Rosco Gray was recommended by (J. Y. Han, 2005) to be superimposed on the acrylic sheet. It has been overlaid on the acrylic sheet carefully with the given specifications of (length 457mm x width 356mm x thickness 1mm). It has various features such as better projection quality, good angular vision field in horizontal and vertical orientations. It provides better image quality of projected digital contents. In addition, the Rosco Gray real projection film helps in avoiding the impact of high ambient light on display in both indoor and outdoor installations. Thus, it is commonly used by researchers into multi-touch tabletop displays. It enables the projected digital information to be obtained on the display accordingly.

The FTIR sensing technique is selected for the development of the multi-touch tabletop display. It is an optical sensing technique, which depends on the presence of infrared light in the medium of the acrylic sheet and its frustrated total internal reflection. In order to achieve the infrared light in the medium of the acrylic sheet, a number of IR LEDs with the given specifications of (type OSRAM SFH485, wavelength 880nm, and quantity 50) are used as the source of light. A U-profile aluminum frame is selected in which holes are made with a drill machine and a distance of two inches is maintained between two holes. Light sources are constructed into frames that are assembled opposite to the edges of the acrylic sheet for the emission of the infrared light inside its medium.

In order to provide a stable and reliable power supply to IR LEDs for working properly into the system, it is planned to design a printed circuit board based on the parallel connection scheme. The main advantage of using a parallel connection scheme is that, when any of IR LED is burned or disconnected due to any reason then other IR LEDs keep functioning accordingly. Whereas, using a linear connection scheme, if any of IR LED is burned or disconnected then all light sources will stop functioning. Subsequently, multi-touch system will stop functioning that means users input cannot be detected. Thus, selection of a connection scheme for IR LEDs into system plays an important role in detecting input. In this respect, a parallel connection scheme has been designed in which all IR LEDs are implemented accordingly. This mechanism provides a stable and reliable power supply to all light sources as compare to a linear connection scheme. The cross section of the multi-touch panel and its IR LED configuration are shown in Figure 4.4.

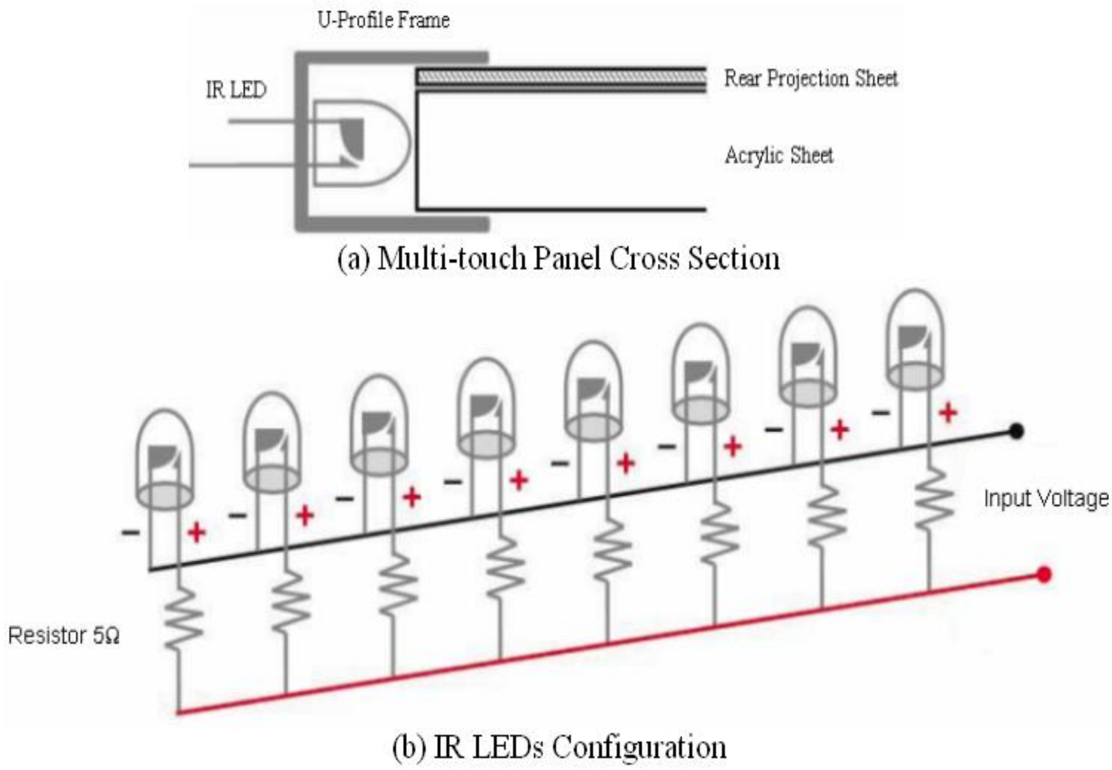


Figure 4.4: Multi-touch panel cross section and IR LED configuration

When the process of interconnecting the IR LEDs is completed then these have been configured opposite to the edges of acrylic sheet accordingly. After that, these light sources are switched *on* for testing their functionality. It is observed that infrared light is emitted by light sources that stroked to the edges of the acrylic sheet. Later on, it continuously propagates into the medium of acrylic sheet and creates Total Internal

Reflection (TIR). This process ensures that the configured infrared light sources work properly.

The superimposition of the rear projection film on the acrylic sheet and the configuration of the IR LEDs in front of its edges produce an optical panel or an FTIR panel. When a user's finger touches the optical panel, the infrared light is frustrated and is scattered down towards the camera. The scattering phenomena of light create fingertip image patterns (blobs) that are detected by the infrared camera as multi-touch input. However, infrared camera is a main source of detecting the multi-touch input in the system. The FTIR panel with its configuration of IR LEDs and its functional phenomena are illustrated in Figure 4.5.

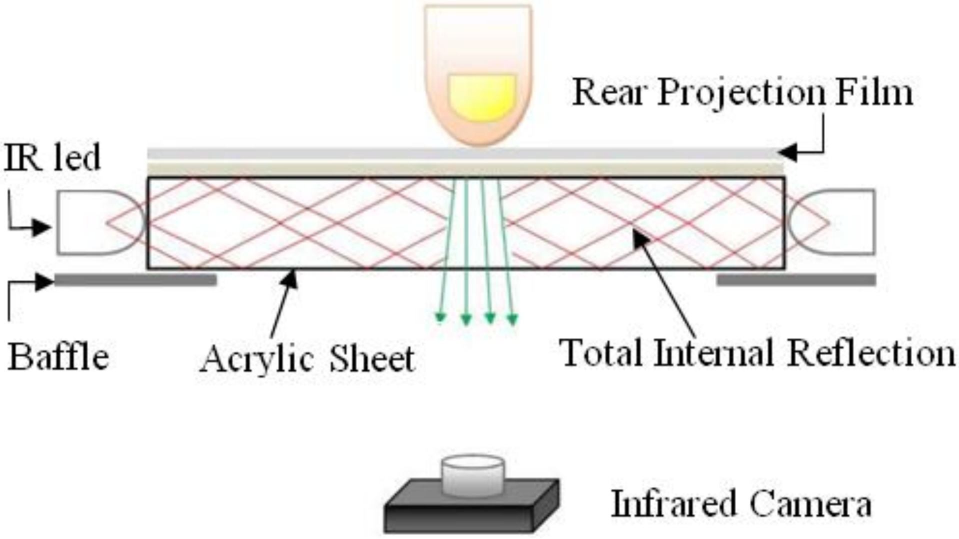


Figure 4.5: FTIR panel with configuration of IR LEDs

The main objective of emitting infrared light inside the medium of the acrylic sheet is to get visible fingertip blobs/image patterns during multi-touch interaction. Because, multi-touch input sensitivity of optical and camera based displays depends on clear and bright fingertip blobs. The creation of bright and accurate fingertip blobs on this panel can be detected by the camera effectively and that, in turn, can increase the performance of the display.

4.3.3.2 Modification of the Camera

As it is discussed before that the FTIR based displays require the infrared camera for multi-touch input detection. In this regard, a webcam called Philips SPC900NC with the given specifications of (640x 480 pixels resolution, 30 frames per second) is used. This normal webcam cannot detect infrared based multi-touch input signals due to the built in infrared blocking filter above the camera image sensor. It blocks infrared input signals and infrared input signals are needed for input detection.

In this respect, it was planned to modify the camera from a normal webcam into an infrared one by removing its infrared blocking filter. Primarily, a webcam is unscrewed carefully and then opened its casing. After that, lens of camera is unscrewed from the printed circuit board. It is most sensible step of modification of camera that needed more carefulness. There is possibility of damaging the camera image sensor. Following that infrared blocking filter is removed accordingly.

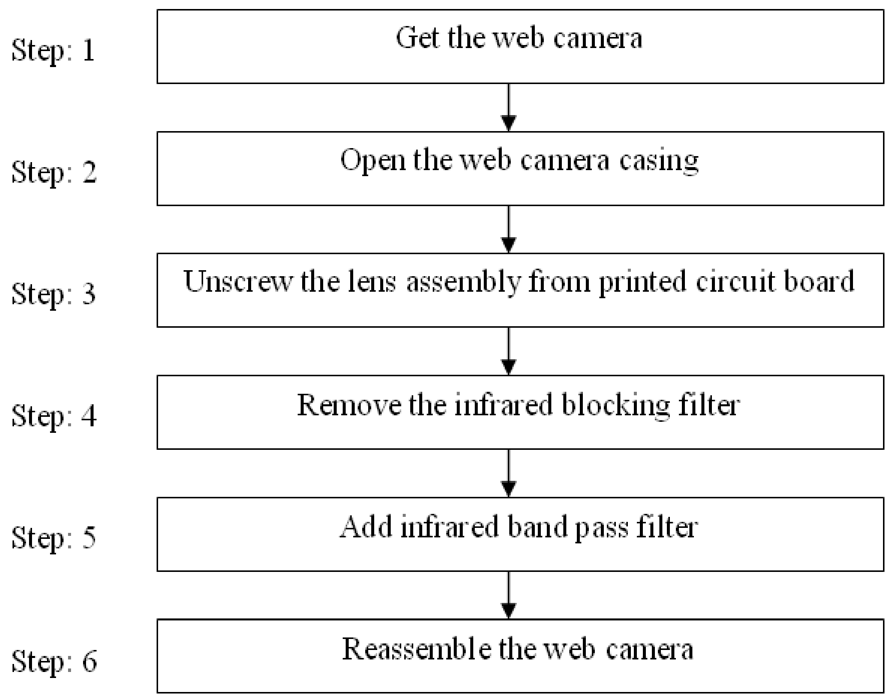


Figure 4.6: Modification of webcam

However, it is reviewed that harsh ambient light conditions have an adverse effect on optical and camera based displays. It generates infrared noise in input during multi-touch interaction (J. Y. Han, 2005). The presence of noise creates ambiguity in detecting the input. In order to avoid the noise, an infrared band pass filter the same size as the infrared blocking filter is placed in front of the image sensor of the camera.

However, the specific steps that help in converting normal webcam into infrared one are shown in Figure 4.6. This figure illustrates the modification process from opening of the assembled webcam to reassembling the webcam accordingly. It assists in obtaining an infrared camera without any damage to the camera sensor. Consequently, the modified camera has been tested by interacting with an optical panel which successfully detects fingertip blobs created during interaction.

It is identified through studies that two main approaches, i.e. bottom-up and top-down approaches are adopted by researchers in order to develop multi-touch tabletop displays. These two approaches play an important role in defining the taxonomy of display and also have number of pros and cons. Using a top-down approach, projector and camera have been configured at fixed position above the interactive surface/display. In which, multi-touch gestures of users hands and fingers is detected by cameras using visual tracking software. Whereas, projector display digital contents on the display that are clearly viewed by users. They can interact with digital contents easily and frequently. However, the problem of this approach is that when users interact with target elements on display then their hands and fingers occlude and break those targets. This phenomenon of interacting with display creates ambiguity in defining multi-touch interaction. In addition, top-down approach for designing the multi-touch tabletop display introduces the portability issue due to fixation of camera and projector at particular place. So, user cannot move the system from one location to another.

Using the bottom-up approach, camera and projector are configured under the interactive surface/ display for the development the system. In which camera detect the multi-touch input be means of some changes/events that occurs on the surface. Whereas, a projector is responsible for displaying digital contents from rear side of surface. The implementation of this idea for the development of multi-touch tabletop display clearly helps in decreasing the occlusion of target elements. Users' hands and fingers do not break the displayed digital contents during interaction. In addition, the configuration of camera and projector under the table's surface increases the size of display but it also decreases the portability issues. This approach is widely used by researchers in order to develop multi-touch tabletop displays as discussed in the second chapter of this thesis. Keeping in mind the pros and cons of both approaches, experience of researchers and developers, the bottom-up approach is adopted for the development of our multi-touch tabletop display. In which, the modified/infrared camera has been configured in a centered location under the table. This approach also helps in avoiding the adverse affect of ambient light on the display. Finally, the camera is connected to the computer system using a USB port and calibrated accordingly.

4.3.3.3 Implementation of LCD Panel

It is reviewed that optical and camera based multi-touch tabletop systems do not have the capability of displaying digital information on their own. Thus, these systems need an LCD panel or DLP projector for displaying digital information. In order to make a unified multi-touch display, an LCD panel with the given specifications of (length 14x width 11.4 x thickness 0.5 inches) is selected and employed under the FTIR panel. However, the choice of selecting and deploying an LCD panel in our system was due to some reasons such as it is a flat, thinner, lighter, brighter, and less expensive. It helps in avoiding the issues of front, above, and rear projection into tabletop displays as compare to DLP projectors.

The multi-touch I/O device is achieved by integrating the FTIR and LCD panels in a particular order. For protection of the device (due to its sensitive physical nature), it is framed in a rectangular wooden frame. In order to obtain the complete tabletop display, a wooden table is made of the specified size (length 14x width 11.4x height 30 inches). The fabricated multi-touch device is installed and this process brings the multi-touch I/O device set-up into a tabletop display.

The proposed design and development of the LCD based tabletop display using the FTIR sensing technique is shown in Figure 4.7. This figure illustrates the system's structure and its implementation accordingly.

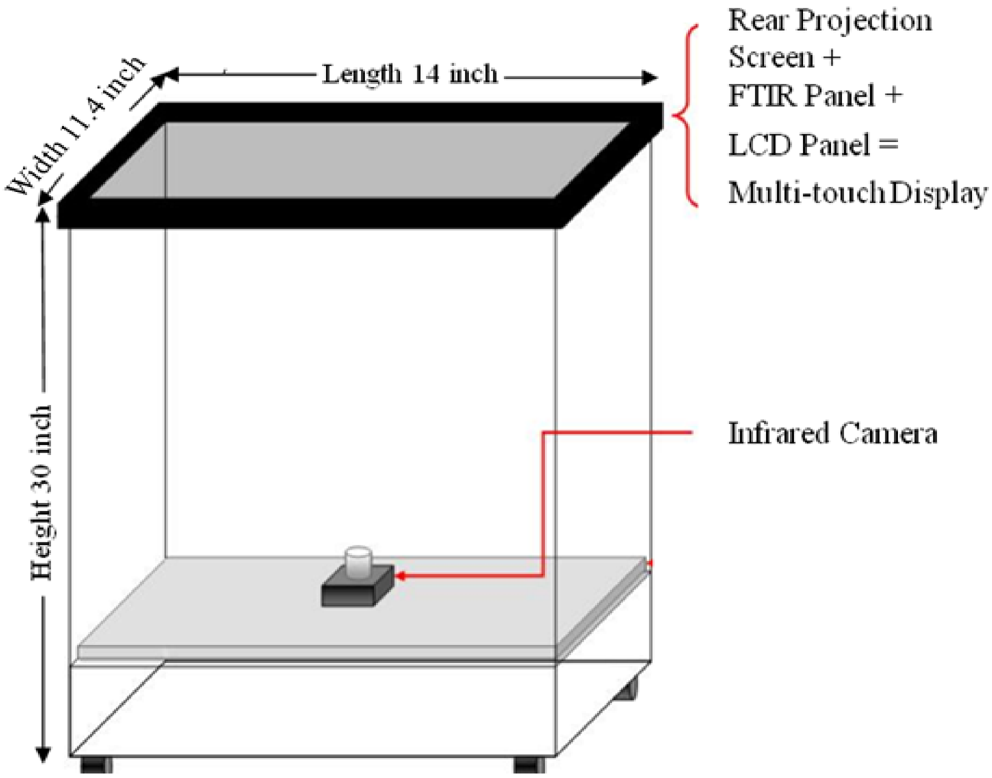


Figure 4.7: LCD panel based multi-touch tabletop display

4.3.4 Software Implementation

Traditionally, a variety of software has been developed for different types of multi-touch displays to detect input. For example, capacitive displays are constructed with a matrix of sensors in which the user's input is computed by the software in the form of an electric current. Whereas, optical and camera based tabletop displays have been developed using vision based technologies; input is detected as fingertip images or blobs. Recently, multi-touch software called TouchLib and Computer Core Vision have been introduced and developed by the Natural User Interface (NUI) group. These are open source and commonly used to test multi-touch displays and conduct experiments related to multi-touch interaction.

It has also been used for the investigation of finger input properties in the context of imprecise selection.

In this study, the multi-touch tabletop display is developed in which TouchLib is implemented to make the display fully functional. It consists of different algorithms that enable the system to detect and track the multi-touch input (fingertip blobs or contact points). The software is capable of computing position, ID and contact area of fingertip blobs. Using this software, the display is calibrated according to its x and y co-ordinates and subsequently it is tested to observe its functionality.

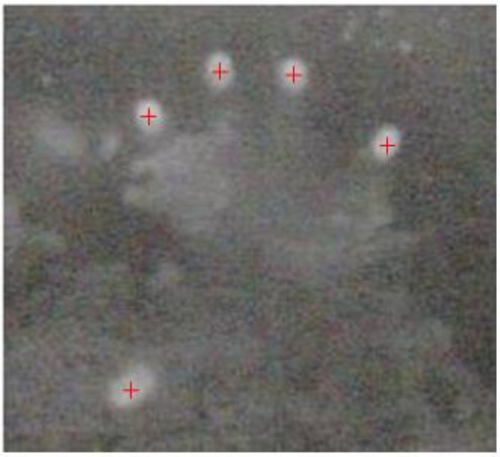
4.3.4.1 Image Processing Pipeline

Using optical and camera based displays, multi-touch input is detected by the camera and it is processed by specific software in a pipeline. As already discussed, the effect of harsh ambient light conditions on the display introduces noise into the multi-touch input. In this respect, the developed tabletop display is tested in regards to noise during the multi-touch interaction. It is observed that unwanted images from the surroundings are detected which increase ambiguity in input detection.

