Empirical Evaluation for Finger Input Properties In Multi-touch Interaction

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ABSTRACT

Current multi-touch interaction techniques typically only use the x-y coordinates of the human finger's contact with the screen. However, when fingers contact a touch-sensitive surface, they usually approach at an angle and cover a relatively large 2D area instead of a precise single point. In this paper, a Frustrated Total Internal Reflection (FTIR) based multi-touch device is used to collect the finger imprint data. We designed a series of experiments to explore human finger input properties and identified several useful properties such as contact area, contact shape and contact orientation which can be exploited to improve the performance of multi-touch selecting and pointing tasks. Based on the experimental results, we discuss some implications for the design of human finger input interfaces and propose several design prototypes which incorporate these implications. A set of raw data and several concrete recommendations which are useful for the research community are also presented.

Author Keywords

Multi-touch technique, finger input property, shape, area, orientation, empirical evaluation

ACM Classification Keywords

H.5.2 User Interfaces: Input devices and strategies

INTRODUCTION

Multi-touch is a novel human computer interaction technique in current HCI. Since the advent of the iPhone series, many people have begun to appreciate the multi-touch technique. Direct use of the bare hand as an input device is an attractive method for providing natural human-computer interactions. Compared to traditional touch techniques, the multi-touch technique allows the user to perform complex manipulations using two fingers, or even ten fingers simultaneously.

However, there are a few distinct drawbacks which limit the application of multi-touch technology. Albinsson and Zhai [1] reported that the occlusion of screen data caused by the fingers and the hand, very low selection precision and arm fatigue were significant limitations of touch devices. These drawbacks need to be overcome by new multi-touch techniques.

To enhance the usefulness of interfaces incorporating multi-touch techniques and to overcome the drawbacks mentioned above, we explore a wide range of finger input properties that are capable of controlling targets, i.e., it is likely that we can control computers with more natural and more comfortable gestures. This kind of study will, in turn, need to be guided by a thorough understanding of finger input properties and abilities as they relate to touch. Figure 1 shows the properties of the fingers in multi-touch techniques: contact area, shape, orientation. Considering the initial discussion of Forline et al. [8], we can further investigate these properties, which may help to overcome current drawbacks and improve the interactive ability of end users, in vertical touch and oblique touch gestures.

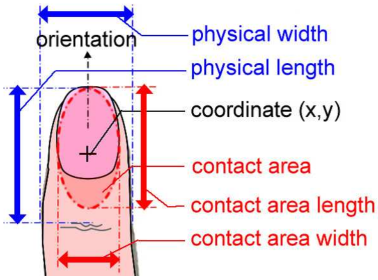

Figure 1. Available finger input properties that may be adopted by multi-touch designers.

Based on a survey of earlier studies, we concluded that current multi-touch techniques do not fully exploit the characteristics of the human hand or fingers. The finger's function in currently available multi-touch interfaces is merely to position the cursor and to click events. But, in fact, the human hand is a complex mechanism. A total of 23 degrees of freedom (DOF) have been identified through medical and anatomical analysis [2]. When one finger contacts the touch panel, the multi-touch device can only output the contact area coordinates (x, y) of the flat (2D) surface. Due to the limitations of fixed 2-D touch screen surfaces, the actual number of DOF is reduced to ten in the condition where five fingers are used simultaneously. This decrease in the DOF number seriously reduces the number of gestures available to interface designers.

Moreover, arm fatigue is caused by two factors: one is con-

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tinual tapping; the other is long-distance movement of the hand across the touch screen. Users are required to tap and move their hands on a screen to generate relevant events such as movement and click events in order to guarantee compatibility with traditional graphical user interfaces (GUIs). Additionally, current multi-touch techniques only adopt variations in the points of contacts to generate recognizable events. For example, the movement of two fingers in opposing directions triggers the "Zoom" function in some common applications.

RELATED WORK

We refer to earlier literature and investigate the use of finger input properties in touch and multi-touch techniques. We then analyze and sort all the input properties of fingers into four aspects and illustrate them in Table 1. The four aspects are position, motion, physical and event properties.

Input Property	Finger Property	Application State
Position property	Coordinate value (x, y)	Widely used, firstly studied by Buxton [5] [6] and Lee [14]
Motion property	Velocity	First adopted by Tuio protocol [14]
	Acceleration	
Physical property	Size of Contact Area	Partially used, i.e., SimPress [4] in the study of Benko
	Shape of contact area	Rarely used [26]
	Orientation	Never used
	Pressure	Used, Pressure Widget [18]
Event property	Tap	Commonly used
	Flick	Used [19]

Table 1. Classification of human finger properties.

Position property

The important advantage of touch techniques is that the bare finger can directly operate on the touch screen without other intermediary devices. The contact position of the finger is the first property considered in widget design. Most commercially available touch screen devices in use today are capable of detecting and tracking a single point on the touch panel of the device. With the recent emergence of many multi-touch prototype devices [7] [10] [14] [20] [22] [25] [24], research on multi-finger and multi-hand touch interactions has increased [17] [25] [24] [27]. In order to ensure compatibility with traditional GUIs and to permit the sharing of the same interfaces (e.g., a cursor, drag and drop technique and click action), the center point of each contact area is often used as the cursor position.

