A MULTI-TOUCH THREE DIMENSIONAL TOUCH-SENSITIVE TABLET

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ABSTRACT

A prototype touch-sensitive tablet is presented. The tablet's main innovation is that it is capable of sensing more than one point of contact at a time. In addition to being able to provide position coordinates, the tablet also gives a measure of degree of contact, independently for each point of contact. In order to enable multi-touch sensing, the tablet surface is divided into a grid of discrete points. The points are scanned using a recursive area subdivision algorithm. In order to minimize the resolution lost due to the discrete nature of the grid, a novel interpolation scheme has been developed. Finally, the paper briefly discusses how multi-touch sensing, interpolation, and degree of contact sensing can be combined to expand our vocabulary in human-computer interaction.

1. INTRODUCTION

Rapid advancement of computer technology has opened a variety of new applications. New applications and users mean demands for new modes of interaction. One consequence of this is a growing appreciation of the importance of using appropriate input technologies (Buxton, 1982). Positioning devices are seen to be essential to graphics applications, image transducers are required for pattern recognition in medical diagnosis, touch screens are useful for the education of young children, and the QWERTY keyboard remains the usual standard for text processing. However, the range of input devices available is still quite limited, as is our understanding of how to use them in the most effective manner.

The intent of the research presented in this paper is to increase the vocabulary that can be utilized in human-computer interaction. Our approach has been to develop a new input technology that enlarges the domain of human physical gestures that can be captured for control purposes. In what follows, we will describe the technology, what it evolved from, and some aspects of how it can be used.

2. OVERVIEW

The transducer that we have developed is a touch-sensitive tablet; that is, a flat surface that can sense where it is being touched by the operator's finger. This in itself is not new. Several such devices are commercially available from a number of manufacturers (see Appendix A). What is unique about our tablet is that it combines two additional features. First, it can sense the degree of contact in a continuous manner. Second, it can sense the amount and location of a number of simultaneous points of contact. These two features, when combined with touch sensing, are very important in respect to the types of interaction that we can support. Some of these are discussed below, but see Buxton, Hill, and Rowley (1985) and Brown, Buxton and Murtagh (1985) for more detail. The tablet which we present is a continuation of work done in our lab by Sasaki et al (1981) and Metha (1982).

In the presentation which follows, we focus mainly on issues relating to the transducer's implementation. Two important contributions discussed are our method of scanning the tablet surface, and our method of maintaining high resolution despite the surface being partitioned into a discrete grid. Additional technical details can be found in Lee (1984).

3. WHY MULTI-TOUCH?

Touch sensing has a number of important characteristics. There is no physical stylus or puck to get lost, broken, or vibrate out of position. Touch tablets can be molded so as to make them easy to clean (therefore making them useful in clean environments like hospitals, or dirty environments like factories). Since there is no mechanical intermediary between hand and tablet, there is nothing to prevent multi-touch sensing. Templates can be placed over the tablet to define special regions and, since the hand is being used directly, these regions can be manually sensed, thereby allowing the trained user to effectively "touch type" on the tablet.

Without pressure sensing, however, the utility of touch tablets is quite limited. One can move a tracking symbol around the screen, for example, but when the finger is over a light button, there is nothing equivalent to the button on a mouse to push in order to make a selection. Yes, we could lift the finger off the tablet, but that would be more like pulling (rather than pushing) the button. And what if we wanted to drag an item being pointed at, or to indicate that we wanted to start inking? Lifting our finger would leave our finger off the tablet, just when we want it in contact with it the most. There are ways around this problem, but they are indirect. If, however, the tablet has pressure sensing, we can push a virtual button by giving an extra bit of pressure to signal a change in state.

Pressure has other advantages. One example is to control line thickness in a paint program. But why do we want multiple point sensing? A simple example would be if we had a template placed over the tablet which delimited three regions of 9 cm by 2 cm. Where we touch each region could control the setting of a parameter associated with each region. If we wanted to simultaneously adjust all three parameters, then we would have to be able to sense all three regions. An even easier example is using the tablet to emulate a piano keyboard that can play polyphonic music.

4. HARDWARE DESCRIPTION

A brief description of the hardware of the fast multiple-touch-sensitive input device (FMTSID) is introduced here. The design of the hardware is based on the requirements of the fast scanning algorithm and on tradeoffs between software and hardware. Many sensors have been examined for our particular application, however (Hurst, 1974; Hillis, 1982; TSD, 1982; TASA, 1980; JSRC, 1981; Metha, 1982) none seemed to have the properties that satisfy the requirements of a FMTSID. The hardware basically consists of a sensor matrix board, row and column selection registers, A/D converting circuits and a controlling CPU.