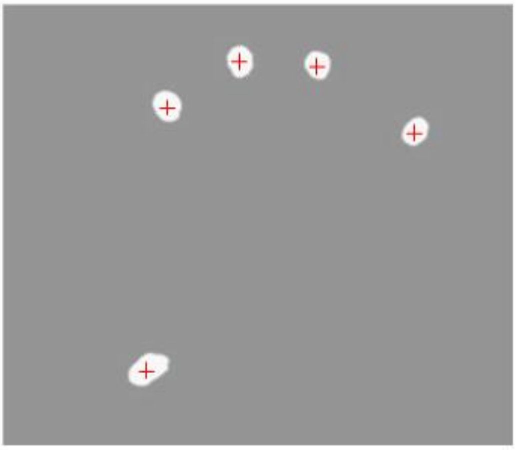
In order to address this issue, a number of filters or programs have been implemented in the multi-touch software that helps in removing the noise. The image processing occurs in a pipeline in various frames, i.e. raw fingertip blobs, background removing filter, rectify filter, fingertip blob detection, fingertip blob tracker, and finally the processed fingertip blobs. Each frame is used as a reference for the next frame during the interaction process.

When a user interacts with a multi-touch display using his/her fingers then raw fingertip blobs are detected by the camera and registered in a capture frame. These blobs contain noise as shown in Figure 4.8 (a). This figure illustrates various spots around the actual fingertip blobs that cause imprecise input. The camera detects the unwanted images from the surroundings of the display.

However, it is not possible for the camera to differentiate whether these spots relate to actual fingertip contacts or other objects. A background removing filter or program is implemented which supports in eliminating these unwanted spots. This process helps in obtaining the correct fingertip blobs as shown in Figure 4.8 (b). This figure illustrates the exact fingertip blobs but there is still some gray background that leads to noise as well.



a) Raw Camera Fingertip Blobs



b) Background Removed Fingertip Blobs

Figure 4.8: Fingertip blob detection process

In order to obtain accurate fingertip blobs, a rectify filter is used which assists in removing the unnecessary background from the current frame. Using this process, accurate fingertip blobs are detected as shown in Figure 4.9.

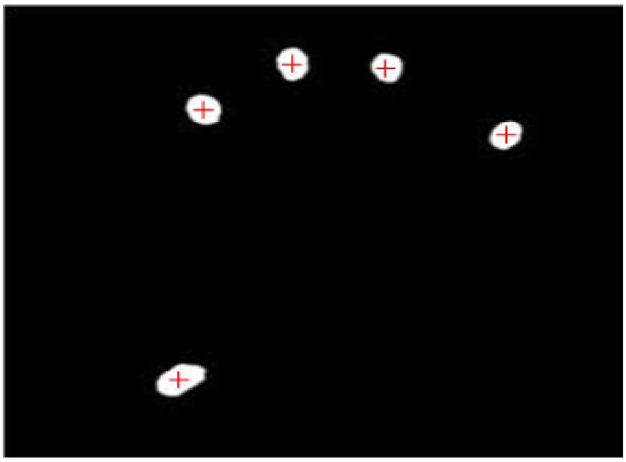


Figure 4.9: Fingertip blob detection

This figure illustrates black and white images in which the black area represents zero pixels and the white area represents a one pixel value. The white areas are actual contact points that are computed with respect to the distribution of pixels in the x and y co-ordinates.

Using different filters, the pre-processing process is very important to obtain bright and accurate fingertip blobs before beginning the blob tracking process; this process needs accurate blobs to be used for multi-touch input. Both the pre-processing (blob detection) and post-processing (blob tracking) processes are highly dependent on each other for precise multi-touch interaction. These binary fingertip blobs are further processed to identify the exact contact points at any particular location using the blob tracker program. This program computes the fingertip blob position, ID and its contact area accordingly. This image processing pipeline which enables the system to detect and track input is shown in Figure 4.10.

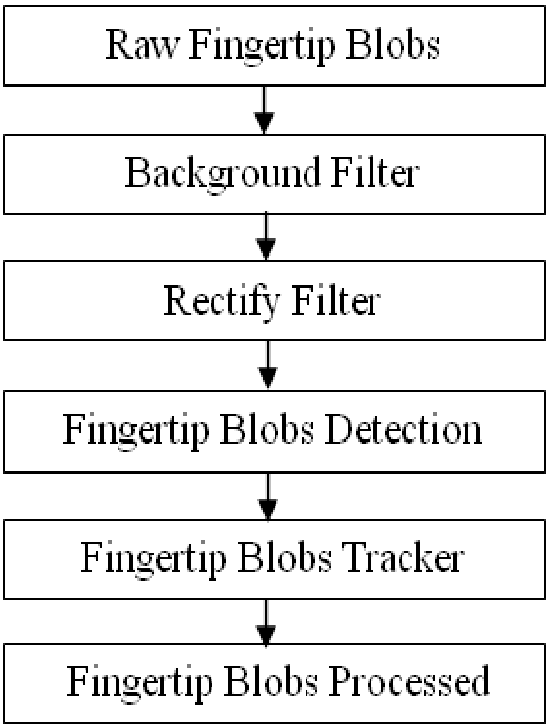


Figure 4.10: Fingertip blob processing pipeline adopted by (Varcholik, Laviola, & Nlcholson, 2009)

4.4 System Testing

When an LCD panel based multi-touch tabletop display has been developed completely, then an attempt is made to test it in the context of multi-touch input detection using the photo application. This test demonstrates that the developed system works as expected accordingly. The outcome of the system's functionality is briefly described and discussed in the following sub-sections.

4.4.1 Multi-touch Input Detection

In order to test functionality of system, the photo application has been implemented accordingly and allowed each user for accessing its features. This system enabled to users for selecting and manipulating photos on the interactive display using their bare fingers. This formal test ensured that the all hardware components and multi-touch software were integrated and calibrated properly. Finally, the developed multi-touch system is capable of detecting the user's input signals. It allows a single user to perform multi-touch interaction on interactive display simultaneously.

However, it is observed that the users have to exert fingertip pressure on the interactive display in order to select and manipulate digital photos. This users' experience of interacting with the display suggests that the developed system has low fidelity in sensing the multi-touch input. In addition, it is also observed that there is a slow response during multi-touch interaction that may lead to users' frustration.

Keeping in mind the concept of the collaborative multi-touch interaction, it is observed that the developed system does not provide a collaborative workspace to multiple users in order to access digital photos. It is not capable of detecting the multi-touch input of the multiple users simultaneously. There are certain reasons such as: it has small size interactive display due to its structure which cannot afford a space for multiple users around the table. It has a lack of the multi-touch input response due to low frame rate of the implemented infrared camera. These factors limit use of this system for the multi-user multi-touch interaction in a collaborative workspace.

4.4.2 Study-I

Since, it is discussed before that a study is conducted by an undergraduate in her final year project to test the potential of multi-touch input detection of our developed multi-touch system and input through optical mouse (Zaidi, 2009). The outcome of this study shows that, 63% participants prefer to use of multi-touch display. It is demonstrated the multi-touch display assists them easily to perform the scrolling, drag and drop the target elements using fingers. Whereas, 37% participants understand that an optical mouse is more easy to use as compare to the multi-touch display. However, it is reported in the results and discussion chapter of her study that a mouse provides an indirect interaction. It limits a single user to select multiple target elements simultaneously. In contrast, the multi-touch display offers a direct and natural multi-touch interaction for single and multiple target selections simultaneously. The overall outcome this study supports in validating the functionality of the system.

Keeping in mind the outcome of used application, it has also been discussed that this multi-touch touch display allow a single user to perform multi-touch input but it limits in allowing the multiple users simultaneously. It is recommended that the multi-touch tabletop display should be developed with the suitable components, because, it has lack of sensitivity and also has low response during multi-touch interaction. It restricts the user in order to select the target elements frequently using bare fingers.

In order to accomplish the collaborative multi-touch interaction for multiple users, it is suggested that this system should be modified in its architecture and some of the hardware components (e.g. infrared camera) should be replaced. It may increase the sensitivity and responsiveness of the system. From this study, it is extracted that the used technology in the system has potential to be used for the development of a large size display that may accommodate a collaborative workspace for multiple users around a table. In addition, it is observed that drawing application should be modified in the aspect of multi-model functionalities. It may establish the different possibilities for selecting the colors and drawing the objects with multiple fingers on the multi-touch tabletop display. After that, a comparative study can be conducted at large scale in order to indentify the users' preference of using the optical mouse or multi-touch tabletop display for drawing the objects accordingly.

4.4.3 Discussion

Since, it has been identified through users' feedback that the developed multi-touch system has lack of sensitivity and low response during interaction. It is studied from existing literature that the performance of the user's input detection of the camera and optical based systems depends on the bright and accurate fingertip blobs. Because, these blobs are used as input signals in optical and camera based systems Thus, it is planned to investigate the resultant fingertip blobs for indentifying their brightness and shapes. The detected fingertip blobs by infrared camera during interaction are shown in Figure 4.11.

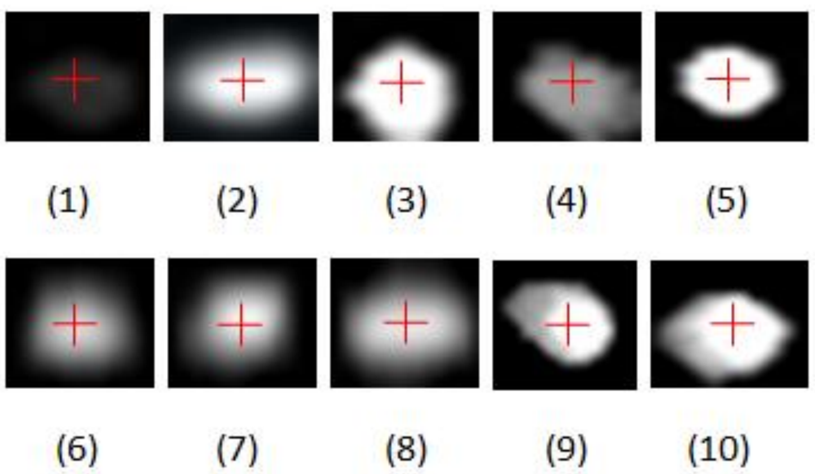


Figure 4.11: Fingertip blob detection using CMOS sensor based infrared camera

The Figure 4.11 illustrates that the resultant fingertip blobs are faint, and they have difference in brightness. Thus, it is hard to detect these fingertip blobs by the image sensor of the camera. This is why fingertip pressure is exerted by users during interaction as they were expecting a soft finger touch with the interactive display. From this, it can be concluded that this system provides an ambiguous input detection. It can be said that the faint blobs are one of the main reason of lack of sensitivity in the system.

Considering the shapes of fingertip blobs, the Figure 4.11 clearly shows that the fingertip blobs are irregular in shape and size. It also confirms that pressure is exerted by the user's fingertip on the interactive display during the selection of the target elements. In addition, the faint and irregular shapes of these blobs also suggest that there is a bad coupling between fingertips and interactive display during multi-touch interaction. In any optical and camera based system, if there would be a bad coupling between fingertip and an interactive display then this situation introduces the false fingertip blob detection. It ultimately results in ambiguity in multi-touch input in optical and camera based systems. It is also observed that, there was more friction between fingertip and interactive display due to exerted pressure. These factors were frustrating to normal user during the selection of target elements using bare fingers.

The variation of brightness in fingertip blobs suggests that there is an insufficient and uneven propagation of the infrared light inside the medium of the acrylic sheet/ optical panel. At some places of the interactive display, the bright fingertip blobs are generated due to the presence of a high intensity of light inside the medium of the optical panel. In contrast, the faint fingertip blobs are generated due to presence of the low intensity of light inside the medium of the optical panel at some places respectively. In addition, the variation in the brightness of fingertip blobs can be occurred due to low and high pressure exerted by fingertips during interaction on the interactive display.

In this regards, the architecture of the system’s optical panel is further taken into consideration for its analysis and to overcome the above issues accordingly. It is identified that there is an inappropriate configuration of the IR LEDs opposite to the edges of the acrylic sheet. The angle of the IR LEDs is not well directed and light has leaked out from the edges of the acrylic sheet. The leakage of infrared light from the edges of the acrylic sheet is reasoned to produce insufficient light into medium of acrylic sheet/optical panel. If there would be insufficient light into medium of optical panel then subsequently there would be possibility of less bright formation of fingertips blobs. So, it can be one of main reason to produce faint fingertip blobs.

These factors have been discussed accordingly with faculty members and lab technologist in electrical department. Finally, it is extracted that the medium of the optical panel must be full with infrared light for obtaining bright and accurate blobs during interaction. In order to achieve that, the IR LEDs must be configured straight and exactly opposite to the edges of acrylic sheet. If the angle of the IR LEDs would be bent downward or upward then the light will be leaked out from the edges of the acrylic sheet. The infrared light will not be transmitted exactly into a medium of the acrylic sheet. In addition, it is observed that the light sources, i.e. IR LEDs were configured in less quantity so it can be also a reason of presence of insufficient light into medium of the acrylic sheet.

From this, it is extracted that light sources must be increased in quantity and configured properly. During the development of this system, the IR LEDs were fabricated into a U-profile aluminum in which two inches distance was maintained between them. This approach of fabricating the IR LEDs also constrained in deploying the more light sources opposite to the edges of acrylic sheet.

Keeping in view above issues and an experience of developing this system bases on trial and error method, it is learnt that the appropriate configuration of the IR LEDs play a vital role in producing a suitable optical panel. This setup may assist in increasing the transmission of infrared light inside the medium of the acrylic sheet properly. This phenomenon of transmission of infrared light into the medium of the acrylic sheet may help in achieving the bright and accurate fingertip blobs. However, considering the low feedback during interaction, it is observed that the used infrared camera has a low frame rate that limits in transferring the captured images to C.P.U. Therefore, it is found that an infrared camera with a high frame rate must be used for increasing the multi-touch input feedback.

The formal test and above discussion about this system suggested that it is not a suitable testbed for the investigation of physical finger input properties in the context of precise selection as planned. However, the experience of developing an LCD based display and its outcome steer for the improvement in multi-touch I/O device architecture and replacement of the camera and an LCD panel. In this respect, the motivation is increased to improve the system in order to produce a suitable testbed for investigation of physical finger input properties accordingly.

4.5 Improved Multi-touch Tabletop Display

Considering the issues as discussed above, a plan has been made to enhance the multi-touch tabletop display in order to meet the objectives of this study. Primarily, it was assumed that first prototype may assist in investigating the fingertip contact area and shape in the context of imprecise selection. When the first prototype is tested accordingly then it is identified that it does not meet the objectives of this study. After that, it is planned to improve this prototype through a proposing an architecture of touch panel. During the development process of the prototype, the trial and error approach is undertaken. The main reason of undertaking this approach was that there is no universal standard for the development of multi-touch tabletop display.

However, the research in the area of multi-touch tabletop is still infant so various prototypes have been designed and developed by researchers and scientists in order to meet the specific objectives of their studies in academic institutes. It is not still identified that which type design and development of the tabletop display suite to single or multiple user setup. There are various ergonomic and interface issues as discussed in the second chapter. These issues are needed to be explored further to overcome them accordingly in the context of users' satisfactions. Keeping in mind the problem statement and objectives of this study, another attempt is undertaken towards the development of multi-touch tabletop display in the area tabletop technologies. The different activities have been undertaken for the development of a multi-touch tabletop display in a cyclic form. This iterative development process can be called as prototype development loop as shown in the Figure 4.12.

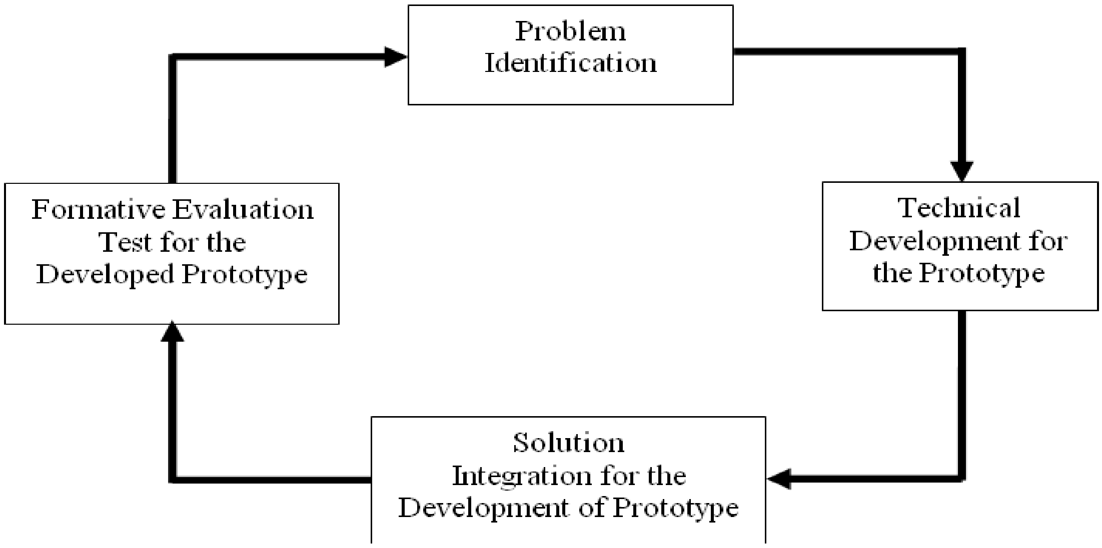


Figure 4.12: Multi-touch tabletop display development process

The Figure 4.12 illustrates the problem identification activity which determines that what kind of problems has been found. So, what kind of possible attempts can be made to avoid from the raised issues accordingly. There is another activity named as technical development for the prototype. It assists in identifying the possible solution on the basis of the technical grounds against identified problems at the first stage. These technical grounds establish a solid base for the implementation of the prototype. This is a stage in which system can be entered in the re-developing process.