While touch screens offer direct manipulation, they do have their limitations. The user's finger, hand and arm can occlude a significant area of the screen that may lead to low selection precision when pointing at targets that are smaller than finger width [1]. Hall et al. [9] investigated the effects of various factors on touch-screen performance. They reported that accuracy varied from 66.7% for targets of 10 mm per side, to 99.2% for targets of 26 mm per side, and that accuracy was maximized once targets were approximately 26 mm per side. But in that study, only the index finger was measured.

Due to the lack of precision [1], there have been significant studies in the area of precise selection. Potter et al. [17] explored a set of strategies for high-precision touch-screen pointing and presented the "Take-Off" technique. The user is capable of controlling a cursor which is located slightly above the finger. In this method the target is selected by releasing the finger from the surface. Albinsson and Zhai [1] compared Potter's approach with the traditional zoom-pointing method and two new interaction techniques: cross-keys and precision-handle. Vogel and Baudisch [23] presented "Shift", a technique for single-touch displays that addressed the problems of the Take-Off technique, not by offsetting the cursor, but by showing a small offset callout that displays a copy of the area under the finger with its cursor. The callout is presented automatically when the finger is determined to occlude a sufficiently small potential target, and, in some variants, the small portion of the display in the callout is zoomed for easier selection.

Motion property

The movement properties of the human finger have been deeply studied in the area of gesture recognition. Apple has filed a patent called "Multi-touch Gesture Dictionary" [3] for iPhone 3G. The dictionary entries include a variety of motions and may take the form of a dedicated computer application. Kaltenbrunner et al. [13] presented the Tuio protocol to meet the requirements of tangible user interfaces for tabletop devices. Tuio is a simple yet versatile protocol that defines the common properties of controller objects on the table surface as well as of finger and hand gestures performed by the user. The movement vector and motion acceleration are adopted by the Tuio protocol.

Physical property

The initial investigation of the use of pressure in user interfaces was presented by Herot and Weinzapfel [11]. They explored the ability of the human finger to apply pressure and torque to a computer screen. Pressure Widget [18] and the subsequent studies of Ramos explored the use of the continuous pressure sensing capabilities of styluses to operate multi-state widgets. Contact area and pressure were studied by Benko et al. [4]. They used the rocking and pressing gestures of the tracked finger to trigger "click" events on a vision-based tabletop.

Forlines et al. [8] indicated that two different finger contact postures, vertical contact and oblique contact, generate different contact area shapes. These differences cause different selection error rates. Their study only reports the difference between the two gestures but there is no follow-up discussion about target selection precision or the usability of the two gestures.

Event Property

Finger tapping is typically adopted to simulate the mouse "click" event. In recent studies about natural gestures, Reetz et al. [19] presented the "Superflick" technique for long-distance object placement on digital tables. The Superflick technique simulated the natural object sliding gesture of the human hand. They designed and evaluated two tabletop interaction techniques that closely mimic the sliding of an object across a table.

In summary, our review indicates that while there is a rich body of literature on finger input properties, there has not been a systematic investigation into the full range of human finger input properties, especially regarding contact shape and finger orientation. Even the currently adopted finger properties, such as coordinate values and contact area, still contain a lot of unexplored issues. Thus, this is an area that is ripe for further research.

EXPERIMENT DESIGN

Goals

The objective of this study is to investigate the potential of human finger input properties. This includes determining the real precision of target tapping in vertical touch and oblique touch gestures, variations in the finger's contact position when tapping, variations in the center point of the finger's contact area in different gestures and variations in finger orientation. An evaluation of the utility of these properties will determine whether they can be integrated into the design of natural gestures in multi-touch techniques.

Apparatus

In order to observe all possible finger input properties on a two dimensional flat panel, we adopted the technology of Han [10] and made a Frustrated Total Internal Reflection (FTIR) based on a multi-touch widget. The touch panel was a transparent acrylic panel, which internally reflects the IR-light. Infrared LEDs were installed along the edge of the acrylic, and infrared light was introduced edge-wise into a platen waveguide.

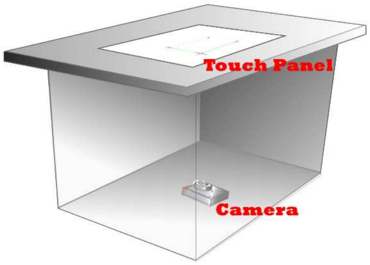

Figure 2. FTIR based multi-touch prototype.

A standard A4 (210 mm × 297 mm) sheet of white paper which was printed as an operational interface (see Figure 2) by color laser jet was firmly pasted on the surface of the touch panel and one camera was fixed at the base of the device, vertically beneath the center of the panel, to detect the finger contact area. The camera was a Philips SPC900NC with VGA CCD Sensor and USB 2.0 interface. The default lens of the camera was replaced with a 4.3 mm CCTV Camera board Lens which did not have an IR-block filter. When a finger makes contact with the touch panel, infrared light escapes from the acrylic so that the camera can detect the finger contact action through variations in the infrared light. The camera was operated at a resolution of 640 × 480 pixels. As an important parameter of the apparatus, the scale of the camera was carefully measured, and the scale of the system in both the x and y axes was 0.4 mm/pixel.

The software was modified and redesigned based on TouchLib [15], an open source multi-touch package. The experimental software was run on a 2.4GHz Core 2 PC with the Windows 2003 Server operating system.