The design of the sensor matrix is based on the technique of capacitance measurement between a finger tip and a metal plate. To minimize hardware, the sensors are accessed by row and column selection. Row selection registers select one or more rows by setting the corresponding bits to a high state in order to charge up the sensors while the column selection registers select one or more columns by turning on corresponding analog switches to discharge the sensors through timing resistors. The intersecting region of the selected rows and the selected columns represents the selected sensors as a group. A/D converting circuits measure the discharging time interval of the selected sensors. A University of Toronto 6809 board is used as a controlling CPU. The touch surface of the sensor board consists of number of small metal-coated rectangular-shaped areas serving as sensor plate capacitors. The design of the metal plate area of a unit sensor depends on the measurable capacitance change that results when the area is covered by a finger tip, and on the resolution that can be implemented.

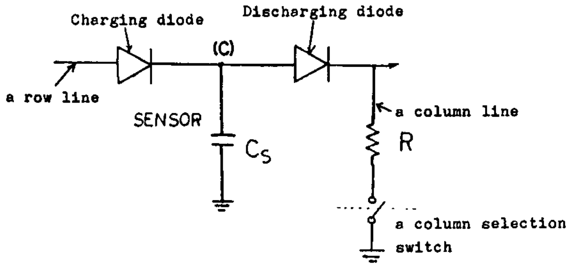


Fig. 1 A model of a selected sensor in the sensor matrix.

In order to select a sensor by row and column access, two diodes are used with each sensor. One diode, connected to the row line, is used to charge up the sensors in the row. It is referred to as the Charging Diode (CD) as shown in Figure 1. The CD also serves to block the charge flowing back to the row line when the row line voltage is dropped to zero. The other diode called the Discharging Diode(DD), connected to the column line, enables discharging of the selected row sensors to a virtual ground. Also the DD blocks charge flow from the sensors in the selected row to the sensors in the unselected rows during the discharging period. The selection of rows, by the row selection procedure, causes the sensors to be charged. The sensors in the column are then discharged through associated timing resistors connected to the column selection switches.

The charges stored in the selected row(s) flow down through the selected switches to the virtual ground of a fast operational amplifier. All the discharging currents are correspondingly added to produce a signal from which the discharging time of all the selected sensors is found by comparison with a threshold voltage.

Pressure sensitivity is incorporated by two measures: First there is the effect, here minor, of compression of the overlaying insulator. Second there is the effect of intrinsic spreading of the compressible finger tip as pressure is increased.

The software in the controlling CPU utilizes communication with the host computer to accommodate the interpolation scheme. The clock rate (10 MHz) allows about 10 counts to correspond to the sensor capacitance change due to a touch. But, of course, the capacitance of all the circuitry attached to the column line during the discharging period is much larger than the sensor capacitance. Thus before scanning the tablet for a touch, it is scanned completely in all possible resolution modes when not touched. The values so obtained are stored as references. Touches are identified by the differences between the reference values and the values measured during use.

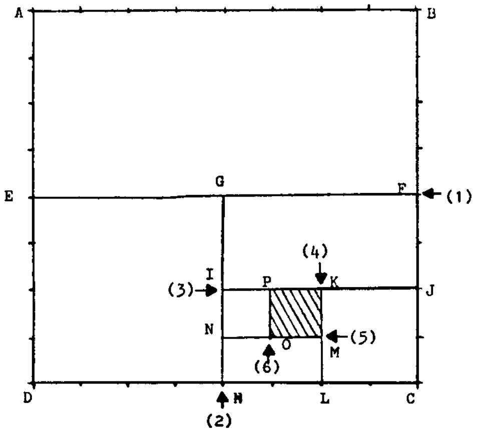
The capacitance change corresponding to the touch by more than one finger (or by the whole hand) is very large. Thus the number of bits in the counter should be enough to measure the maximum capacitance. However it is unnecessary either to have sufficient bits to measure the entire capacitance including the surrounding capacitances, or to store the corresponding "complete" counter values as references. It is necessary only to have one more bit than the number of bits required to count the value of change in the capacitance rather than the complete value in order to measure the differences of capacitance due to touch. Thus only an 8 bit counter is implemented. The counter enables the measurement of a 7 bit capacitance change regardless of the degree of overflow in the counter.

A facility is also provided for identifying templates applied to the surface of the tablet.

5. SCANNING ALGORITHM

One idea of some significance that can be introduced is to avoid scanning of all the pixels in the tablet which contain no information. For example, scanning all 2048 points of a tablet having a resolution 64 by 32 for fewer than 10 points is really quite a ridiculous idea. In fact, if the number of points to be searched is comparably small, then an improved algorithm, here called recursive area subdivision, can be used. A particular implementation example is described as follows.