The solution integration for the development of the prototype is also important stage in a development loop. It helps in identifying that which existing components can be used into a proposed system. Basically, it helps integrating the novel components into system in the context of particular problem and according to new requirements. After going through these activities in the development loop, finally there is a testing activity. Once system is developed, then it is brought into practice for testing its functionality according to the requirements through the user evaluation. These certain activities are undertaken in a cycle which ensured the appropriate planning, requirement analysis, and designing for the development of the multi-touch tabletop display.

In this respect, the system's enhancement is mainly focused on the modification of the FTIR panel architecture and replacing some of the hardware components. In order to develop the system, the same phases are carried out as previously undertaken for the first developed system. These phases are as: system requirements, system architecture, hardware integration, and software implementation. Each phase plays an important role in the system development as discussed in the following sub-sections.

4.5.1 System Requirements

It is learned from previously developed system that the selection of hardware and software components is challenging issue before the development of any physical computing system. The selection of these components plays an important role according to their specifications and functionality into a system. It is observed that some hardware components need to be replaced that may increase the performance of system.

Keeping in mind the multi-touch detection and low response, it is planned to use a CCD sensor based infrared camera rather than using the CMOS sensor based camera. It is studied that performance of CCD sensor based camera is better than CMOS sensor based camera (Hain, Kähler, & Tropea, 2007). Thus, the replacement of the CCD camera may help in detecting the multi-touch input accurately and increases responsiveness of the system surface due to availability of a feature, i.e. good image capturing and high frame rate.

In addition, a Digital Light Processing (DLP) projector is selected for displaying digital information on interactive surface instead of using the LCD panel. The main reason for replacing an LCD panel with DPL projector was that it exits in small size. Although, an LCD panel is flat and thin in physical characteristics but it constraints in developing the large size tabletop displays and interactive walls. It is extracted through studies that the construction of large size displays is useful for investigation of their technical details, individual use, and collaborative use for various applications (Kim, et al., 2007; Wu & Balakrishnan, 2003).

In this connection, DLP projectors are useful for construction of the large size displays and accommodate a setup with high visualization of information on interactive surfaces. Normally, manufacturing companies introduce the long-throw distance projectors that make the tabletop displays unwieldy and fixed at particular place. Considering this issue, recently, the short-throw distance DLP projectors have been introduced and these are commercially available in the market. These projectors make easy to construct the tabletop displays with different size and shapes. However, these are costly as compare to normal projectors and the LCD panels.

The use of DLP projector for the development of multi-touch tabletop display helps in achieving high resolution display images on the multi-touch I/O device. In addition, a silicon rubber sheet is superimposed on the acrylic sheet that brings softness in surface due to its physical characteristics. It helps in establishing a better coupling between the fingertips and the display during interaction.

4.5.2 System Architecture

The proposed architecture has been slightly modified as shown in Figure 4.13. There is only one change is made that is related to displaying digital information. Instead of using the LCD panel, a Digital Light Processing (DLP) projector is selected and implemented in the system for displaying the digital information. This architecture likely illustrates the design and implementation of different hardware components in the system. It helps in understanding the system components' functionality that has been explained and discussed in detail in Section 4.3.2.

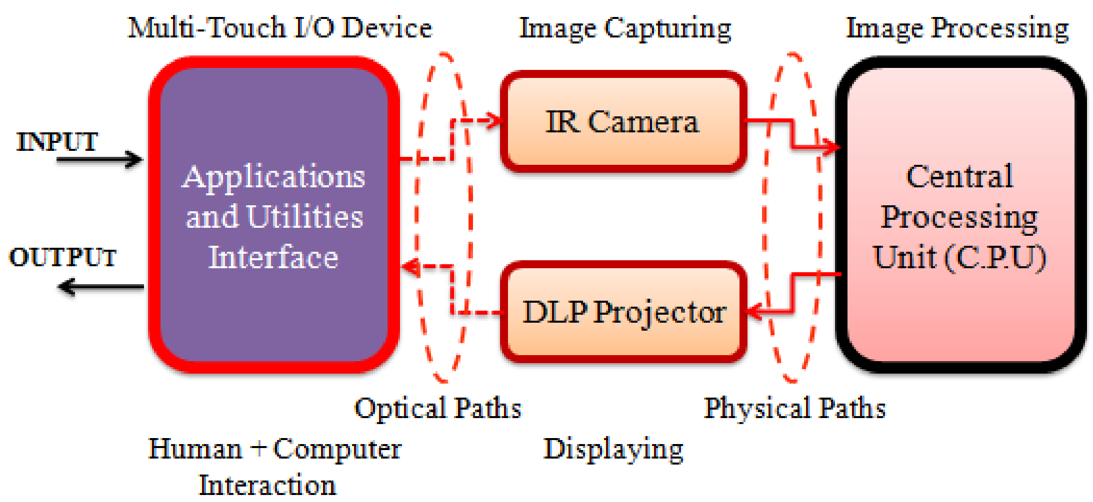


Figure 4.13: Layout of the architecture of the multi-touch display

4.5.3 System Hardware Integration

In order to develop multi-touch tabletop display, different hardware and software components have been gathered. These components have been undertaken in a process for their preliminary testing one by one before to implement in the system. These have been tested according to their functionality. As, it is discussed before that an architecture of FTIR panel would be modified and based on that proposed design the integration of the hardware would be carried out accordingly. The architecture of FTIR panel is modified that is discussed in the following section 4.5.3.1. Following the proposed design, the hardware components are integrated in three main phases, i.e. fabrication of the multi-touch I/O device, modification of the camera and implementation of the DLP projector.

4.5.3.1 Fabrication of the Multi-touch I/O Device

The multi-touch I/O device is fabricated using different hardware components, i.e. an acrylic sheet, a silicone rubber sheet, a rear projection film, Infrared Light Emitting Diodes (IR LEDs) and a DLP projector. The acrylic sheet is transparent, light weight and has a 92% transmission capability for infrared light; therefore it is suitable for the development of a large size display. A transparent rectangular acrylic sheet is used with the given specifications of (length 30 x width 24 x thickness 0.31 inches).

However, it is observed during the development of first prototype, that the nature of light transmission is sensitive with respect to rough surfaces. If the edges of the acrylic sheet are used without making them smooth and shiny, then the infrared light will reflected in many directions. It cannot be transmitted exactly into a medium of the acrylic sheet properly. In this connection, the acrylic sheet that is selected for multi-touch I/O device has rough edges. So, these have been rubbed with sand paper and then polished in order to make them smoother and shinier. These smooth and clean edges of the acrylic sheet help in the transmission of infrared light into its medium appropriately.

In order to enrich the multi-touch input touch detection, a transparent silicon rubber sheet was recommended to superimpose onto the acrylic sheet (Han, 2005).

The selection of the silicone rubber sheet one of the major challenge and it plays an important role in obtaining the bright and accurate fingertip blobs. Considering the color of silicon rubber sheet only, it exists in variety of colors such as milky, translucent, and transparent. It has been experienced during the development of an LCD panel based system that the milky and translucent colored silicon rubber sheets do not provide bright and accurate fingertip blobs. Thus, these false fingertip blobs were not detected by infrared camera properly.

Keeping in mind these factors, a transparent silicon rubber sheet is overlaid on acrylic sheet. In addition, it is also observed during the first prototype that, the thickness of silicon rubber plays a vital role in achieving the bright and accurate fingertip blobs. If, it is thicker and colored then it results in less bright/ faint blobs. It is identified through studies that a silicon rubber sheet can be made by manually through mixing some silicon material. This approach can feasible in terms of cost and creating our specification in terms of the size and thickness. This practice has been done in a controlled environment but could not be made it properly. The air bubbles always remained inside the rubber sheet and the possibility of uneven surface remained. It is identified through studies that if air bubbles remained inside the silicon rubber sheet then it may introduce the noise in input signals.

Considering these issues, finally a built-in transparent and thinner silicon rubber sheet has been purchased and overlaid on the acrylic sheet with the size of (length 30 x width 24 x thickness 0.020 inches). It helps in obtaining the smooth surface on the acrylic sheet. The surface’s smoothness assists in achieving a good coupling between the fingertips and the display. This coupling assists in creating the bright and accurate fingertip blobs during multi-touch interaction. Since, the silicon rubber sheet has not been used in the LCD panel based displays; this could possibly be one of the reasons for the less bright and inaccurate fingertip blob detection by infrared camera.

The optical and camera based surfaces do not have the capability of displaying digital information on their own. Thus, a DLP projector is used for displaying the information. Similarly, a bottom-up approach is used for the development of the multi-touch tabletop display in which the DLP projector is configured at the rear side of surface (inside the table). In this respect, a rear projection film is required for displaying the projected digital information on the multi-touch I/O device. In this respect, a tracing paper was overlaid on the silicon rubber sheet. It was very inexpensive solution for the displaying projected digital information on interactive surface. It provided the displayed digital information with good resolution on interactive surface but it blocks multi-touch input signals. However, this experience suggested it is better to use suitable rear projection screen/film. These films are commercially available in market with variety of specification that makes its selection too challenging. Finally, it is purchased and overlaid on the silicon rubber sheet with the given specifications of (length 30 x width 24 x thickness 0.039 inches).

These superimposed layers have the same size in the aspect of length and width; there is a difference in their thickness only. It has been reviewed, that a maximum thickness of these layers may block multi-touch input signals.

In order to avoid that issue, the above very thin layers are selected and superimposed which do not block the input signals during interaction. The process of coating these layers on the acrylic sheet has been undertaken in a clean and controlled environment in order to protect them from dust particles. The overlaid layers on the acrylic sheet with their specifications are shown in Figure 4.14.

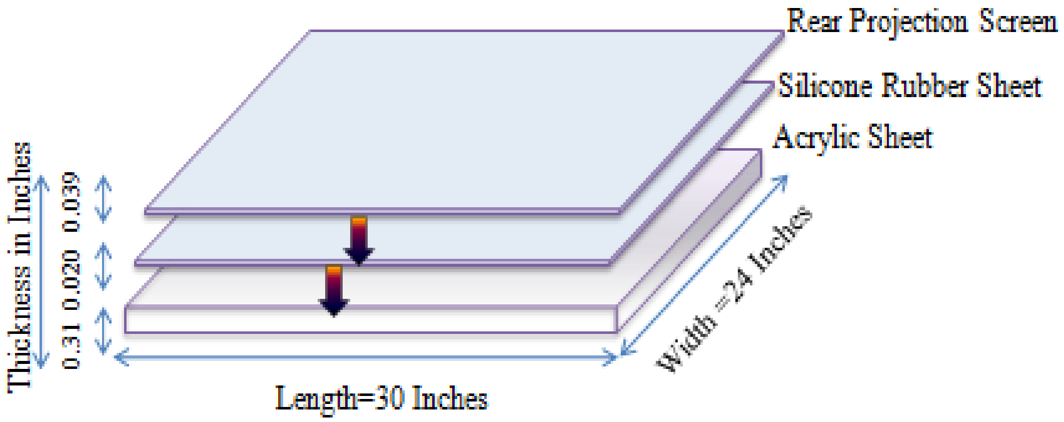


Figure 4.14: Overlaid layers on the acrylic sheet

However, literature suggests that the presence of the high intensity of infrared inside medium of the acrylic sheet can overcome the problem of faint fingertip blob detection (J. Y. Han, 2005). In this regard, the architecture of the optical panel is proposed based on the experience of previously developed system and discussions as shown in Figure 4.15. In this architecture, it is attempted to configure the infrared light sources very close to each other at specific distance. It helps in deploying a large quantity of the infrared light sources opposite to the edges of acrylic sheet. In addition, this architecture assists in keeping the appropriate distance of each light source from the edges of acrylic sheet. It helps in keeping the light sources safe from any physical damage. Consequently, this architecture helps in assembling the array of light sources, i.e. IR LEDs opposite to the acrylic sheet edges properly.

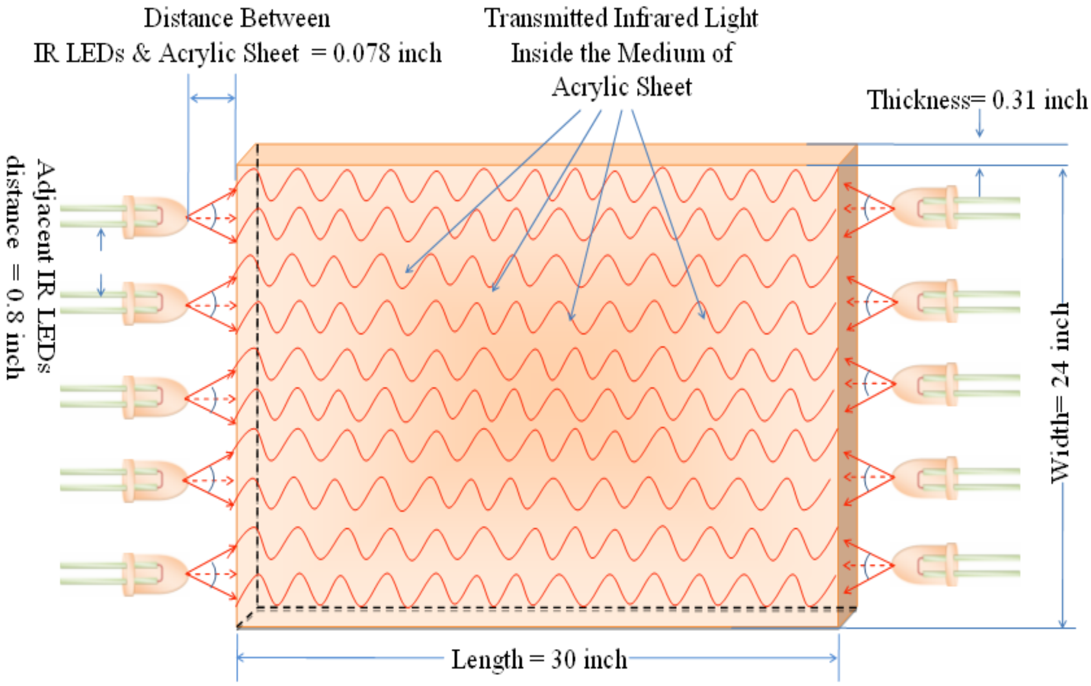


Figure 4.15: Layout of the internal architecture of the optical panel

Keeping in mind this architecture, primarily, a U-profile aluminum frame is selected in which the number of holes is made according to the exact size of the IR LED and a distance of 0.8 inches is maintained between them. Following the design principle, infrared light sources with the given specifications of (10° beam angle and wavelength of 940nm) are configured into the U-profile aluminum frame. These light sources have many advantages, i.e. a narrow emission wavelength, high switching frequency, and low heat dissipation. During the fabrication process, IR LEDs are kept at a distance of 0.078 inches away from the edges of the acrylic sheet to protect them from any unavoidable damage.

After completing this process, a printed circuit board is designed in which the IR LEDs are connected using a parallel rather than series combination. In a series connection, if one light source is damaged due to power fluctuation or any other reason then the rest of light sources will be switched off automatically. This process can lead to the failure of a system's functionality. In contrast, in the parallel connection, if any light source is damaged or switched off, the rest of the light sources remain unaffected. This setup provides reliable power supply to all light sources for proper functionality.

The configuration of the IR LEDs opposite to the acrylic sheet as based on the proposed architecture is tested using the IR Camera. This architecture helps in achieving the FTIR panel or optical panel with a high intensity of infrared light. The medium of the acrylic sheet is flooded with infrared light and it produces a better quality of fingertip blobs as expected.

The optical panel and its printed circuit board are sensitive in their physical characteristics. In order to protect them from any unavoidable damage, a wooden frame is made according to particular specifications. It is framed accordingly and this setup provides for complete protection. In order to bring the optical panel into the tabletop display format, a wooden table is made with the given specifications of (length 41 x width 27 x height 33 inches). It is covered from all sides then the fabricated optical panel is installed into the table accordingly.

4.5.3.2 Modification of the Camera

As discussed earlier, input detection using optical displays depends on an infrared camera. Therefore, the Philips SPC900NC PC Web camera with a VGA CCD sensor and USB 2.0 interface is used instead of the CMOS senor based camera. The CCD sensor has low image noise and it is more effective than the CMOS sensor in detecting images (Hain, et al., 2007). It transmits 90 frames per second and its resolution is 1280x960 Pixels.

It is a webcam in which an infrared blocking filter is embedded in front of its sensor. It cannot detect infrared input signals due to that filter. Therefore, it is modified from the normal webcam to an infrared one following the same modification process as described in section 4.3.3.2 of this chapter.

In order to develop the tabletop display, a bottom-up approach is adopted to configure the modified camera inside the table at a centered location. It is connected to the computer system using a USB port and tested accordingly. This process ensures that the multi-touch input is detected properly by the camera. Finally, it is calibrated with respect to the x and y co-ordinates of the optical panel.

4.5.3.3 Implementation of the DLP Projector

It has been discussed that optical and camera based displays don't have the capability of displaying digital information on their own. These displays need assistance from a projector or LCD panel in order to display information. In this respect, a short throw distance Digital Light Processing (DLP) projector with the given specifications of (1024x768 pixel resolution) is configured behind the optical panel. It is connected to the computer system and calibrated according to the x and y co-ordinates of the optical panel. It provides a better quality of displayed images on the display.

The rear deployment of the DLP projector with a short throw distance in the system enhances the interaction capability of the users on the interactive surface. Using this approach, displayed images on the multi-touch I/O device are not broken by the users' arms and hands during the interaction. However, the rear setup using the DLP projector is a bit more expensive than a front projection. The front projection can be gained through a normal projector (long throw distance) but this setup introduces the portability issues. In addition, it was attempted to make a rear setup of the display with a normal projector using a mirror; however, this setup makes the system architecture complex and introduces the image ghosting problem.

By integrating the specific hardware components consequently produces the multi-touch tabletop display as shown in Figure 4.15. It illustrates the complete internal architecture and functionality of the display.