To obtain as much information from each finger touch as possible, we optimized all possible program codes to improve the processing performance. In the current experimental prototype, 30 frames can be processed in one second. That means we can collect 30 pairs of coordinate values in one second to meet the requirements of data analysis. No visual feedback was given to subjects but they could hear a beep as audio feedback when contact was made with the panel.

Tasks

The experimental task consisted of two parts. One was target tapping and the other was finger rocking and pointing. The multi-touch prototype was placed on the floor. The subject sat in front of the touch panel.

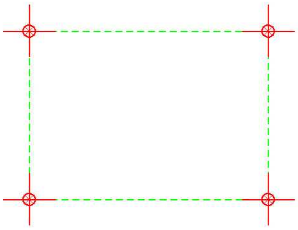

Figure 3. Experimental user interface. The center points of each red circle are the touch targets. The diameter of each circle is 4 mm. The width of the rectangle is 100 mm and the length is 60 mm (cross hair center to cross hair center).

Target Tapping. A tapping task was used. Tapping is a primary natural finger gesture used in most current multi-touch interfaces. We designed a simple tapping task to investigate the precise tapping ability of the five fingers of the dominant hand. The difference from other studies is that the size of the target was fixed. We referred to the experiment design proposed by Sears and Shneiderman [21]. Figure 3 shows the experimental interface and the locations of the four targets. This task includes two sub-tasks: one is vertical touch and the other is oblique touch (see Figure 4).

Finger rocking and orientation. A rocking task was used to investigate the variations in the finger contact area for both gestures and the rotatable range of finger orientation. At first, the subject used his or her finger to vertically touch the

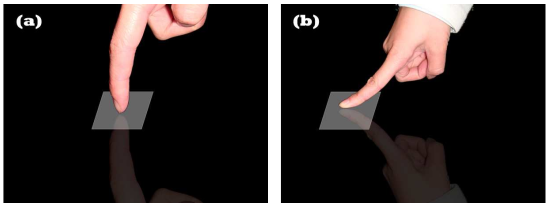

Figure 4. (a) is defined as "vertical touch". (b) shows the gesture of "oblique touch".

widget's panel and then he/she tilted the finger down. And second, when the finger was in an oblique state, the user horizontally rotated the finger clockwise and counter clockwise to change the finger's orientation to the maximum on the premise of maintaining user comfort (see Figure 5).

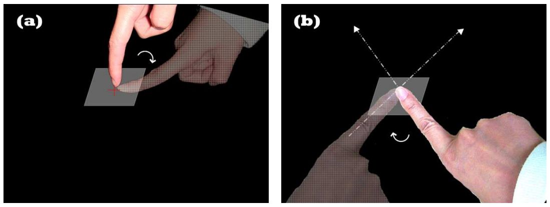

Figure 5. (a) is defined as finger rocking and (b) is defined as finger orientation rotation.

Participants

Eight male and four female volunteers, 26-37 years old, participated in the experiment. All were right-handed and had a little experience using touch devices such as ATMs. The physical sizes of each subject's finger-tips (end joints) were recorded. The average values of physical width (W) and physical length (L) (see Figure 1) are listed in Table 2 in millimeters.

	Thumb		Index		Middle		Ring		Little	
Finger tip	W	L	W	L	W	L	W	L	W	L
AVG	20.1	30.3	16.0	24.8	16.6	25.8	15.0	25.4	13.7	22.6
SD	2.7	3.2	1.9	1.7	1.9	2.4	1.9	2.5	1.7	2.5

Table 2. The physical size of the five finger-tips. W = width, L = length, AVG = average value, SD = standard deviation (unit: mm).

Procedure and Design

The participants were instructed to tap six times on each of four targets using two finger gestures with their five fingers in turn. The participants then landed each finger on the touch panel, rocked it, rotated the orientation and lifted it off the touch screen. In summary, the experiment consisted of:

12 participants ×
5 fingers ×
2 tasks ×
2 sub tasks ×
6 repetitions
= 1440 trials.

Prior to performing trials for each task, participants were given a short set of warm-up trials to familiarize themselves with the touch manner. Participants were instructed to perform the tasks as quickly and accurately as possible. The experiment lasted approximately 20 minutes for each participant. A short questionnaire was administered at the end of the experiment to gather subjective opinions. For each trial, we collected all the finger touch data (position, shape, size of contact area, width of contact area, length of contact area). An audible beep provided feedback when each trial was successfully completed.

RESULTS

Touch Area Center Point Variation

As a flexible motor system, distortion of the finger is inevitable while it is touching the hard screen panel. This distortion is disadvantageous for gathering contact area position measurements. We adopted the traditional centroid algorithm [16] to calculate the coordinate value of the contact area because the precision of such an algorithm is capable of attaining sub pixel level accuracy and is enough to guarantee the results of our analysis.

Snapshots of the full finger tapping procedure, from initial landing on the screen to lifting from the screen, were captured (see Figure 6). The blue cross represents the center of the contact area. It is easy to see that the center point of each image varies during the tapping procedure.