Consider a tablet with resolution 8 by 8 to be searched for a touch point as shown in Figure 2. First, check the tablet for touch as a whole region as shown by the area ABCD in the figure. If touch is detected, divide the tablet into two equal regions shown by the line EF and check each of the two regions ABEF and EFCD for touchedness. Select the touched region, region EFCD in this case, and divide this into two equal regions as shown by the division line GH. Continue this process on the touched region until no further division is possible, that is, until a unit sensor, designated as the region PKMO in Figure 2, is reached. The figure also shows the sequence of subdivision in the recursive subdivision scheme.



(n)-Sequence of subdivision in binary operation.

Fig. 2 Recursive subdivision operation for 8 by 8 tablet.

Using this algorithm, a search for one point on a tablet having a resolution 64 by 32, requires 22 scanning times, that is

2 * {log sub 2} (64 * 32) = 22

If there is no overhead in the recursive subdivision process and scanning begins at the "top of the tree" (that is, with a region in which all pixels are grouped together), then using this scheme, the number of touched points that can be identified in the time that it would take to detect one touch directly (that is, if all pixels are scanned one by one sequentially) is

N = {(64 * 32) over 22} = 186.

This shows immediately that the recursive subdivision scheme is much superior to sequential scanning if the number of points to be scanned is fewer than 186.

6. INTERPOLATION

It may seem that the resolution of the hardware is too low for use in graphics applications. However touch intensity and multi-touch sensitivity can be used to enhance resolution. This is possible because the center of a touch can be most accurately estimated by an interpolation utilizing the values of the adjacent sensor intensities.

Direct interpolation schemes for a few cases has been implemented. One of interest is to interpolate an array of 3 by 3 sensors using a touched point in the center. Another is to interpolate all points on the tablet. The later one obviously provides the highest resolution but as a result it simply emulates a single touch tablet with very high resolution.

7. PERFORMANCE

7.1 Sensor

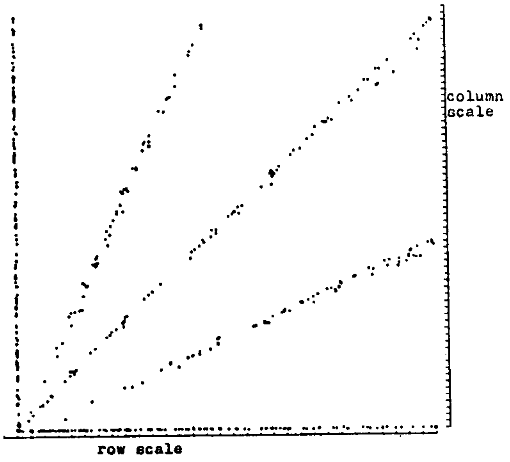
An ideal sensor matrix for a FMTSID would be one that has uniform and small reference values over a grouping level, a large variation of intensity due to a touch, and fast measurement time. The sensor matrix of the prototype, however, has a relatively wide range of reference values. However these values do not change very much over extended periods of time. The results show that doubling the number of sensors in a group in the column direction increases the reference value by a factor of about 1.5. This corresponds well to theoretical estimates. As well the results show that increasing the number of sensors in a group in the row direction, in contrast, does not increase the reference value in general, even if the number of the sensors is doubled in a group. The reference value ranges from 40 (for a single sensor in a group) to 580 (for the entire array of 64 by 32 sensors considered as a group).

In order to account for time and other variations of the reference values, a threshold is included which must be overcome in order for a touch to be detected. The threshold used ranges from 2 to 7 counts depending on group size. Using these threshold values the CPU does not report untouched points wrongly over intervals of at least 3 hours in either sequential or recursive subdivision modes. The recursive subdivision scheme uses 6 different thresholds, consequently it is very unlikely to report a wrong point whereas the linear scanning mode using only a single threshold is likely to be more sensitive.

The intensity of a single touch for a single sensor group varies over the tablet but usually ranges above the threshold value by as much as 15. For a single 64 by 32 sensor group, the intensity varies from person to person but it ranges from the threshold to 124. This maximum is obtained when a palm rather than a finger touches the tablet. Another interesting feature is that the response time becomes faster as the number of sensors in a group becomes larger, and furthermore that for the 64 by 32 sensor group, it is possible to detect of a hand merely placed in the vicinity of the tablet.