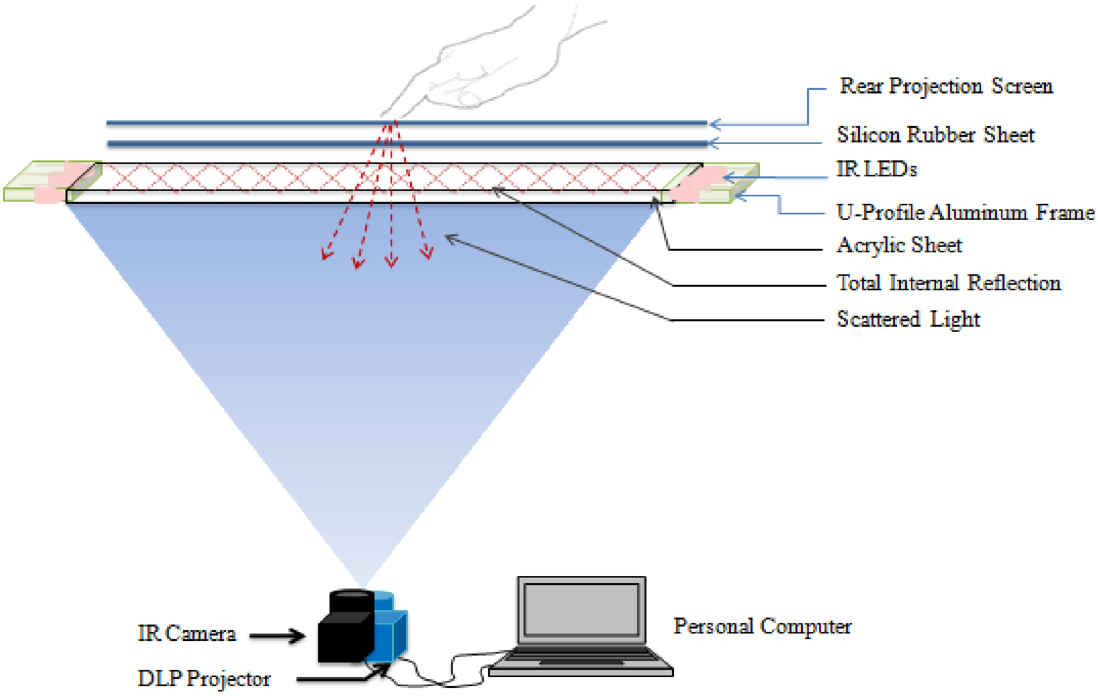


Figure 4.16: Layout of the internal architecture of the multi-touch tabletop display

4.5.4 Software Implementation

After completing the hardware integration process, the multi-touch software called TouchLib is implemented and multi-touch tabletop display is calibrated properly. This software enable the enables the system to detect and track multi-touch input accordingly. When a user interacts with the display using his/her bare fingertips then infrared light is frustrated in the optical panel and scattered down. This phenomenon of interaction is called Frustrated Total Internal Reflection (FTIR) in which fingertip blobs are created during interaction. These blobs have been detected by the camera and then sent to the computer system for further processing accordingly.

4.6 System Testing

During the development phase of multi-touch tabletop display, each hardware component is carefully checked and implemented accordingly. This preliminary checking of these components encouraged in the development of multi-touch tabletop display based on proposed architecture. In this system, specifically architecture of FTIR panel/optical panel is modified and infrared light sources are configured accordingly. The appropriate fabrication of the IR LEDs opposite to the edges of an optical panel increased the transmission of infrared light inside its medium. The overlaid layers on the acrylic sheet provides good coupling between fingertips and the interactive display during interaction. In addition, the implementation of CCD camera in the system increased its performance in terms of detecting multi-touch input and its response accordingly. The improved version of the multi-touch tabletop display is shown in Figure 4.16.

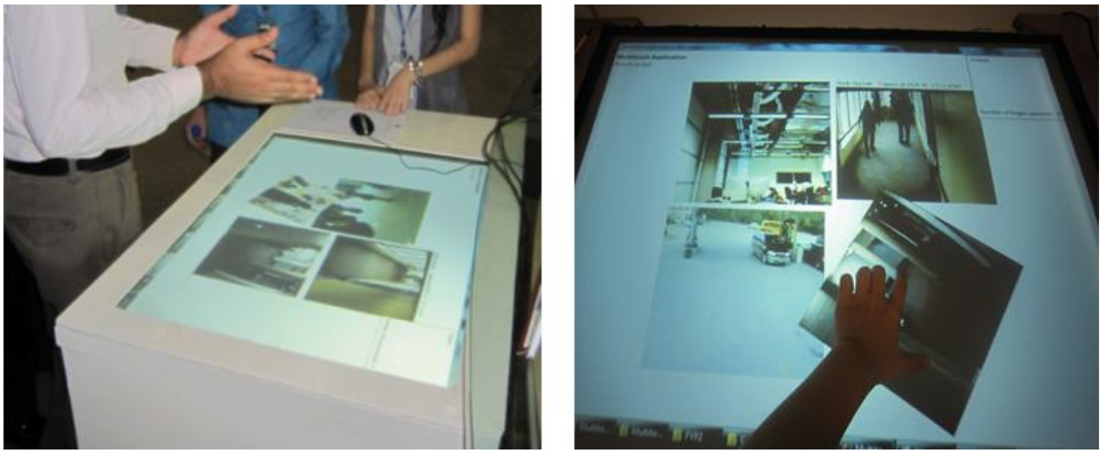


Figure 4.17: Multi-touch tabletop display

Since, the development of the multi-touch tabletop display is completed then similarly a plan is made to test its functionality in the context of multi-touch input detection. In order to test the display, the security surveillance video application is developed and installed in the system and finally allowed users to access the application accordingly. This process ensured the system's functionality as expected accordingly. The overall outcome of the system is described and discussed briefly in the following sub-sections.

4.6.1 Multi-touch Input Detection

The users identify live/recorded surveillance videos on the multi-touch display as shown in Figure 4.16, and select and manipulate photos frequently using their bare fingers. In this application, normally users perform three different gestures, i.e. move, resize, and rotation during the selection and manipulation of photos directly. The taxonomy of these gestures/actions is illustrated in the following Figure 4.17.

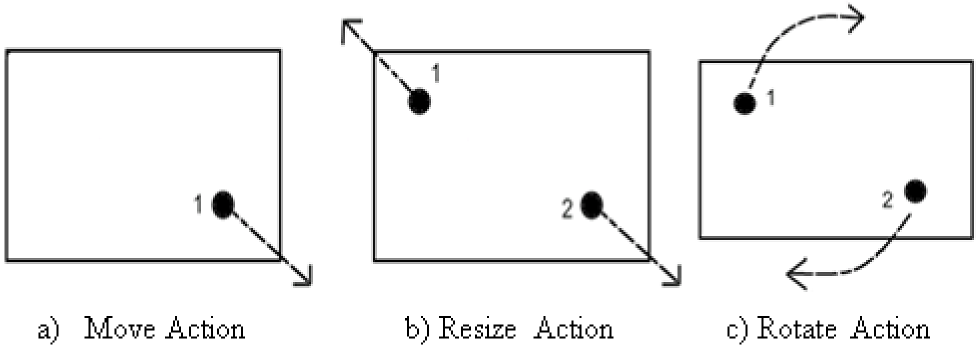


Figure 4.18: Design of direct finger gesture

Considering move action, user needs to use one finger only to touch the photo and drag it to any place within the screen area. For the resize/scale action, at least the two fingers are required to touch the targeted photo and then these fingers needs to move away from each other in any direction within the screen area. Whereas, for performing the rotate action, similarly at least two fingers are needed to touch the target object and then fingers tends to be rotated in any direction or to perform an arc in opposite direction within the screen area.

The multi-touch tabletop display facilitates users to visualize the output of the single and multiple video cameras and assist them to perform direct multi-touch interaction simultaneously. During this study, it has been identified that the tabletop display technology provides the great potential to visualize the video output at large scale interact it through multiple fingers. The outcome of this study suggests, it was first experience for users to use multi-touch tabletop display. It enables them to move, resize and rotate the surveillance videos easily using multiple fingers directly. It is good to enlarge the videos at large scale and this phenomenon makes the possible for users to visualize the objects easily on the display. It is also observed that users feel the natural state of art of interaction when target objects are moved, resized, and rotated with multiple fingers. The multi-touch tabletop display can increase the efficiency in monitoring the activities and behaviors of the people or objects. Keeping in view the concept of the collaborative multi-touch interaction, this system accommodates a space around the table and allows multiple users to select the digital photos simultaneously. The undertaken formative evaluation test process confirmed that the system is capable of detecting the direct and natural multi-touch input.

4.6.2 Study-II

Since, it is discussed before that again another study has been conducted by an undergraduate student in her final year project for testing the functionality of an improved version of our multi-touch tabletop display. In this study, the manipulation of video surveillance system using the multi-touch tabletop display was considered (Eileenkho, 2010). Because, recently video surveillance systems are widely used in the organizations of all sizes, including industry, retail shops, education, government, and even at home. Originally these systems are developed to provide ultimate security in places that are of high risk of crime. Nowadays, the closed-circuit television and video surveillance system software are inexpensive and simple enough to be used by average customers as well.

However, the foremost example is the HomeCamera webcam security software. With only a webcam, subscribers are able to conduct internet home surveillance, office surveillance, and etc. Another software named NetCamCenter that is based on an IP video program for the network camera and video server which provides IP-based video surveillance. As analog CCTV systems are expensive and requiring complicated installations, thus, there are plentiful of software available to provide IP security systems to the users. Security systems using IP cameras are easy to install and maintain. These software contain a lot of features in providing a security solution. They allow users to view live video with IE, record video, playback video, using their PC, PDA, and mobile phone. Some even support the motion detection that will send alerts to the subscribers through their email and mobile phones.

The GUI of these software is like a control center providing multiple video windows in a 2x2 or 3x3 matrix (depending on the number of camera inputs) on a screen showing live video from different camera inputs. The GUI of some software contain some buttons that allow users to start/stop the motion detection, start/stop the recording, search for the recorded video, and more. The GUI is user-friendly and simple-to-use.

On the other hand, the advancements in touch sensing technologies, reductions in their cost, and other factors have made multi-touch input devices becoming more popular and common in many industries. In the last couple of years, the use of touch screens seems to be everywhere, including information kiosks, GPS receivers, cell phones and PDA. The main reason of implementing touch screens is that it can be used to maximize the information visualization capabilities. However, in public places, like museum, there are always multiple users at once. The touch screens which allow only a single touch at the time and these are not feasible in these places as everyone needs to wait for their turn. In contrast, the multi-touch tabletop displays technology accommodates shared workspace that supports multiple users for simultaneous interaction. It has made the use of these interfaces significantly in recent years.

However, the problem with existing video surveillance systems is that the structure of each surveillance video is too small. It makes difficult for users to watch the large screen of live videos simultaneously. This problem gets worse if the output of too many cameras to be displayed on a small screen as shown in Figure 4.18.

Figure 4.19: Surveillance videos (Eileenkho, 2010)

Although, some CCTV systems allow an enlarged screen of a live video when a press button is activated but it limits in displaying other surveillance videos at the same time. In the case of emergency, like intrusion, it is important to watch and trace the suspicious people and objects at an enlarged size of the live videos at a time. In order to address this problem, an interface is developed for the displaying the video surveillance system using multi-touch tabletop display.

In order to support this study, a small portion of her study is undertaken which suggests that the developed multi-touch tabletop display allow users to perform direct and natural multi-touch interaction. There is no intermediary device like mouse and keyboard for accessing the digital information. Users can perform different gestures, i.e. move, resize and rotate directly as shown in Figure 4.19.

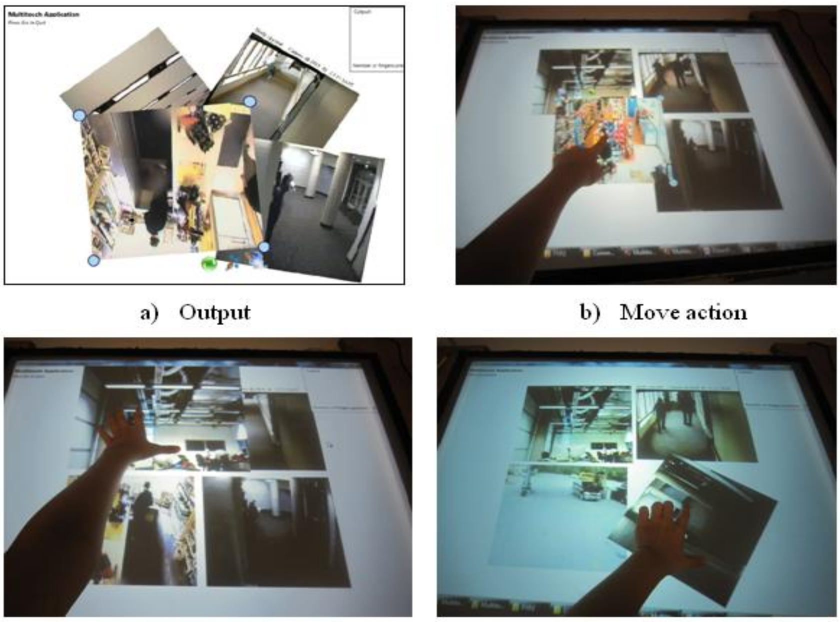

a) Output b) Move action
c) Resize action d) Rotate action

Figure 4.20: Direct gesture of fingers on the multi-touch tabletop display

The multi-touch tabletop display facilitates users to visualize the output of the single and multiple video cameras simultaneously and assist them to perform direct multi-touch interaction. During this study, it has been identified that the multi-touch tabletop display technology provides the great potential to visualize digital information at large scale. The outcome of this study suggests, it was first experience for users to use multi-touch tabletop display. It enables them to move, resize and rotate the surveillance videos easily using multiple fingers directly. It is good to enlarge the videos at large scale and this phenomenon makes it possible for users to visualize the objects easily on the display. It is also reported that users feels the natural state of art of interaction when target objects are moved, resized, and rotated with multiple fingers. The multi-touch tabletop display can increase the efficiency in monitoring the activities and behaviors of the people or objects.

In addition, it is reported that the multi-touch tabletop display may not only be used for security surveillance systems but it has also great potential to be used for medical image analysis. It can encourage the physicians for collaborative diagnosis of the multiple medical images with high visualization of digital information. This study ensured that multi-touch tabletop detect the multi-touch input and assist multiple users to select and manipulate digital contents using bare fingers. However, it is reported that multi-touch tabletop display detects multi-touch of single accurately and efficiently but it has low fidelity in sensing the multi-touch input of multiple users simultaneously. In order to encourage the concept of collaborative multi-touch interaction, it is recommended that tabletop display need to be calibrated effectively.

4.6.3 Discussion

Since, the fingertip's contact area and shape significantly matters in designing and configuring the target elements on touch screens. Thus, instead of testing of the system's functionality only, it is planned to investigate the fingertip blobs in the context of the brightness and accurate fingertip blobs. This process may also ensure the improved prototype is useful for the investigation of the fingertips contact area and shape in the context of imprecise selection.

In this respect, the some of the detected fingertip blobs by the system are illustrated in the Figure 4.21. It illustrates that blobs are bright and accurate. The obtaining the bright and accurate fingertip blobs ensure that the proposed architecture of optical panel and replacement of few hardware components works properly. It confirms that the optical panel is flooded with infrared light that supports the infrared camera in detecting the input accurately and effectively. These fingertips blobs are smooth that ensure that there is the better coupling between fingertips and interactive display. However, these fingertip blobs represent their different size and shape. It reflects that users may have different fingertips size in the dimensions accordingly. The detail description of these fingertip blobs is given in the next chapter.

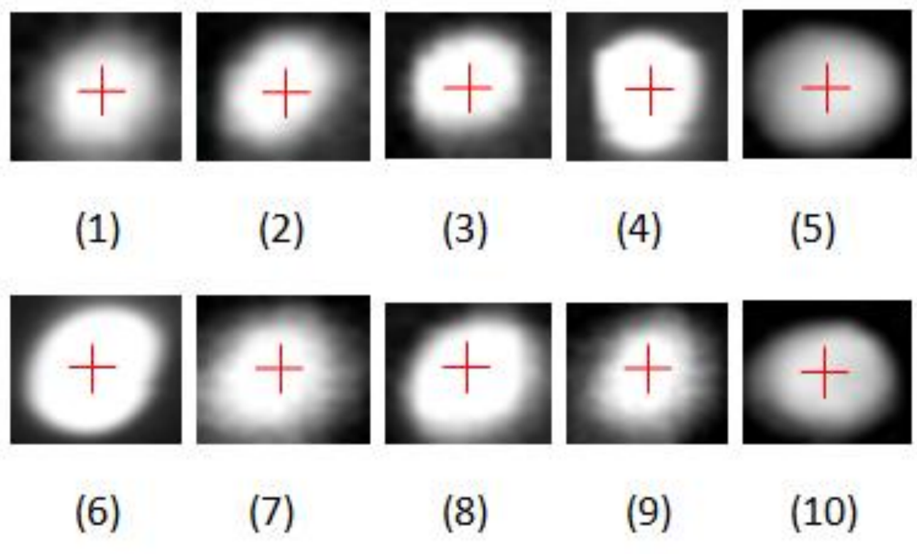


Figure 4.21: Fingertip blobs detection using CCD sensor based infrared camera

Keeping in mind, the detection of the faint/false and irregular fingertip blobs using the LCD panel based multi-touch display. It has been identified that the more pressure is exerted by fingertip in order to accomplish bright fingertip blobs. After that, infrared camera was able to detect the fingertip blobs. In the first prototype, the one of the major shortcoming was the in appropriate configuration of infrared light sources. In addition, there was bad coupling between fingertips and interactive display due to absence of silicon rubber sheet inside the interactive surface. These issues has been addressed properly and finally obtained the improved version of multi-touch tabletop display. However, keeping in view the outcome of this improved prototype/multi-touch tabletop display, it is identified that there is no more fingertip pressure is needed to obtain bright and accurate blobs. Users normally interact with display using their bare finger then the blobs are created accordingly and detected by camera.

In the Figure 4.21, the detected fingertip blobs justifies that optical panel is flooded with infrared light and it assists in creating the good frustrated total internal reflection. It ensures that the configuration infrared light sources opposite to the edges of the acrylic sheet work properly and these emit the light inside its medium as expected accordingly. It is observed that, still infrared light is leaked from the edges of acrylic sheet which introduces the infrared noise detected by the camera. It can be improved through providing an appropriate assistance to the acrylic sheet from its down side.