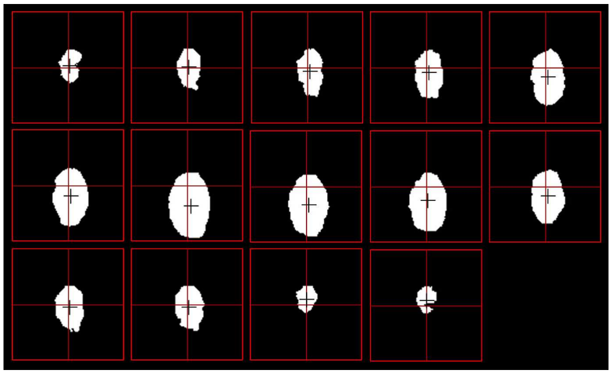

Figure 6. Snapshots showing the finger's contact with the screen over the full procedure.

In order to deeply study the finger touch procedure and to obtain more precise position coordinates, we divided the tapping procedure into three states: Land On, Stable and Lift Up, in each of the touch gestures. Land On refers to the state in which the user first contacts the screen and the moment when the multi-touch device detects the finger's initial contact. Stable refers to the state during which the finger is stably in contact with the screen surface. Lift Up is the final state where the finger lifts up from the touch screen. We used the first recorded data of each touch as the Land On coordinate value and the last data of the procedure as the Lift Up coordinate value. We adopted the data showing the contact area with maximum size as the center point of the Stable state.

As mentioned above, four targets are located on the paper and the accurate coordinates of targets are determined in advance. The distance from the center point of the Land On state to the center point of the Target (Land On-Target), the distance from the center point of the Stable state to the center point of the Target (Stable-Target) and the distance from the center point of the Lift Up state to the center point of the Target (Lift Up-Target) were calculated by a two-point formula (see Table 3).

	Thumb	Index	Middle	Ring	Little
Veritical touch					
Land On-Target	6.03	6.44	6.75	6.72	7.15
(SD)	(2.95)	(3.00)	(3.32)	(3.68)	(3.79)
Stable-Target	5.56	5.83	6.37	6.38	6.67
(SD)	(2.69)	(3.00)	(3.19)	(3.21)	(3.31)
Lift Up-Target	5.70	5.56	6.48	6.35	6.61
(SD)	(2.72)	(2.67)	(3.28)	(3.32)	(3.34)
Oblique touch					
Land On-Target	8.14	6.29	7.02	6.71	7.36
(SD)	(4.03)	(2.82)	(3.49)	(3.30)	(4.22)
Stable-Target	7.68	5.85	6.08	6.08	6.99
(SD)	(3.76)	(3.09)	(3.13)	(3.15)	(4.12)
Lift Up-Target	8.11	5.87	6.58	6.45	6.99
(SD)	(4.04)	(2.80)	(3.34)	(3.17)	(4.13)

Table 3. The average distances of the three sets of data (Land On-Target, Stable-Target, Lift Up-Target) of five fingers in two gestures, SD = standard deviation (unit: pixels, scale = 0.4 mm/pixel).

Table 3 shows that the values of Land On-Target are larger than the values of Stable-Target and Lift Up-Target. The values of Stable-Target and Lift Up-Target are closer. There are significant differences between Land On and Stable ($F_{1,8}$ = 9.56, $p < .05$), and between Land On and Lift Up ($F_{1,8}$ = 5.75, $p < .05$). However, no significant difference was found between Stable and Lift Up.

This result suggests that in multi-touch widget design, the coordinates of the Land On state are not accurate enough to be adopted as the cursor position. A comparison of the values of Stable-Target and Lift Up-Target for the five fingers reveals that the center point of the Stable state represents the cursor position more accurately. We adopt the Stable state as the default state in the subsequent sections if without additional comment.

In order to investigate variations in coordinate values in the tapping procedure, the average distance deviation for Land On-Stable (from the center point of the Land On state to the center point of the Stable state) and Stable-Lift Up (from the center point of the Stable state to the center point of the Lift Up state) in two touch gestures were calculated and listed in Table 4. The maximum average deviation in distance for Land On-Stable is 3.06 pixels (1.22 mm) and for Stable-Lift Up is 3.46 pixels (1.37 mm). Due to the natural increase in the contact area, the distance deviation in the oblique touch gesture is greater than in the vertical touch gesture.

	Thumb	Index	Middle	Ring	Little
Veritical touch					
Land On-Stable	1.99	1.99	1.44	1.36	1.54
(SD)	(2.08)	(2.17)	(1.30)	(1.36)	(1.78)
Stable-Lift Up	1.70	1.71	1.05	1.14	1.04
(SD)	(1.63)	(2.40)	(0.99)	(0.97)	(1.17)
Oblique touch					
Land On-Stable	2.87	3.06	2.79	2.25	2.74
(SD)	(3.05)	(3.08)	(2.65)	(2.20)	(2.57)
Stable-Lift Up	3.20	3.46	2.46	1.93	2.20
(SD)	(3.23)	(2.96)	(2.34)	(1.88)	(2.24)

Table 4. The average distances of the two sets of data (Land On-Stable, Stable-Lift Up) of five fingers in two gestures, SD = standard deviation (unit: pixels, scale = 0.4 mm/pixel).

Tapping Precison

Though the finger which is relatively stubby cannot obtain the same selection precision as a stylus, the finger's fundamental target selection ability is worthy of study. In multi-touch techniques, all the fingers of the two hands have the potential to work together to affect events more efficiently.