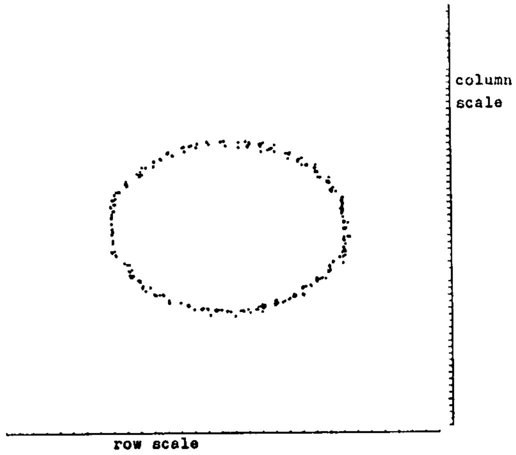
7.2 Spatial Resolution

One possible and immediate interpolation scheme is to interpolate a "touched" point with all adjacent values which may not be large enough to be reported as touched. A local array of 3 by 3 points can be used for this interpolation. Some examples drawn on a laser printer (consequently having no intensity scale) are shown in Figure 3. These pictures are produced without feedback, that is, drawn without the operator looking at the output screen. This does not allow the operator to compensate, that is, to select points where data are sparse in comparison with the intended figure, but rather takes direct input from the location of the figure drawn on the input device. The first picture (a) is drawn by moving a finger in a straight line (guided by a ruler) for various angles and the second one (b) is drawn by moving a finger in a line gude by a circle drawn on a template. These tests show that interpolation actually increases the spatial resolution as well as the locatability of a fine point on a screen.



(a) Straight lines drawn by the tablet using 3 by 3 sensor array interpolation.

The scales shown represent the boundaries of the actual sensors.



(b) A circle drawn by the tablet using 3 by 3 sensor array interpolation.

The scales shown represent the boundaries of the actual sensors.

Fig 3 Points drawn by the tablet using an interpolation method.

Since the spatial resolution in the local interpolation scheme is limited by the number of bits available from the intensities of an array of 3 by 3 sensors, other scheme was considered. In this scheme, all the points from a complete scan of a tablet are interpolated allowing the potential resolution to be almost infinite. However this process simply emulates a projective device and accordingly reports only single point, which is interpolated from all the points on the tablet. However with this scheme, there are a great many ways of pointing to a specific location on a display screen, a feature with some intriguing application possibilities.

7.3 Response Time Delay

The response time delay is the time delay from the beginning of a touch to an output received either by local terminal or by an output device attached to the host computer. For multiple touches, this delay will increase with the number of touches. The prototype used with a 9600 baud-rate terminal to measure time delays. Actual response times were measured several times and averaged for various cases and are tabulated in Table 1.

Case	best	typical	worst
(a) pts/sec msec/pt	17.6 56.8	15.2 65.8	12.8 78.1
(b) pts/sec msec/pt	19.2 52.1	17.2 58.1	16.0 62.5
(c) pts/sec msec/pt	24.0 41.6	22.0 45.5	18.8 53.2

TABLE 1. Actual Response Time Delays

The cases in Table one are to be interpreted as follows:

a one sensor touched continuously

b two sensors touched at the same time continuously

c four sensors touched at the same time continuously

8. CONCLUSIONS

A prototype of a fast-scanning multiple-touch-sensitive input tablet having both the adaptability and flexibility for a broad range of applications has been designed and implemented. Capacitance measurement of individual sensor(s) which can be uniquely addressed using two diodes per sensor, makes it possible to sense both the positions and intensities of one or more simultaneous touches without ambiguity. The sensor matrix is controlled by University of Toronto 6809 board whose serial port is connected to one of the I/O ports of a host computer. Software that utilizes the recursive subdivision algorithm for fast scanning an array of 64 by 32 sensors on the tablet, and that communicates with the host computer, has been implemented and tested.

9. ACKNOWLEDGEMENTS

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TSD (1982), Touch Screen Digitizer Data Sheet, TSD Display Products Inc., 35 Orville Drive, Bohemia, NY 11716.

11. APPENDIX A: TOUCH TABLET SOURCES

Big Briar: 3 by 3 inch continuous pressure sensing touch tablet

Big Briar, Inc.
Leicester, NC
28748

Chalk Board Inc.: "Power Pad", large touch table for microcomputers

Chalk Board Inc.
3772 Pleasantdale Rd.,
Atlanta, GA 30340

Elographics: various sizes of touch tablets, including pressure sensing

Elographics, Inc.
1976 Oak Ridge Turnpike
Oak Ridge, Tennessee
37830

KoalaPad Technologies: Approx. 5 by 7 inch touch tablet for microcomputers

Koala Technologies
3100 Patrick Henry Drive
Santa Clara, California
95050

Spiral Systems: Trazor Touch Panel, 3 by 3 inch touch tablet

Spiral System Instruments, Inc.
4853 Cordell Avenue, Suite A-10
Bethesda, Maryland
20814

TASA: 4 by 4 inch touch tablet (relative sensing only)

Touch Activated Switch Arrays Inc.
1270 Lawrence Stn. Road, Suite G
Sunnyvale, California
94089