Since, the multi-touch tabletop display has been designed and developed then its functionality tested through user evaluation and obtained their feedback accordingly The overall users feedback suggest that multi-touch tabletop display detects the users multi-touch. Users can play with digital photos directly using their fingers. There is no intermediary device between users and interactive display. They can select, rotate and zoom-in and zoom-out these digital photos on the display. This method of interaction establishes a temptation in order to perform natural interaction. The developed multi-touch tabletop can be used for interactive learning games and medical image analysis in a collaborative manner. This setup can be helpful in identifying and analyzing the collaborative interaction using the same and different application on the display.

However, it is observed that the developed multi-touch tabletop display needs an appropriate user interface design for supporting the single and multi-user interaction. The existing software interface does not assist the users in terms of using their natural interaction capabilities as they have. In addition, the users' experiences also suggest that this system lacks in supporting the multi-users multi-touch interactions on the same workspace. It provides high fidelity in sensing the single user's multi-touch input but still it has low fidelity in sensing the multiple users' input. According to the users' experience, this system does not provide provides quick touch response during the collaborative multi-touch interaction.

During the experiments, it is observed that the harsh ambient light adversity affects on the resolution of the display. It degrades the visibility of target elements when display is placed under harsh light conditioning environment. Specifically, if it is to be placed under the sun light then it may degrade the visibility target elements and it ultimately may affect on the users' performance. This problem can be overcome by superimposing a layer named as infrared blocking foil inside the system surface.

Instead of these limitations, the overall outcome of the developed multi-touch tabletop display encourages for the investigation of physical finger input properties such as fingertip contact area and shape in the context of imprecise selection. Thus, it has been used as the testbed for conducting the experiments relate to the investigation fingertip contact area and shapes and for examining the finger's angle of approach of users on tabletop display.

4.7 Summary

This chapter introduces to the design and development of the multi-touch tabletop display. Keeping in mind the objectives of this study, the related literature is reviewed and a multi-touch tabletop is developed based on the proposed architecture. For the development of the system, a bottom-up approach is adopted in which a camera and a projector are configured from the rear side of the display. The proposed architecture helps in integrating all hardware components and assists in understanding the functionality of each integrated components in multi-touch tabletop display.

In the first attempt of this study, a small size multi-touch tabletop display has been developed and it is tested in the context of functionality. The outcome and an experience of design and development of this tabletop display introduced various challenges and issues. In order to meet those challenging issues, another attempt is undertaken for development of multi-touch tabletop display. In which, the architecture of the display is modified and replaced few hardware components. This developed system is tested according to its functionality through users' evaluation. The outcome of this prototype suggested that, it detects the multi-touch input and allows users to select and manipulate the digital photos. The whole design and development process is undertaken in a cycle based on trial and error. Although, the improved tabletop display has some limitations, but it can be used be as a testbed for the investigation of fingertip contact area and shapes in the context of imprecise selection. It is also used for examining the fingertip finger's angle of approach. The next chapter will present the findings and analysis of the studies related to the evaluation of physical finger input properties.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Overview

This chapter introduces the results and discussion related to the investigation of physical finger input properties, specifications of the finger's angle of approach, and finally evaluation of physical finger input properties of index finger. In this study, an attempt is made to answer some specific questions, i.e. "Is there any difference in individuals' fingertip contact areas and shapes?", "Does the finger's angle of approach impact on the variation of the contact areas and shapes?", "How much variation exists among the individuals' fingertip contact areas?", and "Is there any significance difference among the individuals' fingertip contact areas accordingly?" The research approach that has been undertaken in order to conduct this study in the context of these questions is described and discussed in the third chapter of this thesis.

5.2 Experiment-I: Investigation of Physical Finger Input Properties

Human fingers possess different input properties that can be used for interacting with multi-touch displays. Specifically, the physical finger input properties such as contact area and shape are very useful properties for frequent as well as precise multi-touch interaction.

However, it is reported that fat fingers create imprecise selection of small target elements in direct multi-touch input. Why this problem is introduced? It is because, in previous studies the size of target elements were proposed based on assuming the fingertip size. Later on a few small studies have been conducted in order to identify the fingertip size and shape. These studies suggested for designing the proper size of target elements then experiments were conducted for obtaining precise selection.

These studies supported in achieving the precise selection as discussed in second chapter of this thesis in detail. Despite of that, there is still imprecise selection, and it is recommended that physical finger input properties to be explored extensively for obtaining the high precise selection. In this connection, realizing the importance of physical finger input properties, a motivation is increased to conduct a study on the investigation of fingertip contact area and shape. These two physical properties of fingers are directly related to size and shape of target elements. Thus, this study may help in obtaining the proper values for designing and configuring the target elements. Consequently, it may help in obtaining the precise and frequent multi-touch interaction using bare fingers.

5.2.1 Results and Discussion

Figure 5.1 illustrates the black and white regions of the fingertip blobs, the white regions represent the actual fingertip contact areas, occupied by individuals during interaction with the display. These white regions show the distribution of (*on*) pixels in the x and y co-ordinates whereas black regions represent (*off*) pixels. These fingertip blobs are processed to compute the total sum of (*on*) pixels that are distributed in the x and y co-ordinates. This process helps in identifying how much of the individuals' fingertips occupy contact areas and is there any distinction exists accordingly.

The results are shown in Figure 5.2 in which the fingertips are represented in the x axis and the sum of their pixels in the y axis. The mean and standard deviation of these fingertip blobs are computed, i.e. (Mean=280 pixels, SD= 157). The sum of the pixels of the individuals' fingertip blobs illustrates that there is a variation in the physical size of the individuals' fingertips thereby causing them to occupy different contact points. Most specifically, the physical size of an individual's thumb occupies more space than rest of his/her fingers. It is observed that the physical characteristics of the fingers such as the fingertips' soft tissue, force and their angle of approach are reasoned to produce the variation in the fingertips' contact areas.

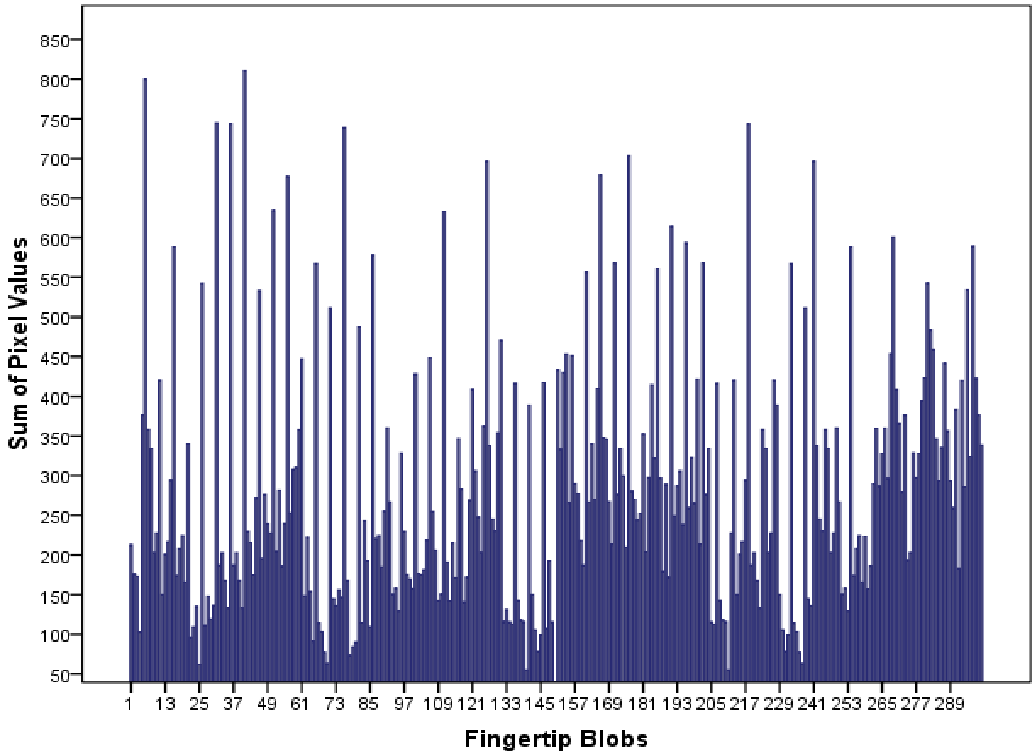


Figure 5.1: Sum of pixel values of the fingertip blobs

However, the presence of differences in the users' fingertip contact areas may adversely affect the precise selection of small target elements. This study suggests that if the pixel size of the target elements is less than the actual fingertip contact area on a sensitive display then a high error rate may be expected in the direct touch input. In addition, this study suggests that the finger's angle of approach (e.g. oblique v/s vertical touch) may lead to variation in the occupied fingertip contact area due to these physical characteristics. Thus, considering the physical characteristics of the fingertips' contact areas are further investigated and discussed in the context of pixel scattering on the display.

5.2.1.1 Oblique Touch

In order to understand the physical characteristics of fingertips, a geometric model using the oblique touch is presented as shown in Figure 5.3. It provides a clear view of the physical characteristics of fingertips which impact directly on contact points made during interaction. It also helps in describing the contact points made by the fingertips from the p1 and p2 in the x and y co-ordinates on the display and its outer edge as well. It suggests that when a user interacts with a display using a bare finger then its soft tissue disperses and impacts on the distribution of the pixels accordingly. In addition, it also suggests how a maximum and minimum distortion of the fingertips can occur on the display.

This phenomenon of interacting with sensitive displays is important to understand properly because it may help in designing and configuration of target elements. Assuming that, if target elements are closely associated/configured on the sensitive display and users apply oblique finger touch method to select any of target element. After that, it is sure that fingertip will occupy more space rather occupying exact target point due to its physical characteristics. Thus, it is important to analyze closely that how fingertip land-on and occupy the space at display during oblique touch.

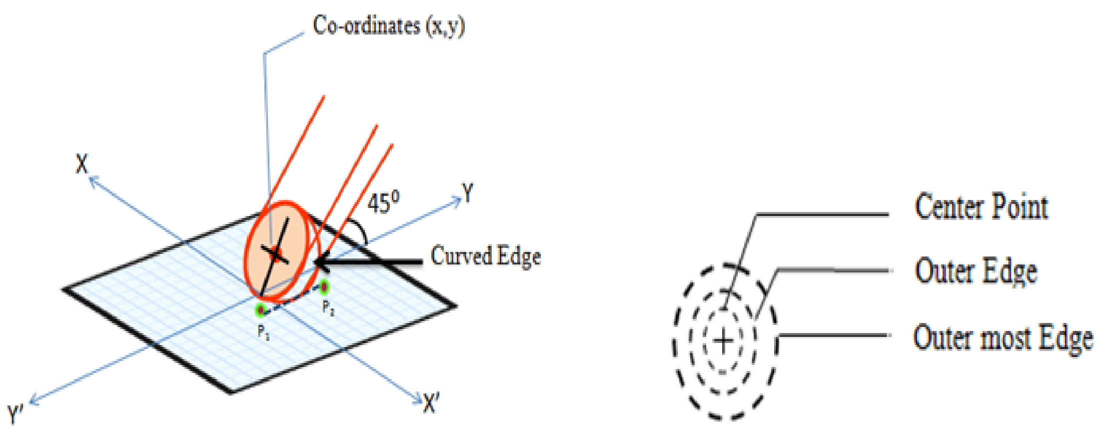


Figure 5.2: Geometric model of a fingertip using the oblique touch

The above figure shows that the oblique finger touch may occupy more contact area because its angle supports the soft tissue in dispersing towards the outer edges accordingly. It can occupy even more space if a user’s fingertip is fatty in its physical characteristics. Considering these factors, a fingertip blob is undertaken and processed to investigate its pixel distribution in the x and y co-ordinates. The outcome of the processed fingertip blob is shown in Figure 5.4 and illustrates a fingertip contact point in figure (a) and its pixel scattering phenomenon in figure (b).

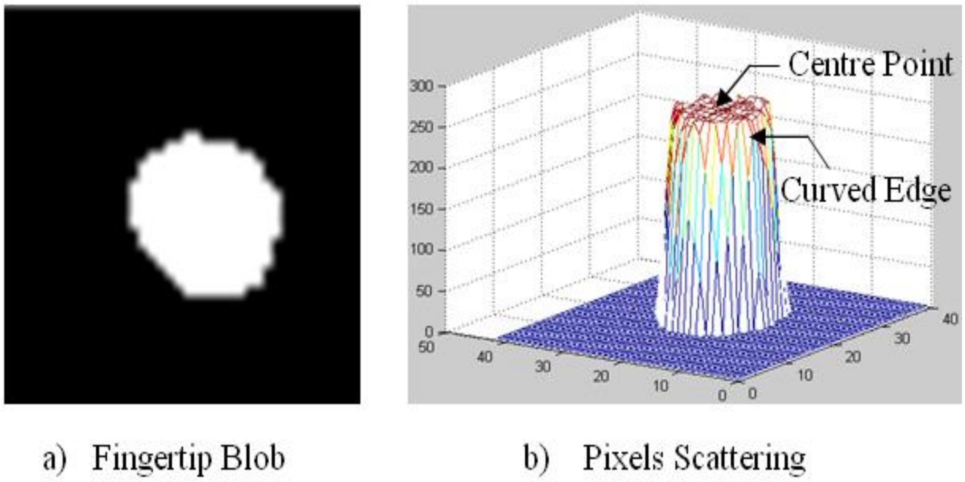


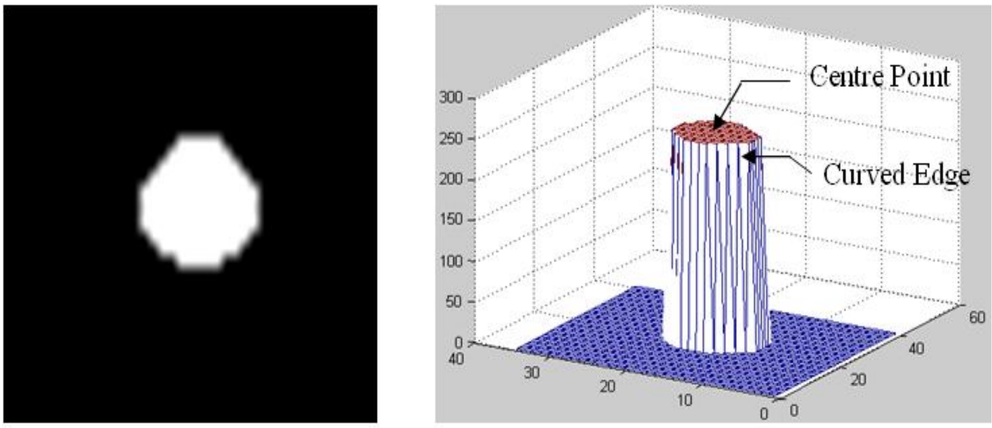
Figure 5.3: Fingertip blob (a) and its pixel scattering (b) for oblique touch

Figure (a) shows that the user's fingertip blob is found to be of an irregular shape. It can be due to the physical characteristics of the individual's fingertip and the exerted pressure. It is observed that the physical characteristics of the individuals' fingertips are soft and curved rather than flat. Therefore, diagram (b) illustrates that the fingertip's curved edge has not contacted precisely with the tabletop display and results in the low pixel distribution in the x and y co-ordinates. However, the centre point of the fingertip contacted properly with the display and subsequently resulted in high pixel distribution in the x and y co-ordinates.

5.2.1.2 Vertical Touch

Keeping in mind the outcome of the oblique finger touch, the motivation is increased to investigate the vertical finger touch, too. A fingertip blob is undertaken and processed accordingly as shown in Figure 5.5. It illustrates the fingertip contact area in figure (a) and its pixel distribution in the x and y co-ordinates in figure (b).

Figure (b) shows the centre point at which the fingertip contact is made properly and subsequently resulted in the high distribution of pixels in the x and y co-ordinates. It reflects a high intensity of pixels. Whereas, the fingertip's curved edge represents a low intensity due to less contact made during interaction. However, the distribution of pixels relating to the vertical touch illustrates that it occupies less contact area as compared to the oblique touch.



a) Fingertip Blob b) Pixels Scattering

Figure 5.4: Fingertip Blob (a) and its Pixel Scattering (b) for vertical touch

However, it is observed that the fingertip's soft tissue disperses at a small area on the display due to the vertical angle of approach of finger during the interaction. It is convincing that the fingertip occupies less space during the vertical touch and it may be useful for precise selection of small size target elements on displays. It confirms that the finger's angle of approach plays an important role in occupying the contact area. Another end, it is personally observed that vertical touch without any additional assistance to user's hand may introduce ergonomic issues and arm fatigue. In addition, user's vertical touch may limit in selecting, scaling and rotating digital documents on sensitive display due to its angle and nail. Since, the technology of multi-touch tabletop displays and interactive walls brings the hands on computing. In which users want precise and frequent interaction according to their natural state of art capabilities of interaction. Considering the case of tabletop displays, it may be hard for users to drag and drop the target elements from one location to another precisely and frequently.

However, the presence of variance in the contact area in oblique and vertical finger touches may increase the error rate in selecting small size target elements during direct touch.

5.2.1.3 Analysis of Fingertip Shapes

It has been discussed earlier that fingers have different physical properties, i.e. shape, contact area and orientation. In regards to this, recently, the shape touch is also used to select the target elements on multi-touch displays. Thus, it is very important to investigate more users' fingertip shapes. This investigation may help in designing target elements accordingly. The design of target elements according to users' fingertip shapes may enrich the precise selection and frequent multi-touch interaction. Since, it is studied that size of target elements and size of fingertip contact area can play an important role in obtaining in achieving the high precise selection. Similarly, it is observed that shape of fingertip contact area is also equally important in the context precise selection. Thus, it is very important to observe shape of fingertip and shape of target elements in the scientific studies. In this regard, fingertip blobs are further processed to identify their shapes using an edge detection algorithm as shown in Figure 5.6. Each fingertip shape consist of different characteristics, i.e. edge of contact area, co-ordinates, contact area, physical length and width.