From the basic analysis of the data, the results for the five fingers show the same trends. Due to the limitation of space, we only present the scatter diagrams and distribution diagrams for the index finger (Figure 7). Figure 7a and Figure 7b show that the center points of the touch area are evenly distributed around the coordinates of the target within a definable range. The histograms in Figure 7c and Figure 7d show that the distribution of data is approximately in accord with the normal distribution in vertical and oblique touch gestures. In such premises, upper level of 95% confidence interval can be considered to be the effective target size.

Table 5 lists all the tapping deviation data for the five fingers (thumb, index, middle, ring and little) with two touch gestures. All the data of the vertical and the oblique touch events are calculated respectively. Average Values (AVG), Standard Deviation (SD), Lower Level of 95% Confidence Interval (LLCI) and Upper Level of 95% Confidence Interval (ULCI) are listed in the Table 5.

Regarding touch precision, there is no significant difference between the vertical touch gesture and the oblique touch gesture, when using the index finger, middle finger, ring finger, or little finger. However, there is a significant difference when using the thumb ($F_{1,22}$=12.5, $p < 0.05$).

Two results can be analyzed from Table 5, Figure 7 and relevant ANOVA results.

First, the precision for target selection of the index finger, the middle finger and the ring finger is relatively better than the precision of the thumb and the little finger. The average value and upper level of 95% confidence interval of "All Data" in Table 5 show that the index, middle and ring fin-

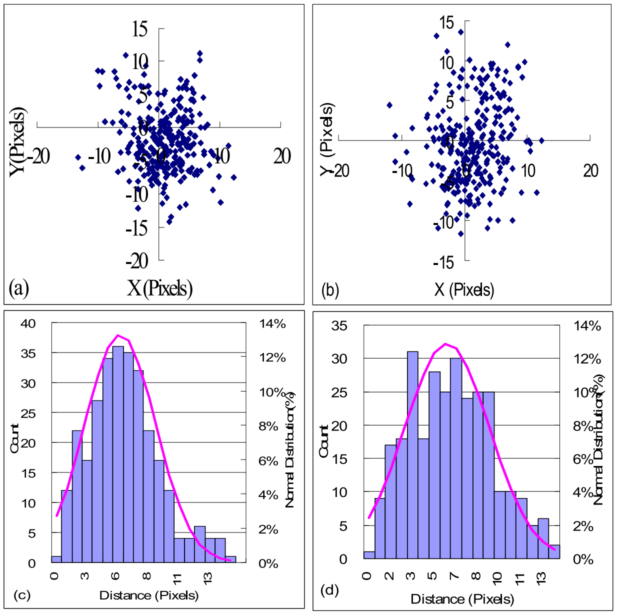

Figure 7. Scatter diagrams and normal distributions diagrams of the index finger in the vertical touch (a)(c) and oblique touch gestures (b)(d). The origin of the coordinate system (zero) in (a)(b) represents the position of the target. The blue point is the position of each tap. The distance value in (c)(d) is the value of Stable-Target.

gers are more accurate than the thumb and little fingers. In the subjective investigation, 12 subjects all reported that the little finger was difficult to use in the tasks. This is consistent with the experimental data.

Second, the radius of circular targets needs to be greater than 14.38 pixels (5.76 mm) and square targets need to be at least 28.76 pixels (11.52 mm) per side to maintain direct touch precision. According to the statistical theory, each upper level of 95% confidence interval value of five fingers in Table 5 can be regarded as the effective target size of each finger under the prerequisite that the distance data is in accord with the normal distribution. This effective target size also indicate finger touch accuracy. In order to meet the requirements of five fingers with two gestures, the minimum optimal size of targets is determined from the value of maximum upper level of 95% confidence interval (little finger of “All Data”) in Table 5. It is obvious from the data (see Table 5) and the scatter diagrams (see Figure 7) that the value is the optimal radius of the target. If we consider the square target, the size must be 14.38 × 2 (28.76 pixels, 11.52 mm) per side to guarantee a 95% confidence level.

Finger Touch Area Shape, Size and Orientation

Shape. Figure 8 shows the shape of the finger contact area. The shape of the contact area can be approximately represented by the equation of a rectangle or an ellipse. Three parameters, i.e., width (minor axis), length (long axis), slant angle, can describe one touch area of a finger. Table 6 presents the average statistical width and length for the two touch gestures. The real size of the contact area is calculated directly from the finger imprint (see Figure 8) and is different from the value of width × length.

		Thumb	**Index**	**Middle**	**Ring**	**Little**
All Data	**AVG**	6.63	5.84	6.22	6.23	7.57
	SD	3.44	3.05	3.16	3.18	4.14
	LLCI	0.97	0.83	1.02	0.99	0.75
	ULCI	12.28	10.85	11.43	11.46	14.38
Vertical Touch Data	**AVG**	5.56	5.83	6.37	6.38	6.67
	SD	2.69	3.00	3.19	3.21	3.31
	LLCI	1.14	0.89	1.12	1.09	1.23
	ULCI	9.99	10.76	11.62	11.66	12.11
Oblique Touch Data	**AVG**	7.68	5.85	6.08	6.07	6.99
	SD	3.76	3.09	3.13	3.15	4.12
	LLCI	1.49	0.76	0.92	0.89	0.21
	ULCI	13.87	10.94	11.23	11.26	13.76

Table 5. The tapping data for the five fingers in three conditions: the average values (AVG), standard deviation (SD), lower level of 95% confidence interval (LLCI) and upper level of 95% confidence interval (ULCI) (unit: pixels, scale = 0.4 mm/pixel).

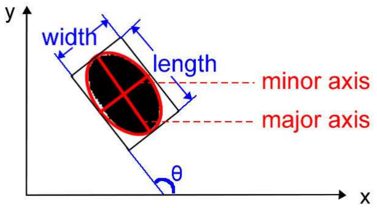

Figure 8. Shape of the contact area of the finger. The area with the black color shows the finger imprint.

Based on the data of Table 6 regarding the physical size of the finger, the width and length of the contact area in vertical touch is approximately 30% - 40% of the physical width and length of the full finger-pad (end-joint). In the oblique touch state, the average width is approximately 90% of the physical finger tip size, while the average length is approximately 70% - 80% of the physical finger tip.

Orientation and area size. The human finger has the ability to indicate direction in common life. In multi-touch techniques, the finger has the same ability to indicate direction on a 2D touch panel. When the finger touches the panel in the oblique gesture, the finger’s pointing direction can be defined as “finger orientation”.

The average size of the contact area in the vertical touch state (VA), the average contact area in the oblique touch state (OA), the proportional relation between VA and OA and the maximum orientation rotatable range are listed in Table 7.

Table 7 presents the finger’s ability to control according to

	Thumb	Index	Middle	Ring	Little
Physical Width (PW)	50.0	40.0	40.0	37.5	35.0
Physical Length (PL)	75.0	62.5	65.0	62.5	57.5
Veritcal touch					
Width	14.9	13.8	14.6	15.3	13.8
Length	18.0	16.7	18.1	18.5	17.9
Width/PW (%)	30	35	37	41	39
Length/PL (%)	24	27	28	30	31
Oblique touch					
Width	42.9	36.0	36.9	34.3	31.2
Length	58.3	50.9	47.1	47.3	44.5
Width/PW (%)	86	90	92	91	89
Length/PL (%)	78	81	72	76	77

Table 6. The average width and length of the contact area for the two touch gestures. Physical width and length of the finger-tip (see Table 2 but with different unit) (unit:pixels, scale = 0.4 mm/pixel).

	Thumb	Index	Middle	Ring	Little
Vertical Touch Area (VA)	194.0	178.1	196.3	209.5	179.7
Oblique Touch Area(OA)	1831.2	1375.3	1301.2	1158.0	1031.6
OA/VA	9.4	7.7	6.6	5.5	5.7
Range of Orientation	106.3	127.3	128.9	132.1	130.6

Table 7. The average size of the contact area for the two touch gestures. Range of orientation represents the horizontal rotation ability (unit: VA and OA = pixels^2, Range of orientation = degrees).

the finger's orientation property. The orientation of the finger can comfortably vary by more than 100 degrees. All subjects reported that it is easy to perform such actions.

In addition, the size of touch area has significant difference between two gestures. The area of oblique touch is at least 5.5 times the area of vertical touch.

DISCUSSION

Device Stability and Measurement Precision

This study is based on our own prototype FTIR multi-touch widget. The stability of the device is obviously a crucial factor in the study. In our experiment, we have verified the target location 6 times. The variation of the target coordinates, which is less than 0.5 pixels (0.2 mm), fully proves the stability of the device.

Another issue that could possibly affect the precision of the set-up is the indirect display of the interaction interface on the touch screen. The experimental interface is printed on plain paper instead of being displayed by a projector. Whether the current device can meet the requirements of precise measurement is the most important issue in the current study. In order to guarantee measurement precision, the device was carefully calibrated before the formal experiment. The camera was fixed vertically beneath the center of the touch panel in order to minimize distortion of the image. We checked the image scales of the four corners and found that the difference in these scales is less than 0.02 pixels (0.008 mm). In the environment where a projector is used, the camera cannot be fixed beneath the panel because the influence from the strong lights of the projector would significantly distort the test environment. Furthermore, images captured from a camera in a tilted position would lead to barrel distortion and significantly affect the accuracy of the results.

The results of this study suggest that the optimal minimum radius for a circular target is 5.76 mm. This result is significantly different from that of the study by Hall et al. [9], who reported that accuracy varied from 66.7% for targets of 10 mm per side, to 99.2% for targets of 26 mm per side, and that accuracy was maximized once targets were approximately 26 mm per side. But the result of the study of Sears and Shneiderman [21] is very close to the current result in our study. In their study, they reported that the accuracy was maximized when targets were 32 pixels per side (13.8 × 17.9 mm). We analyzed the differences among the three studies and concluded that differences in the devices are the main cause of the different results. Variation in measurement resolution is also a possible cause of such significant differences.

The Physical Size of Fingers and Relevant Questions

Each person's fingers are different in size. Whether this difference will change the result of the current study is a key question. We investigated the physical size of the fingers of the participants. Based on this investigation, we noticed that there is a relationship of scale between the physical width and physical length of the end joint of the human finger. The physical length of the human finger-tip is about 1.5 times its width. Even when pressing on the touch screen with strong pressure, the finger width is only 10% larger than the original width, i.e., the width without strong pressure. This degree of distortion does not significantly affect the measurement of the width, length or area.