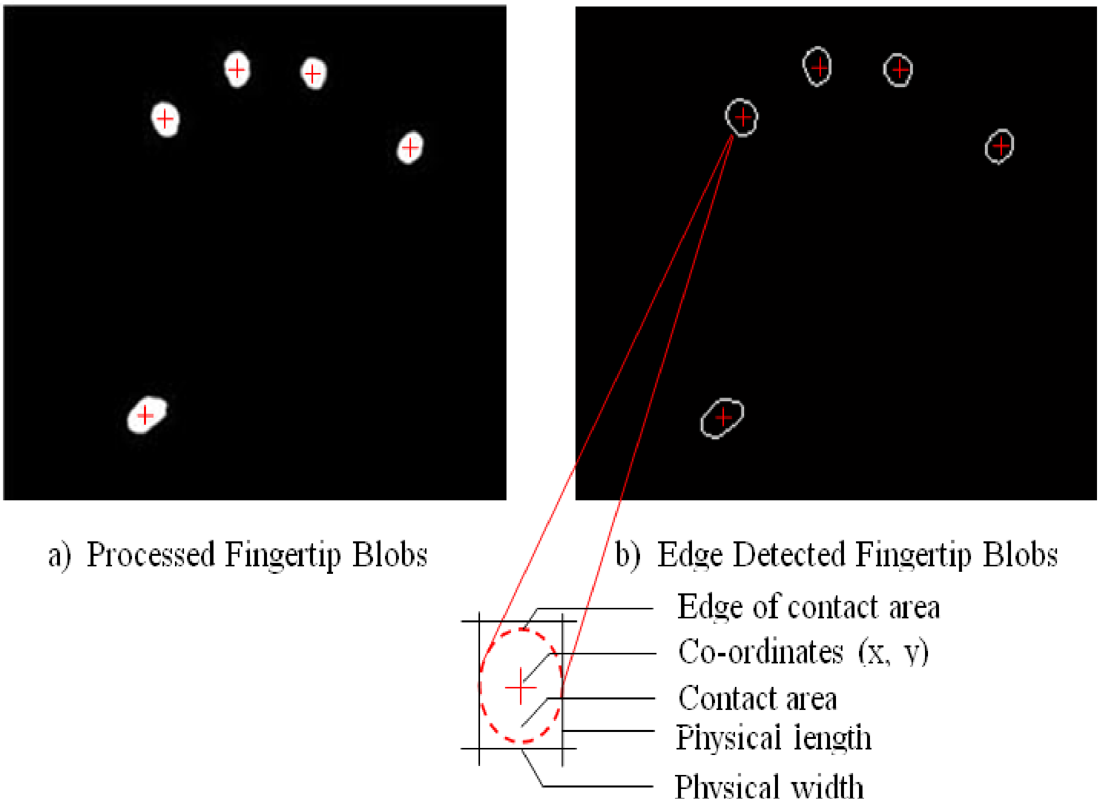


Figure 5.5: Investigation of fingertip shapes

Figure 5.6 (b) shows some contours of fingertips in which edge of each contour represent that the user's fingertips made circular shapes during interactions according to their physical length and width. These shapes seem to be slightly irregular and also occupy different contact areas. In particular, the contour of the thumb demonstrates that it occupies more space than the rest of fingertips.

The investigation of fingertip ensures that the physical characteristics of the fingertips, i.e. physical length and width have a great impact on the variation of their shapes and sizes. Considering the shapes of the target elements, it found that these target elements normally found in the square and rectangular shapes on sensitive displays and desktop computers. The most of studies related to the precise selection of have also been conducted by researchers using the square and rectangular shape of target elements. These studies need to be conducted using circular and elliptical shapes of target elements in order to differentiate the results and users preference. Although, the square and rectangular shapes of target elements are commonly used in existing Graphical User Interface and assisted in many ways to users for interacting with computers. However, in the case of Natural User Interface using the multi-touch tabletop display, it is difficult for multiple users to select these unidirectional target elements. For example, if multiple users around the tabletop display want to access multiple target elements then these elements introduce the orientation problem.

As, invention of touch screens, multi-touch tabletop display, and interactive wall size display appeal for a suitable user interface design and accordingly appeal for the suitable shape and size of target elements. However, this investigation opens up the possibility of designing target elements in circular and elliptical shapes of different sizes. In addition, the finding suggests that human finger have certain distance among each other so it reflects sense that how circular and elliptical target elements would be configured on sensitive displays. How much distance should be managed among these target elements? Considering the example of virtual keyboard of mobile touch screen, it is too small in size thus users have to pay much attention press on key at time with finger or stylus. This approach of interaction limits performance and capability user's interaction.

Whereas the multi-touch tabletop display provides a large space in which an specific size of virtual keyboard can be designed that may support users to *key-in* the text frequently as done through physical keyboard. Since, it has been studied that multi-touch tabletop displays support the collaborative workspace at which multiple users can access the target elements. What kind of shapes and sizes of target elements would suit to users for interacting with display precisely and frequently? In this regard, the appropriate design and configuration of the circular and elliptical target elements on sensitive displays may enrich the precise and frequent selection during direct multi-touch interaction. Thus, the different studies can be conducted in order to know users preference and precise selection on mobile touch screens and multi-touch tabletop displays according to usability goals.

5.3 A Study on the Specification of Finger's Angle

In the first experiment, physical input properties of the fingers, i.e. contact areas and shapes have been investigated accordingly in the context of the imprecise selection. The outcome of this study in section 5.2.2 suggests that the finger's angle of approach impacts on the variation of the fingertip contact area and shape. It may lead to a high error rate in selecting small size target elements. Prior to interaction design for the tabletop display, it is very important to know users' preference of interaction in the context of user-centered design and engineering. What kind of interaction method they really prefer on tabletop display for selection and manipulation of target elements with bare fingers. Assuming that, users preference is not considered in designing method of interaction for tabletop displays then it may lead to many user based issues as ergonomics, imprecise selection, mental workload and many unexplored issues.

Thus, the motivation is increased to find out the users' preferences related to the method of interacting with multi-touch tabletop displays either by using oblique or vertical finger touch. Ultimately, normal users have to interact with proposed target elements on displays. Thus, it is very important to know users preference through their feedback about vertical and oblique finger touch method. This study may support in establishing a base for further evaluation of the physical finger input properties on a large scale in the context of imprecise selection.

In general, the user's hand structure allows him/her to use different finger angles of approach to select target elements. Since, it is difficult to control the users' approach when interacting with the display using different finger angles. To ensure the precise interaction, researchers have classified interaction methods into two categories; they are the oblique and vertical touches. This may help in conducting the experiments in order to collect data for the design and configuration of target elements and consequently may help in achieving precision accordingly.

5.3.1 Results and Discussion

The outcome related to the specifications of the finger's angle of approach consists of three sub-sections, i.e. the users' prior experience, specification of the finger's angle and observations. These are briefly discussed as follows.

5.3.1.1 Users' Prior Experience

Figure 5.7 illustrates the outcome of a question related to the users' prior experience in using sensitive input devices. It is identified that, all users had experience of using the ATM machine and laptop touchpad. This experience users shows that these devices are commonly available in the market. For example, the ATM machines have been introduced by banks at the public places and laptop touchpads are embedded in laptop computers which are very common nowadays. It ensures that users are aware about features these technologies. These devices are in the reach of common users and it is easy for them to access digital information using their fingers accordingly

Whereas, the 16 respondents had experience in using the mobile touch screens and 4 respondents had experience in using the tablet PCs. Keeping in view, the feedback of 16 respondents represents that mobile touch screens have been common due to their low cost. Thus, the respondents are familiar about the touch enabling technologies and accessing the digital contents using their fingers. It is observed that resistive mobile touch screens detect the input through nail and stylus. Whereas, capacitive mobile touch screens detects the input using bare fingers. As far as concerned to tablet PCs, it is identified that only 4 respondents had experience of using this device. It suggests that these devices are not still common in practice of users like ATM machines, touchpads and mobile touch screens.

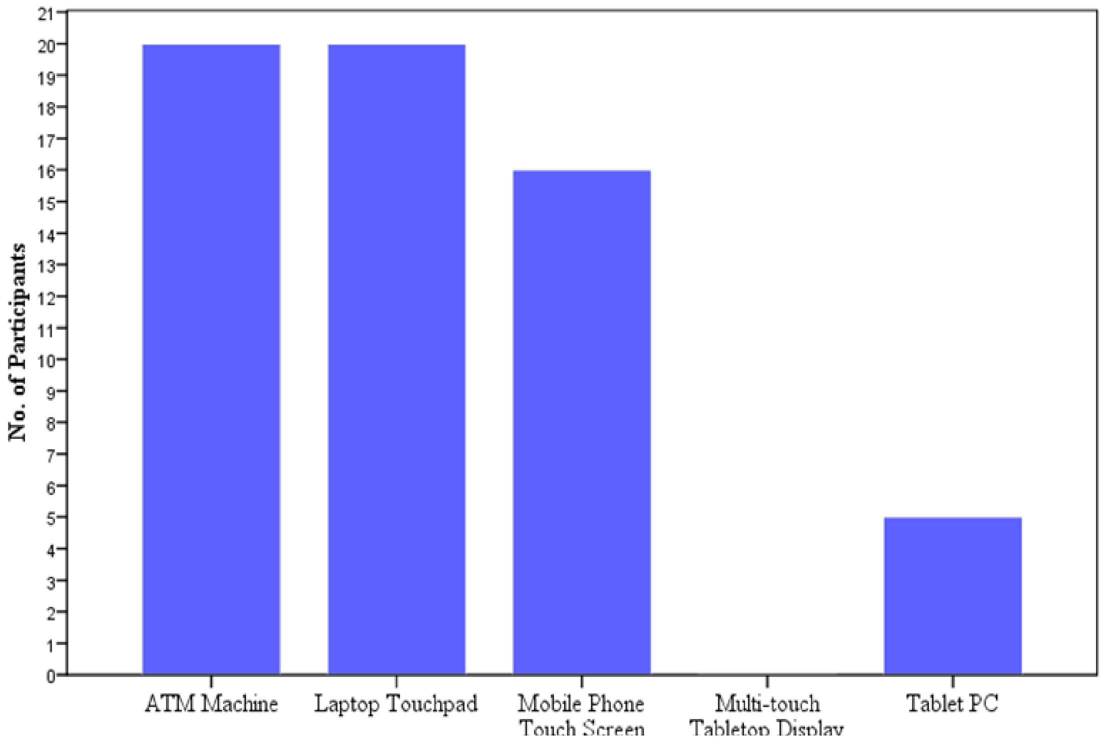


Figure 5.6: Users' prior experience related to sensitive input devices

Keeping in view the overall feedback of users, it identified that many of users have interacted with touch sensitive devices in order to select and manipulate target elements. However, it is identified that there was no any respondent who ever have used the multi-touch tabletop display. They had not experience of interacting with tabletop display to select the target elements using bare fingers.

It suggests that still multi-touch tabletop technology is still infant and growing rapidly. Recently, multi-touch tabletop display named as MS Surface has been commercialized in the market, but it too costly. The multi-touch tabletop display technology shows a great potential to be used in the offices for meeting, and in education for interactive learning games, and many other public places. It allows direct and natural interaction using bare fingers. There is no intermediary device between users and interactive displays.

In this connection, users have been informally interviewed related to the multi-touch tabletop display technology after the completion of the questionnaire. The majority of users liked the tabletop display technology due to the availability of direct and natural multi-touch interaction. However, many of respondent were asking about the orientation tabletop display and its user interface design for single and multiple users. It was very impressive question what would be orientation of target elements interface, if there would be more than two users around the table simultaneously. In addition, another question was about how the tabletop display would support different users if they want to perform different tasks simultaneously.

5.3.1.2 Specification of Finger's Angle

Although, all respondents had no prior experience in using the multi-touch tabletop display, but their overall experience of dealing with the sensitive input devices encouraged us to specify the finger's angle of approach to be used. Figure 5.8 illustrates that, 17 respondents preferred to interact with the tabletop display using a 45˚ finger angle of approach. This finger's angle of approach maintains oblique touch method.

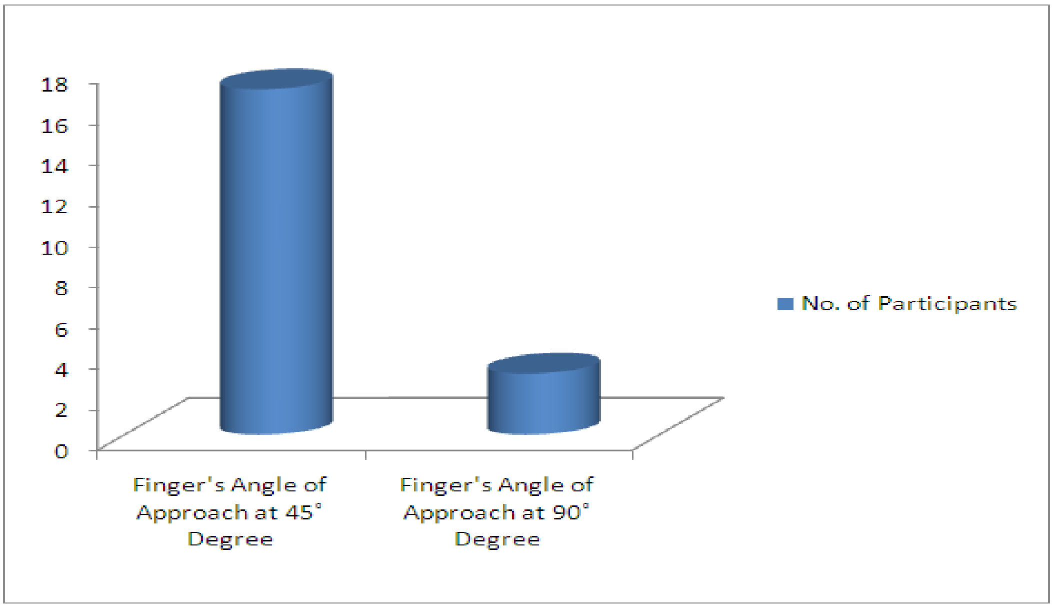


Figure 5.7: Specifications of finger's angle of approach

However, only 3 respondents preferred to interact with the tabletop display using a 90˚ finger angle of approach. This finger's angle of approach maintains the vertical touch method. Users have been informally interviewed related to specifications of finger's angle of approach on tabletop display. They responded that the vertical finger touch method is difficult to use for the scaling and rotating the digital photos on a large size multi-touch tabletop displays. Considering, physical structure of human finger it seems odd to use this approach during multi-touch interaction. Whereas, users responded that the oblique finger touch method is easy to use and allows us to select, scale, rotate and drag and drop the digital photos directly and naturally.

5.3.1.3 Observations

Since, it has been identified that the vertical finger touch maintains a 90° angle of approach during interaction on the tabletop display. It causes arm fatigue when multiple tasks are performed iteratively. Specifically, when the targets elements are placed on interactive display at long distance, then, it is difficult for users to select those elements. It is difficult to drag, rotate and scale photos frequently. It can be difficult to use for scrolling a bar, drawing a picture and selecting text. It may also produce a fingertip tendon injury due to continuous rubbing of the fingertips on the display.

In addition, it is observed that the FTIR based multi-touch tabletop display is not able to detect fingernails and styluses. It introduces a problem for those females who normally keep long nails; so, it is difficult for them to use the vertical touch method to perform multi-touch interaction. However, the vertical touch can be useful for interacting with resistive touch screens because these are able to detect the users' nails and styluses.

In contrast, it is observed that the oblique finger touch maintains approximately a 45° angle of approach during interaction on the tabletop display. It occupies more space as compared to vertical touch; therefore, it may limit the precise selection of small size target elements. Nevertheless, users can select and manipulate target elements frequently using the oblique finger touch. Users can select, zoom-in, zoom-out, rotate, drag and drop target elements naturally.

The oblique touch can help in scrolling a bar, drawing pictures, keying-in the text and making selections easily. It can mitigate the user's arm fatigue issue due to the lower degree of the angle. There is a better coupling between the fingertip and the display which may in turn lessen the chance of friction and fingertip tendon injury during continuous multi-touch interaction. In addition, it may increase the bandwidth of user's unimanual and bimanual multi-touch interaction on the tabletop display. Keeping in view the pros and cons of vertical and oblique touch, a study can be conducted in order to identify the users' performance during the selection and manipulation of the target elements. This study may enrich the direct and natural interaction using multi-touch tabletop displays.

5.4 Experiment-II: Evaluation of Physical Finger Input Properties (*Index finger*)

The outcome related to investigation of physical input properties suggested that there is variation in users' fingertip contact areas and shapes due to the physical size of the fingertips, the finger's angle of approach and the applied force. A study related to the users' preference of the finger's angle of approach suggested that users prefer to interact with the tabletop display using the oblique touch rather than the vertical touch due to the reasons as discussed in the above sections. Most importantly, it s observed throughout both studies that users normally use their index fingers to select and manipulate target elements. Considering the outcome of both studies, the motivation is increased to evaluate the users' index fingers using the oblique touch in the context of imprecise selection.

5.4.1 Results and Discussions

By analyzing the individuals' fingertips occupied contact areas, it is identified that there is a difference in the physical length and width of each individual's fingertips. As, it is discussed in the above section 5.2.2 that there is variation in individuals fingertips contact area due to exerted pressure, angle of approach and physical characteristics of fingers. The outcome of first study illustrated that fingertip size vary from person to person. If this variation exists occurs then it may increase the error rate in selecting the small size target elements.

Keeping in view the variation in size of fingertips, the scope of study has been narrow down and only focused on the index fingertip of the individuals. This study ensures that total contact area of the index fingertips does not only vary among the different age groups but also varies in the same group of population. Naturally, the fingertips are stubby in their physical structure due to the presence of soft tissue at its end joint. These distort during direct touch on the hard surface (e.g. touch display). The fingertip tissue scatters even more on the display when a certain amount of pressure is exerted by the finger. It leads to more variation in the contact area. In addition, the angle of approach (e.g. oblique touch) plays a vital role in occupying more space.

Considering the above factors, the total contact area for each group is calculated and its outcome is simulated in the graph accordingly. The five different graphs are combined and presented in Figure 5.10. Each group's graph illustrates that there is variation in the individuals' fingertip contact areas. It ensures that the physical length and width of the individuals' fingertips significantly impact on the variation of the total contact area. In addition, the pressure exerted by the user during interaction and the finger's angle of approach (e.g. oblique touch) also equally impact on the variation of the fingertip contact areas. This suggests that age factor can also be one of the major reason in the variation of fingertips size. It can be claimed that as individuals age grow then size of their fingertips grow accordingly.