The second question needing to be discussed is whether the current study's results are only relevant to adults but not to children. We therefore measured the fingers of 6 children. The result shows that the width and length of the fingers produce the same results by scale.

As mentioned in the previous sections, the resolution of the video image is 640 × 480 pixels. The physical properties of five fingers are precisely evaluated in the study. Of course, the measured values in different devices are possibly different because of the different physical characteristics of each device, e.g., resolution and sensitivity. Though most current commercial multi-touch products cannot support this high resolution, we believe that the results in our study, especially the proportional relations between each property, always exist and will be useful for all kinds of multi-touch devices.

The Contact Area and Relevant Questions

The contact area of a finger can be used in computer control as event trigger. Forlines et al. [8] discussed the finger contact area and its effect in target selection. Benko et al. [4] adopted the finger contact area to trigger "click" events. We further explored the significance of variations in the finger contact area for both gestures. Table 7 clearly shows the result of contact area variations for both gestures. The size of the contact area can be used to trigger an event because of three factors: (1) The area in the oblique touch state is at least 5.5 times larger than the area in the vertical touch state; (2) The results of 6 repetitions in the task show that the values of area size in vertical touch and oblique touch gestures (see Table 7) are stable; (3) All subjects reported that it was easy to perform such actions.

The Determination of Stable State

Table 3 shows that the center point of the Stable state may represent the cursor position more accurately. The first touch coordinate cannot be treated as the final touch position. In the real system, the method for determining the Stable state is a problem that requires more consideration. Based on the current investigation, the estimate of the Stable state coordinates is the simplest and most accurate way to determine the coordinates of the finger's contact area. When the width of the contact area is greater than a predetermined threshold and the length is greater than the width, the state can be considered to be the Stable state. Of course, the empirical value of the threshold should be tested under experimental conditions.

In low-resolution multi-touch sensitive devices, variations of coordinates in different states are not a critical problem. However, in high-resolution devices, such variations must be considered in the system design. For example, in traditional touch techniques where the finger's lift-up action triggers a "click" event, any deviation in the coordinates will possibly cause a wrong target selection. With the advent of new high-resolution multi-touch sensitive panels, further consideration of the Stable state are necessary.

The Limitations of Using Finger Properties

We investigated all the available finger input properties. However, there are a few limitations when we try to use these properties simultaneously because of anatomical limitations. For example, the contact area for one finger cannot be used as an event trigger when multiple fingers of one hand are simultaneously involved in the interaction. If one finger is rocked from the vertical state to the oblique state to change the contact area, the area of the other fingers will also change. Similar limitations exist in the orientation property. When the user rotates a finger horizontally to change the finger's orientation, the orientation of all the fingers will change. However, these limitations do not influence the adoption of these properties in multi-touch techniques because tasks can be deployed to different hands. For example, the preferred hand can be used for target selection and the non-preferred hand can be used to trigger menu and select menu item.

IMPLICATIONS FOR DESIGN

Guidelines

The results of our experiment suggest several guidelines for the design of multi-touch widgets:

Choose the coordinates according to the most precise of the three touch states, i.e., use the coordinates derived from the Stable state rather than from the Land On or Lift Up states. Distortion of the finger will affect the precise center point of the touch area. Table 3 presents the deviation of distance for contact of the five fingers' during the three touch states. Compared with the Stable state and Lift Up state, the deviation of the Land On state is larger. In the design of multi-touch devices, the first contact position is not accurate for consideration. Especially in high resolution multi-touch devices, the coordinate data should be derived from the coordinates of the Stable state.

Direct touch targets should be greater than 11.52 mm per side for square targets (or 5.76 mm radius for circular targets) in GUI design. In the user interface design of multi-touch widgets, the size of square targets must be larger than 11.52 mm (28.76 pixels) per side. When we design circular targets, the radius should be greater than 5.76 mm (14.38 pixels). These design paradigms can ensure a high touch precision with all fingers including the thumb and the little finger and with all tapping gestures.

Decrease arm movement and tapping actions in gesture design. Arm fatigue is the main drawback of multi-touch techniques. Constant tapping and the movement of the wrist or arm between points on the screen cause fatigue. The larger the touch screen, the more fatigue the arm will feel. To decrease the effect of arm fatigue, the movement of the hand and the tapping action should be kept to a minimum in gesture design. Based on the results in the study, more natural gestures (i.e.,contact area, orientation) can be designed than those used in currently available widgets. For example, variations in the size of the contact area can be used to trigger an event in an application. The rocking of fingers can control the movement of cursor. The arm movement can be decreased.

Decrease the influence of the occlusion of the display by the fingers. The occlusion of the interface display by the fingers and the hand further increases the difficulty of target selection. The user cannot determine the precise position of the target under such circumstances. In order to improve the usability of multi-touch techniques, finger orientation and finger contact area can be used to determine the position of the area obscured. Based on this determination, GUI designers can avoid improper layouts in user interfaces.

Widget Designs

Based on our experimental results and our findings from the previous section, the design space of finger input properties is explored here. To support our exploration, it is useful to define certain parameters of the design space.