In regards to age factor, it is identified that if a child is about 10 years old then he/she has small fingertips size whereas an adult who has age about 20 years old then certainly his/her fingertip size can be larger than a child. In this case, a child can select a small size target element precisely as compare to adult one. In addition, an adult's fingertip size can be small in size as compare to an old age person. There can be two factors, i.e. age and weakened muscles.

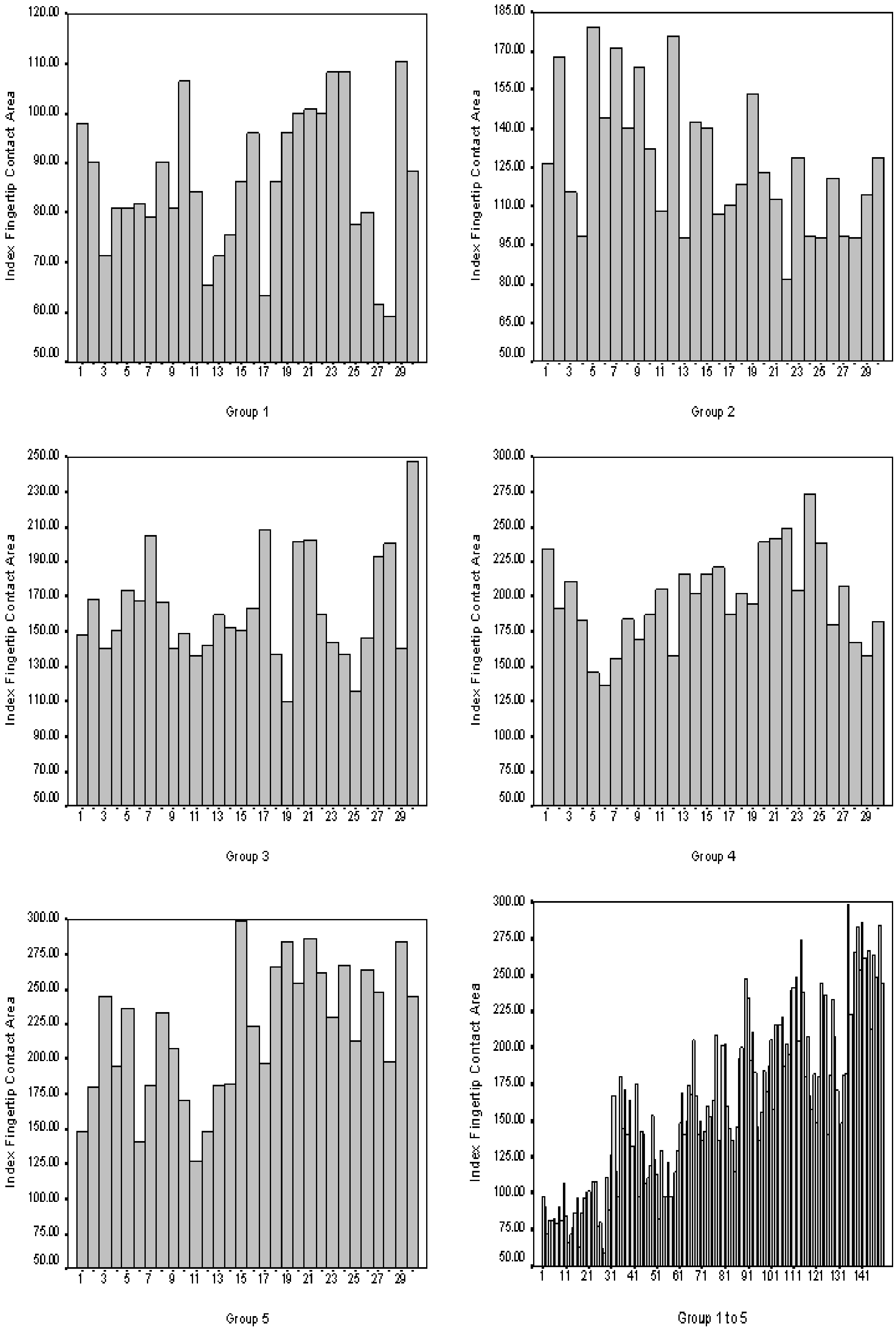


Figure 5.8: Analysis of index fingertip contact areas of different groups (*the unit of contact area is mm*^{2})

It is identified that when an old age person interact with display then his fingertips soft tissues occupies more space as compare to adults one. In this phenomenon, the fingertip pressure, its angle of approach and physical length and width are directly involved in the variation of occupied contact areas as mentioned above. Keeping in mind the variance in each group's data, it is planned to identify the overall variance in the five groups. In this regard, the imprinted data samples of all groups are simulated in a single graph as shown in Figure 5.10. It depicts that the variation in the index fingertip contact areas increases gradually group by group. Since the scope of this study has been narrowed down and only focused on the evaluation of individuals' index fingertips contact area. From this, it is extracted that the imprinted data samples of the index fingertips contact areas are not different only in each group but there is also variance among the groups.

In this study, it is interesting to know that if the target elements would have been designed and configured on sensitive displays without any investigation of fingertip contact areas and shapes then it would be very difficult to overcome the imprecise selection problem. By identifying the variation in fingertip size in each group, it is possible to fix the problem of imprecise selection. In this study, it is also observed that difference in the fingertip size suggest for user centered design interface for multi-touch displays. It may enrich the performance of users during the selection and manipulation of target elements.

5.4.1.1 Statistical Analysis of Index Fingertip Contact Areas

For further analysis of the individuals' index fingertips of the five different groups, means and standard deviations are measured with the help of the physical length, width, total area and per side area of the fingertips, and are presented in Table 5.1 Each group has different ages which are given in column 1 of the table whereas values for other related variables are shown in the next columns in the same row accordingly.

Considering the first group of participants with ages ranging between 8 – 10 years old, the mean values for physical length, width and total area of the index fingertips are calculated and found to be 9.17 mm, 9.32 mm and 85.94 mm^2 respectively. Besides this, the per side length/width mean value of the total contact area is calculated through the square root function that is found to be 9.24 mm as shown in Table 5.1. While, the standard deviation values for the physical length, width, total area and per side area are found to be 0.86 mm, 0.88 mm, 14.43 mm^2 and 0.79 mm respectively.

However, in regards to the second group of participants having ages ranging between 11-20 years old, the mean values for the physical length, width and total area of the index fingertips are calculated and found to be 11.45 mm, 10.95 mm and 126.45 mm^2 respectively. Moreover, the per side length/width mean value of the total fingertip contact area is calculated through the square root function that is found to be 11.19 mm as also shown in Table 5.1. While, the standard deviation values for the length, width, total area, and per side area are found to be 1.54 mm, 0.96 mm, 26.55 mm^2 and 1.17 mm respectively

Table 5.1: Index Fingertip Contact Areas

Different Groups Index Fingertip Size		**Length (mm)**	**Width (mm)**	**Area (mm^2)**	**Per side (Length/Width, mm)**
Group 1 (8-10 yrs)	Mean	9.17	9.32	85.94	9.24
	St Dev	0.86	0.88	14.43	0.79
Group 2 (11-20 yrs)	Mean	11.45	10.95	126.45	11.19
	St Dev	1.54	0.96	26.55	1.17
Group 3 (21-30 yrs)	Mean	13.48	11.81	159.65	12.59
	St Dev	1.72	0.82	26.22	1.03
Group 4 (31-40 yrs)	Mean	15.38	12.79	197.23	14.00
	St Dev	1.93	0.77	31.05	1.11
Group 5 (41- 50 yrs)	Mean	16.59	13.14	219.73	14.73
	St Dev	2.61	1.18	47.70	1.65

However, considering the third group of participants having ages ranging between 21-30 years old, the mean values for the physical length, width and total area of the index fingertips are calculated and found to be 13.48 mm, 11.81 mm and 159.65 mm^2 respectively. Moreover, the per side length/width mean value of the total fingertip contact area is calculated through the square root function that is found to be 12.59 mm as also shown in Table 5.1. While, the standard deviation values for the length, width, total area, and per side area are found to be 1.72 mm, 0.82 mm, 26.22 mm^2 and 1.03 mm respectively. Similarly, mean and standard deviation values for the physical length, width and total area of the index fingertips for the rest of the two groups are calculated accordingly and are also presented in Table 5.1.

This study has discovered the mean and standard deviation values measured through the physical length and width of the individuals' index fingertips using the oblique touch. The identification of these values establishes the strong foundation for the design and configuration of the target elements for the sensitive displays. There is no need of assuming the size of target element for conducting the experiments related to precise selection. Although, there is variation in the individuals' fingertip contact areas but it is identified how much variation exist. It may help in restricting to design target element below or beyond the actual size of users' fingertips. Following the obtained results, the appropriate design and configuration of target elements is possible for all type sensitive displays. It may enrich the precise selection of target elements during direct multi-touch interaction.

Thus, it is good to know the overall variance in the fingertip contact areas of each group; however, yet to be identified is the mean difference among the various groups. Thus, it is planned to analyze the mean differences among all the groups. All these mean values are simulated and presented in Figure 5.11. It describes a variance in the mean values of the total contact areas of all the groups. It is also depicts that the mean values of group 3 and 4 are seemingly closer to each other. In addition, the mean values of group 4 and 5 seem to be even closer to each other accordingly. From this, it can be perceived that as these groups of people reach at their age range in between 30 to 50 years old then their body growth gradually decreases and it is maintained accordingly. This can be a reason of obtaining the closer values of their fingertips to each other.

The Figure 5.11 illustrates that in groups 1 and 2 people have smaller size of fingertips as compare to the groups 3, 4, and 5. This graph clearly suggesting that age factor introduces the variation in fingertip contact areas. Thus, it is very important to consider age factor before designing and configuring the target elements for touch screens. In addition, it can be considered in designing the touchpad buttons for mobile touch screens. Keeping in view the design and implementation of the target elements based on the obtained results, a comparative study can be conducted for identifying the accuracy and performance of adults and older age people.

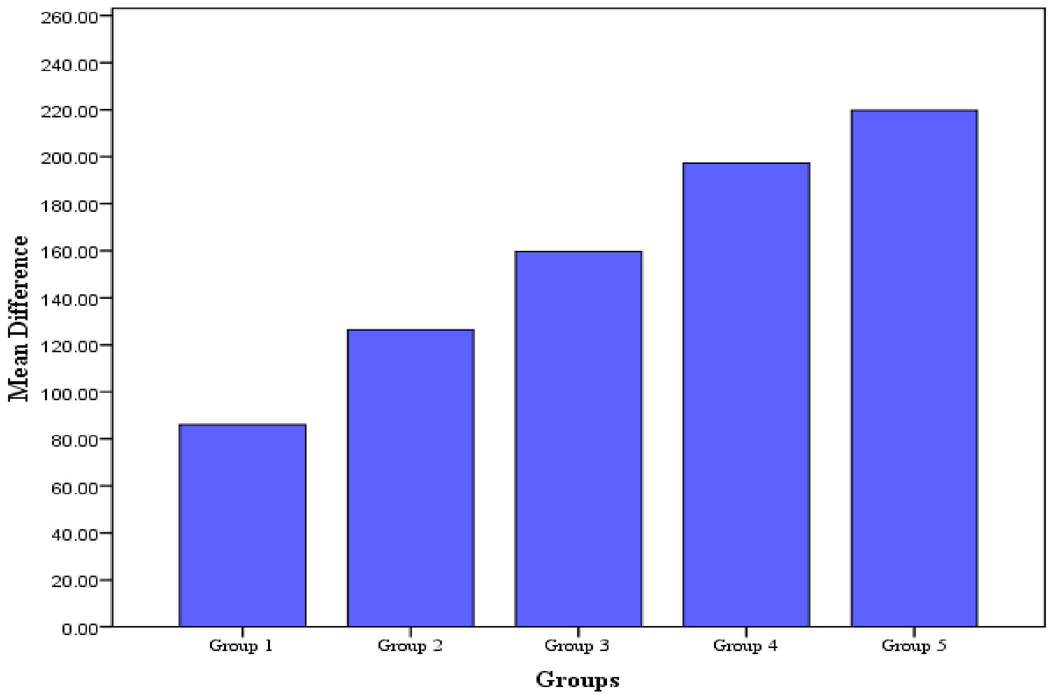


Figure 5.9: The mean analysis of different age groups

It is good to discover the mean difference among each group through analyzing the graph but it has yet to be confirmed whether these means are significantly the same or different among the groups. In this regard, a statistical test called a one-way analysis of variance is planned to be applied in order to identify the significant difference.

However, before confirming the significant variance among all the groups, it is important to know the outliers in their data sets. It is important to know whether the medians of different groups appear to be different or the same. In addition, it is also important to identify; if there are outliers in each group's data set and a constant variance in the median values of different groups, then analysis of the variance may give incorrect results. In this regard, a box plot technique is used to address these issues in the data sets of different groups accordingly. It is considered as a pre-requisite for performing the analysis of variance.

5.4.1.2 Data Analysis Using a Box Plot

The box plot technique is useful to quickly and easily compare two or more data sets or to identify the overall pattern of the data sets. It has the potential to summarize the more detailed data in one graph which is accordingly useful for the analysis. Keeping in mind these features, the box plot technique is applied on the data sets of the index fingertips of the five different groups and subsequently, their box plots are obtained as shown in Figure 5.12.

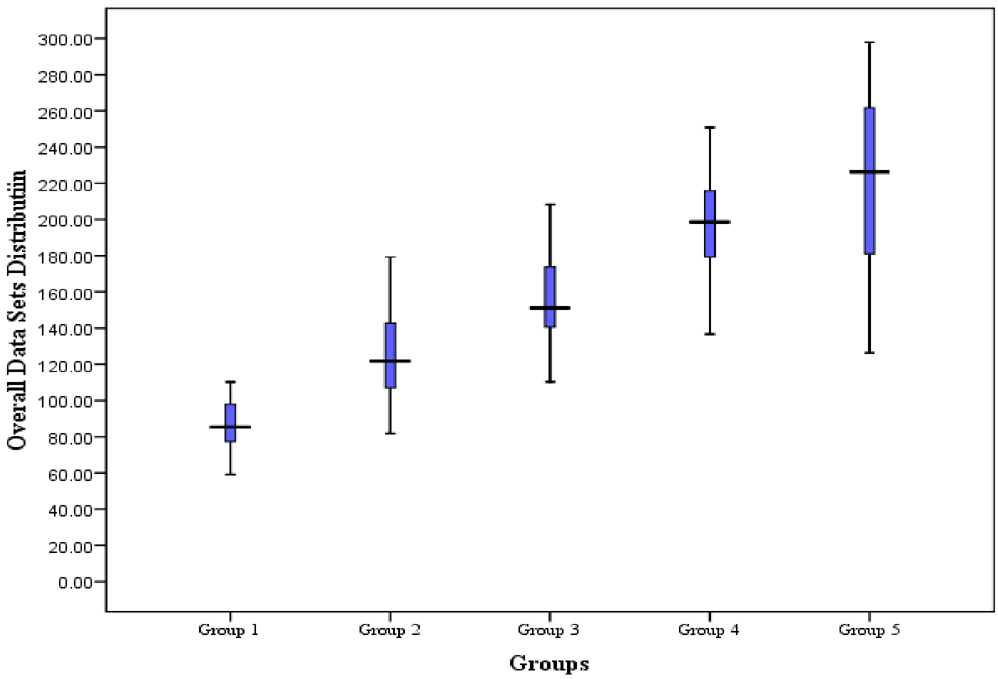


Figure 5.10: Overall data set distribution of the different groups

Each box in Figure 5.12 represents the middle 50% of the distributed data and a line inside the box represents the median value of that data. In addition, the upper and lower ends of the box are hinges (upper and lower quartiles) that illustrate how that data is positively and negatively distributed in a group.

Considering the box plot of group 1in which a line inside the box demonstrates that the middle value is found to be (Median = 85.26 mm) and the lower hinge of the box describes that the data is a little bit negatively skewed. Whereas, a line inside the boxes of groups 2 and 3 describes that their middle values are found to be (Median =121.80 mm, Median =151.20 mm) and the upper hinges of those boxes demonstrate that the data is a little bit positively skewed. Similarly, for groups 4 and 5, the middle values are found to be (Median = 198.67 mm, Median = 226.40 mm) and the lower hinges of both groups' boxes depict that their data is negatively skewed.

By analyzing all box plots, it is concluded that there is no outlier in the data set of any group which confirms the data accuracy. In addition, the median values of each group are different and there is no constant variation. Moreover, the box plot testing establishes a suitable ground for applying the one-way analysis of variance.

5.4.1.3 Hypothesis Validation

Although, it has been discovered through descriptive statistics that there is difference in individuals' fingertip contact areas of five different groups but, it is still not confirmed that, is there any significant difference among these groups accordingly. Thus, in order to identify and validate it, a null hypothesis is formulated and described as follows.

H_0: There is no significant difference between the individuals' fingertip contact areas

For confirming this hypothesis, the data sets of the total contact areas of each group are taken and a statistical test named one-way Analysis Of Variance (ANOVA) is used accordingly. The descriptives table (see below) is generated which provides a useful statistical information including the No. of samples, mean, standard deviation, standard error, and the upper and lower bounds at 95% confidence intervals for dependent variables (Index fingertip Contact Area) for every group (Group 1, Group 2, Group 3, Group 4, and Group 5) accordingly.

Table 5.2: Descriptive statistics of the different groups

Index Fingertips	No. of Samples	Mean	Std. Deviation	Std Error	95% Confidence Interval for Mean		Min:	Max:
					Lower Bound	Upper Bound		
Group 1	30	85.94	14.43	2.63	80.55	91.33	59.13	110.21
Group 2	30	126.45	26.55	4.85	116.54	136.36	81.84	179.34
Group 3	30	159.65	26.22	4.79	149.86	169.45	110.25	208.28
Group 4	30	197.23	31.05	5.67	185.64	208.83	136.64	250.71
Group 5	30	219.73	47.70	8.71	201.92	237.54	126.44	297.96
Total	150	157.96	57.43	4.69	148.69	167.22	59.13	297.96

Consequently, the mean, standard deviation, standard error, lower and upper bounds, and the minimum and maximum values of each group in the descriptives table verify that there is variance in the individuals' index fingertip contact areas in each group. The individuals' fingertip contact area values do not overlap each other at a 95% confidence level. It confirms that each individual has a different fingertip size in physical length and width. Notably, the descriptives table illustrates that the mean values of the five groups are different. It proves the existence of variance in the overall population of samples of the index fingertip contact areas at a 95% confidence level.