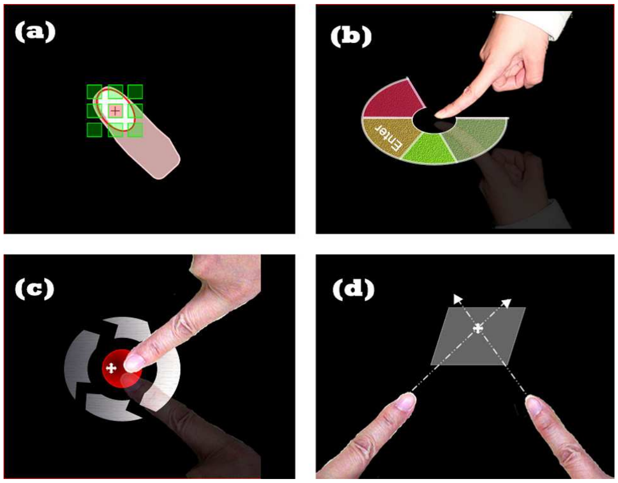

Figure 9. Widget design demo, (a) finger combination cursor, (b) finger sector menu, (c) finger pointing stick, (d) finger cross selection.

Finger Combination Cursor. We informally define "Combination Cursor" as the combination of one area cursor and one point cursor. The shape of the finger imprint is treated as an area cursor and the center point of the contact area is a point cursor. The area cursor is a cursor that has a larger than normal activation area. The area cursor simply has a larger hot spot. There is evidence that performance with area cursors is better than performance with regular cursors for some small target acquisition tasks [12].

The human finger is a natural area-cursor input device. Based on the previous section, the shape of the finger's contact area can be described by an elliptical equation. The center coordinate value of the contact area can be treated as the position of the common point cursor. Figure 9a shows the combination cursor. The finger combination cursor is capable of improving GUI performance in target selection tasks. When the finger touches the screen, two strategies are adopted to determine the selected target: (1) If only one target is covered by the tapped area, the target can be selected directly by the area cursor technique; (2) If there are more than 2 targets in the contact area, the target nearest to the center coordinates is the target. At the same time, we can adopt a "Shift" technique [25], where a callout can be used to display the finger touch area. The finger combination cursor combines the advantages of area cursor and point cursor.

Finger Sector Menu. Pie menu use is widespread in GUI design. In multi-touch techniques, a pie menu is often triggered by a finger touch. But some menu items are always obstructed by the finger. We present a new sector menu technique to resolve the occlusion of the finger. Incorporation of the newly defined finger properties improves the usability of the pie menu and makes the operation more natural. Figure 9b shows the finger sector menu in use. The finger sector menu is triggered by variations in the finger contact area. When the contact area is greater than a predetermined threshold, a finger sector menu is triggered and displayed following the orientation of the finger. The position of the hand can be determined by variations in the direction of the contact coordinate(s): when a user touches the panel with the vertical touch gesture, the coordinates of the touch point (x1, y1) are obtained; the user then tilts the finger down; when the finger is in an oblique state, the second touch point (x2, y2) is obtained; the direction from the (x1, y1) to (x2, y2) is considered to be pointing towards the position of the hand. In the premise of knowing the finger physical position, the occlusion of the display menu item by the finger can be avoided. The user can select one menu item by rocking the finger or changing the finger's orientation. With the support of the finger sector menu technique, the user can pop-up the finger sector menu and select one menu item in a natural gesture without any additional finger movement.

Finger Pointing Stick. The pointing stick is an isometric joystick used as a pointing device that is used in notepad computers such as the IBM/Lenovo Thinkpad series. The finger looks and operates like a joystick while in vertical contact with the screen. The finger can simulate most functions of the pointing stick naturally. From the vertical to oblique positions, the center of the touch area can be used to move the cursor. The user can rotate the finger horizontally to fine-tune the cursor. With a proper setup of the control display ratio, the rocking of the finger can control the cursor movement in one direction (see Figure 9c). The finger pointing stick is also capable of controlling the pop-up menu's selection.

Finger Cross Selection. Multi-touch screens are usually used in out-door information displays and interactions. The size of the screens is increasing in order to satisfy the requirements of special applications. The "Finger Pointing Stick" technique is a good way to control cursor movement by simply rocking the finger. The finger cross selection technique is an extension of the finger pointing stick. Figure 9d shows the concept of finger cross selection. In order to select a distant target, the orientation of two fingers can present two radial lines. We can select the target by controlling the position of intersection of the two lines. The Finger Cross Selection technique is especially useful in wall-size display technology if the position of target is out of the user's reach.

CONCLUSION

We designed an FTIR based multi-touch device and used it to implement a series of experiments in order to investigate readily available human finger properties. Our results indicate that the five fingers of one hand present different abilities and potentials for target selection. The target selection precision of the index finger, the middle finger and the ring finger are better than the precision of the thumb and the little finger. Based on the results of our experiment, the shape of the finger contact area, the size of the contact area and the orientation of the contact finger are effective finger properties that are useful for the design of natural multi-touch gestures.

Future intended work on this subject mainly includes the evaluation of newly proposed designs. Their impact in reducing interference issues should be carefully evaluated, as well as evaluating the discrete control level of these input properties especially the finger contact area and the orientation. We will also investigate the effects of using direct multi-touch devices and indirect multi-touch devices and we will assess how they differ from our current results and observations.

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