Table 5.1 shows that there is variance in the index fingertips contact areas of individuals in same and different groups but it is also identified that how much variation exists. It is identified that there is mean, minimum and maximum, upper and lower values of each groups that also introduces a possibility of the design and implementation of the target elements for sensitive displays accordingly. The different types of studies can be conducted in order to ensure the precise selection of target elements.

Nevertheless, the descriptive statistics in the above table does not tell us the significant difference between the mean values of the five different groups. In this regard, the main ANOVA table is illustrated (see below) and its output is interpreted accordingly. The ANOVA table provides useful information about the effects among the different groups (due to experimental effects) and within group effects (this is the systematic variation in data). The row labelled with 'between groups' provides an overall experimental effect on the data (the effect of different groups on the variation of the index fingertip contact areas). In this way, the sum of the square model (SSM = 346233.171) represents the total experimental effect whereas the mean square model (MSM = 86558.293) represents the average experimental effect accordingly.

Table 5.3: Significant difference in index fingertip contact areas of different groups

Index Fingertips	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	346233.171	4	86558.293	89.418	.000
Within Groups	140362.526	145	968.017		
Total	486595.697	149			

In addition, the row labelled with 'within the group' provides details of the unsystematic variation that exists within the data (the variance due to natural individual differences in physical length and width of the individuals' index fingertips). In this regard, the residual sum of squares (SSR = 140362.526) demonstrates the overall unsystematic variation within the group data whereas the residual mean square (MSR = 968.017) shows the average amount of unsystematic variation.

Hence, the column labelled with F in the table represents a certain ratio also called the F-ratio which is used to test whether the means of the different groups are significantly different or the same based on their data. For identifying the experimental effect in these data, the F-ratio is obtained by dividing the mean square for the effect by the mean square for the residual. Thus, the degrees of freedom are used to assess the F-ratio, in this respect the F-ratio are the degrees of freedom for the effect of the model (dfM = 4) and the degrees of freedom for the residual of the model (dfM = 145) accordingly.

Whereas, the column labelled with sig. in the table shows how likely the F-ratio would have occurred by chance. Usually, scientists use a ‘cut of point of’ or p-value which is 0.05 as the criterion to find the statistical significance. If the observed significance value is less than the p-value 0.05, then it can be claimed that there is significant difference between the means of the different groups.

From the ANOVA table, it is analyzed that the F-value is large which shows that distribution of data samples of among the five different groups do not overlap each other and their p-value is less than 0.05.

Hence, the analysis shows that there is a significant variance among the mean values of the different groups as determined by the one-way ANOVA, $F (4, 145) = 89.418$, $p<.000$).

According to above statement, the null hypothesis is rejected and it is claimed that there is at least one significant mean difference. It justifies the overall significant variance among the groups but there may be more. Thus, it is still to be known and determined as to which of the means are significantly different from each other. In this regard, the Scheffe’s post-hoc test is used to identify and verify where significant differences lie between each group accordingly. It is the technique most commonly used over others to find significant differences between the means of different groups. This test is more conservative and capable of pair-wise comparison of the multiple means of different groups simultaneously.

Table 5.4 illustrates the means difference in the third column that is reported with an asterisk on the upper right side of each group. In addition, the column labelled with sig. reports that all means of the different groups are significantly different from each other at the 0.05 level and 95% confident interval. However, this table also indicates that the means of groups 4 and 5 are not significantly different from each other. From this, it can be understood that the age factor influences the variance in their fingertip contact areas.

Table 5.4: Scheffe's post-hoc test for multiple comparisons for means of different groups

Index Fingertip		Mean Difference Between Groups	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Group1 (85.94)	126.45	-40.50933*	8.03334	.000	-65.5757	-15.4429
	159.65	-73.71633*	8.03334	.000	-98.7827	-48.6499
	197.23	-111.29600*	8.03334	.000	-136.3624	-86.2296
	219.73	-133.79333*	8.03334	.000	-158.8597	-108.7269
Group2 (126.45)	85.94	40.50933*	8.03334	.000	15.4429	65.5757
	159.65	-33.20700*	8.03334	.003	-58.2734	-8.1406
	197.23	-70.78667*	8.03334	.000	-95.8531	-45.7203
	219.73	-93.28400*	8.03334	.000	-118.3504	-68.2176
Group3 (159.65)	85.94	73.71633*	8.03334	.000	48.6499	98.7827
	126.45	33.20700*	8.03334	.003	8.1406	58.2734
	197.23	-37.57967*	8.03334	.000	-62.6461	-12.5133
	219.73	-60.07700*	8.03334	.000	-85.1434	-35.0106
Group4 (197.23)	85.94	111.29600*	8.03334	.000	86.2296	136.3624
	126.45	70.78667*	8.03334	.000	45.7203	95.8531
	159.65	37.57967*	8.03334	.000	12.5133	62.6461
	219.73	-22.49733	8.03334	.104	-47.5637	2.5691
Group5 (219.73)	85.94	133.79333*	8.03334	.000	108.7269	158.8597
	126.45	93.28400*	8.03334	.000	68.2176	118.3504
	159.65	60.07700*	8.03334	.000	35.0106	85.1434
	197.23	22.49733	8.03334	.104	-2.5691	47.5637

*The mean difference is significant at the 0.05 level.

Keeping in mind the overall empirical analysis in this chapter, it is concluded that there is significance difference in the individuals' index fingertip contact areas. This study suggests that if the size of the target elements is smaller than the size of the fingertips, then it may increase the error rate of selecting these elements during the direct touch input. If the target size is similar to the size of the fingertips, then a high precision rate can be achieved as well as direct mapping. In addition, if the size of the target elements is larger than the fingertips, then these elements would occupy more space on sensitive displays, specifically on mobile phone touch screens. Table 5.4

illustrates the overall report of Scheffe's post-hoc test for the means of differences between the different age groups.

In this study, the obtained results and their analysis establish a strong foundation for the design and implementation of target elements for sensitive displays. In addition, the obtained results suggest that the different size of target elements should be designed and implemented accordingly. After that, a large scale study can be conducted in order to measure the performance of users during interaction and precise selection using Fitts law.

5.5 Comparison

In order to accomplish the precise selection, different studies have been conducted. In which, it is argued and discussed that users cannot reliably acquire the target elements on the touch screens if they are smaller than certain size of fingertips. However, the large size target elements occupy more space on the touch screens and specifically more problematic for small size touch screens (e.g. mobile devices). It is identified through literature review that the different size of target elements have been proposed based on assumptions rather than the evaluation of physical finger properties and conducted the experiment related to precise selection (Hall, et al., 1988) (Hrvoje Benko, et al., 2006) (Vogel & Baudisch, 2007). Although, the existing findings support in accomplishing the precise selection of target elements on the touch screen during touch input. Despite of that, it was very important to propose the target elements based on the evaluation of physical finger properties.

Therefore, few studies have been conducted to measure users fingertips contact area and shape (Hall, et al., 1988) (Vogel & Baudisch, 2007) (Wang & Ren, 2009) (Wang, et al., 2009). In these studies, different authors have identified different values for target elements size e.g. 26mm (Hall, et al., 1988), 11.5mm (Wang & Ren, 2009), and 10.5mm (Vogel & Baudisch, 2007). The findings of these studies significantly contribute in proposing the target elements and assist in accomplishing the precise selection during direct touch input.

Based on the overall findings and observations of these studies, it has been suggested that the minimum target elements size should be anywhere between 10.5mm (Vogel & Baudisch, 2007) and 26mm (Hall, et al., 1988) per-side. Recently, another study is conducted (Wang, et al., 2009) in which different mean values of fingertip contact areas are identified based on the vertical and oblique touch. It is reported that contact area of fingertip is significantly different during vertical and oblique touch. Pertaining to that, the mean contact area during vertical finger touch is found between 5.3mm and 5.7mm (per-side). Whereas, the mean contact area during oblique finger touch is found between 12. 8mm and 17.1mm (per-side).

However, the findings of a study (Wang, et al., 2009) involve only 8 participants and another study involve only 12 (Wang & Ren, 2009) participants, having age ranged from 26-37 years old. So, the obtained findings cannot be generalized for all users. These studies lack in determining that the proposed values for target elements are given based on users' five fingers or any specific finger (e.g. index finger). In addition, these studies lack in identifying that which factors affect on the variation of fingertip contact area and shapes, and how much variation exists in the fingertips contact area.

Realizing the importance of appropriate size of target element for obtaining the precise selection, a motivation is increased to conduct a study for evaluation of physical finger properties at large scale. In this study, the two different experiments are conducted. In the first experiment, users' five fingers focused in which users' five fingers are focused. However, in the second experiments, only users index finger is targeted for evaluation of fingertips contact areas and shapes. This experiment involves 150 volunteer participants and these participants have been categorized based on their age as described in Table 5.1 rather than ethnicity, particular region, and gender.

Keeping in view the outcome of first experiments, it is identified that there is variation in fingertip contact area and shape. This claim of our study enriches and confirms the finding of existing studies (Wu & Balakrishnan, 2003) (Wang & Ren, 2009) (Wang, et al., 2009). This study also identifies the factors affecting in the variation fingertips contact area and shape.

Considering the outcome of second experiment of this study, different values have been identified and proposed for the size of target elements as given in Table 5.1. More specifically, it is identified that the minimum size of target element for touch screens should be 9.24mm (per-side) and maximum size of target should be 14.73mm (per-side). Based on the overall findings of index fingertips contact area, it is identified that size of target element should be 12.5mm (per-side). It may enrich the precise selection during direct touch input. However, it is observed that the findings of our study also cannot be generalized likewise to other studies. The obtained results can be influenced, if the different studies would be conducted on the gender, ethnicity, and region basis.

Following the outcome of this study, it is identified our findings are different from existing studies (Hall, et al., 1988) (Vogel & Baudisch, 2007) (Wang & Ren, 2009) (Wang, et al., 2009). The difference in findings can be due to age of participants and index fingertip is focused only. However, it is also difficult to claim that our finding are significantly different from studies conducted by (Vogel & Baudisch, 2007) (Wang & Ren, 2009) (Wang, et al., 2009), except a study conducted by (Hall, et al., 1988). Because, our proposed mean value of overall data is 12.5mm (per-side), which is closer to proposed values other studies, i.e. 11.5mm (Wang & Ren, 2009), and 10.5mm (Vogel & Baudisch, 2007).

Meanwhile, it is found that the obtained findings of this study enrich the existing body of knowledge of physical finger input properties, size of target elements, and precise selection. Based on the findings of existing studies and our study, the target elements can be designed and implemented for touch screens. After that, a comparative study can be conducted in order measure precise selection during direct touch input.

5.6 Summary

In this chapter, three main studies have been conducted and their results are described and discussed accordingly. The first part of this chapter introduced the investigation of physical finger input properties in which fingertip blobs and shapes are analyzed.

This analysis showed that there is a difference in fingertip contact areas and the shapes of individuals' fingertips. It also depicts that individuals' thumbs occupies more space than the rest of the fingers. Moreover, it is concluded that the physical size of the fingertips, angle of approach and exerted pressure reasoned to produce variation in their contact areas and shapes.

The second part of this chapter introduced the specifications of the finger's angle of approach in which the users' prior experience in using sensitive input devices is analyzed. In addition, the users' preference of the angle of approach (e.g. oblique and vertical touch methods) for interacting with the multi-touch tabletop display is examined. This study shows that, users have experience in using some form of sensitive input devices but no one has experience in using multi-touch tabletop displays. The users prefer to interact with the display using the oblique touch method rather than the vertical. Moreover, this analysis establishes a foundation for the evaluation of physical finger input properties on a large scale using the oblique touch method.

The third part of this chapter introduced the empirical evaluation of physical finger input properties. In this study, only the index fingertips of the different groups are focused on to examine the contact areas and shapes. It is investigated to find out if there is a difference in the individuals' fingertip contact areas and shapes in each group. It is validated that there is a significant difference in the overall data of the different groups. In addition, it is also validated that the means of the different groups are significantly different from each other.

CHAPTER 6

CONCLUSIONS

6.1 Overview

The multi-touch sensitive displays offer direct and natural interaction in which users can select target elements using their fingers. However, some issues have been found when using these displays. One such issue is that, a fat finger creates imprecise selection of the small size target elements in direct multi-touch input. Considering this issue, it is aimed to investigate the physical finger input properties, i.e. contact area and shape in order to contribute towards a more precise selection.

In order to investigate the physical finger input properties, a multi-touch tabletop display is designed and developed using the FTIR sensing technique. It is tested according to its functionality. It allows users to select and manipulate target elements using their fingers directly and naturally. Consequently, the multi-touch tabletop display is used to investigate physical finger input properties accordingly.

In the first experiment, results show a variation in the individuals' fingertip contact areas and shapes. The results also suggest that the individuals' thumbs occupy more space as compared to rest of the fingertips. Moreover, it has been identified that fingertips occupy more contact area using the oblique touch method. The outcome also illustrates that the fingertips form different shapes according to their physical characteristics; these shapes are normally found to be circular and elliptical. Additionally, finger's angle of approach and the pressure exerted influences the variance. Considering these issues, motivation is increased to conduct a study to specify the finger's angle of approach using the tabletop display. The outcome related to specification of finger's angle of approach shows that the majority of users preferred to interact with the tabletop display using the oblique touch method rather than vertical touch. Users perform multi-touch interaction easily using the oblique touch. This study provided a suitable foundation to evaluate the physical finger input properties of *index finger* on a large scale.

In the second experiment, results show that there is a variance in the individuals' index fingertip contact areas and shapes among members in each group. It is identified that the physical length and width of the individuals' fingertips, angle of approach, and the pressure exerted all have an influence on the variance. It is discovered that the age of the individuals' in each group can be another factor for obtaining the variation. The undertaken statistical analysis validates that there is a significance difference in the individuals' fingertip contact areas of the five different groups. In addition, it is also validated that there is a significant variance in each group; but the difference is not significant in groups 4 and 5 only. With this study, it is confirmed that the physical size of the fingertips varies from person to person and produces the variation in the contact area and shape. This variance in the size of fingertips may increase the imprecise selection of target elements in direct multi-touch input.

6.2 Contributions

This study contributes as follows,

Multi-touch Tabletop Display

- Multi-touch tabletop display is developed based on the proposed architecture. It detects the multi-touch input and allows users to select and manipulate the target elements.

- It supports in investigating the physical finger input properties, in identifying the users' prior experience, if any, and also in specifying the finger's angle of approach.

- It can be used for further experiment related to precise selection, user interface design, and multi-touch interaction techniques.

Evaluation of Physical Finger Input Properties

- Investigation of individuals physical finger input properties confirms the difference in their contact area and shapes.

- Specification of users' finger's angle of approach and their prior experience of using sensitive input devices laid foundation for the evaluation of physical finger input properties of index finger on a large scale.

- Evaluation of individuals' physical input properties of *index finger* also confirms the variation in their fingertip contact area as well as help in achieving the specific values as mentioned in fifth chapter. These values assist in design and configuration of appropriate size of target elements that may enrich precision accordingly.

6.3 Recommendations

On the basis of the results and analysis obtained in 5th chapter, some recommendations have been made in order to enrich precise selection of the target elements.

- Our experience and results suggest that the developed multi-touch tabletop display is lacking in its ability to sense multi-users' input. It can be improved by embedding infrared light sources inside the edges of the acrylic sheet and the high frame rate camera.

- Fingertips normally form circular and elliptical shapes. Thus, the design and configuration of the target elements should be according to those shapes.

- Results provide the minimum, maximum, median and mean values of the physical length, width, total contact area, and per-side (length/width) of the index fingertips. In this regard, user interface designers can design and configure the different sizes of target elements accordingly.

- Using the mean value of the first group only, the square size of target elements should be length 9.24 mm x width 9.24 mm. Similarly, for the rest of the groups, the square size of the target elements should be according to their mean values.

- In general, the mean value of all the groups suggests that the square size of the target elements should be length 12.56 mm x length 12.56mm. This may enrich the precise selection in direct multi-touch input.

6.4 Limitations of this Study

There is no scientific study undertaken by humans that comes without limitations. Similarly, this study also has some limitations which are described as follows.

- In this study, results are obtained based on the age so these results may be influenced if the study would be conducted based on the male and female classification.

- In addition, the obtained results may be influenced if the study would be conducted based on the different regions and ethnicities.

6.5 Future Work

- Throughout this study, some research questions have been raised, i.e. "What are the capabilities of multi-touch pads, multi-touch displays, and multi-touch tabletop displays?" and "How can these displays be used extensively for single user and multi-user multi-touch interaction?"

- Users' satisfaction can be measured using the desktop computer, single touch display, multi-touch display, and multi-touch tabletop display.

- Based on the author's recommendations, different sizes and shapes of target elements can be designed and configured to identify a high precise selection in direct multi-touch input. After that, users' satisfaction, performance, and mental workload can also be measured by performing the single touch and multi-touch tasks.

- In addition, target elements can be designed and implemented using different shapes, sizes and colors to identify the satisfaction of normal and color blind users.
- The fingertip as a text highlighter can be designed and implemented for precise selection.

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APPENDIX A

QUESTIONNAIRE

This survey is a part of research work titled as "evaluation of physical finger input properties on the multi-touch tabletop display".

DISCLAIMER: Information gathered from this questionnaire will strictly be confidential. Entire information will be used for research purposes only and will not be shared with third party under any circumstances.

Participant #: _____

Gender (circle one): Male Female

Age: ______

1. Please select the following touch sensing input devices that you have been used in the past.

☐ Laptop Touchpad ☐ ATM Machine ☐ Tablet PC

☐ Mobile Phone Touch Screen ☐ Multi-touch Tabletop Display

2 Please select the finger's angle of approach that you prefer to interact with multi-touch tabletop display.

☐ 45° Degree ☐ 90° Degree

Thank you for your cooperation.