The touch-sensitive screen as a flexible response device in CAI and behavioral research*

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Two different touch-sensitive surface units are described and evaluated from a technical as well as an applications standpoint, with particular emphasis on their use as response devices in computer-assisted instruction with young children. Several other interesting touch-sensitive surface concepts and laboratory applications are also described.

Early in 1964, the Learning Research and Development Center (LRDC) and the Westinghouse Research Laboratories began a joint development project to design and construct a prototype "touch-sensitive" surface that could be incorporated into a computer-assisted instruction terminal designed for small children. The final outcome of the project, after the usual round of engineering modifications, was an 18 x 18 in. translucent touch-sensitive surface upon which slide images could be displayed from the rear, using a conventional Kodak slide projector under computer control. The surface was designed so that a computer could determine the X-Y coordinates of any point touched. In conjunction with computer-controlled random-access audio, a touch-sensitive terminal of this type has been used successfully at LRDC since 1967 in a wide variety of computer-assisted instruction (CAI) and on-line psychological research activities. Although the joint project with the Westinghouse Research Laboratories was terminated in 1967, developmental work has continued at LRDC, and a variety of touch-sensitive surfaces have been designed and constructed.

This paper will describe the touch-sensitive surface developmental activity from a technical as well as an applications standpoint, with particular emphasis on the design of touch-sensitive displays for use in CAI

with young children. Two different touch-sensitive surface designs and several interesting applications will be discussed.

THE WIRE-WIRE GRID TOUCH Technical Description

The original touch-sensitive surface, developed jointly by the Westinghouse Research Laboratories and LRDC, is constructed from a heavy sheet of acrylic plastic, .75 in. thick and 20 in. square. A 9 by 9 matrix of 2-in. squares is milled into the surface, leaving a grid of narrow ridges standing .125 in. above the screen surface (see Fig. 1). A network of orthogonally crossed .003-in. stainless steel wires, spaced .375 in. apart, is stretched across the screen supported by the ridges. These ridges are notched so that the wires of one axis are held .03 in. above the wires of the other (see Fig. 2). A sheet of flexible Polacoat^(R)1 lens-screen covers the entire grid and forms the projection surface upon which slide images are displayed by a rear-mounted random-access slide projector (see Fig. 3). When the surface is touched anywhere within one of the 2-in. squares, one or more horizontal X-axis

wires are placed in contact with vertical Y-axis wires, completing a switch closure uniquely defining the position of the square touched. Adjacent wires in each of the 2-in.-wide rows and columns are connected at the edge of the screen so that the maximum resolution of the surface is 2 in. This was done largely to simplify the device, since finer resolution was felt not to be required.

Computer Interface

The interface between this touch screen and LRDC's PDP-7 computer is extremely simple and is generally reliable, although in some respects it is not ideal. The interface consists of a series of biasing resistors and divider networks (see Fig. 4). Each vertical wire set is connected to a divider network (R_1 - R_2 - R_3) whose output node is normally at -3 V or logical "1" level. Each horizontal wire is normally held at ground by a bias resistor (R_4). Touching one of the 2-in. squares forms a new divider network (inset, Fig. 4), and the node between R_2 , R_3 , and R_4 (horizontal output) goes to -3 V. Because R_1 and R_2 are equal, the vertical output goes to ground. A one-shot delay circuit is used, which delays setting the flag to the computer for 40 msec after a touch is detected, since contact bounce is unavoidable. If a touch is still present when the one-shot times out, the flag is set, and an interrupt signal to the computer is generated.

The divider network approach has proved to be an inexpensive and simple solution to the problem of interfacing the touch screen to the computer. A major shortcoming of the method, however, is the inability to reject "multiple touches"; that is, simultaneous touches on two or more squares, producing illegal and uninterpretable coordinate data. Multiple touches are currently rejected by systems software, although

Fig. 1. Overall view of the wire-wire grid touch screen.

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Fig. 2. Sectional view of the wire-wire grid touch screen showing four 2-in. squares.

Fig. 3. One of the earlier computer terminals using the wire-wire grid touch with a Kodak slide projector.

hardware rejection could be implemented. This multiple touch characteristic is the primary reason why the divider network interface was not adopted on the new gridless touch to be discussed later.

Controlling Systems Software

The systems software in use at LRDC for controlling the wire-wire grid touch is quite straightforward. Excluding those features specific to the LRDC time-sharing system, this software in its present form can be implemented on any system.

The controlling software consists of two main segments. The first is a request processing routine which is called whenever a user program desires input from the touch-sensitive surface. Since the touch hardware requires no initialization and is always in a state of receptiveness, the primary purpose of this routine is to set a software flag to indicate that touch input is to be accepted. Depending upon parameters specified in the user's calling sequence, this request processing routine either

returns control immediately or places the calling program in a suspended state.

Program suspension may be specified as either unconditional or conditional. If unconditional, the user program is reactivated when touch input is received. If conditional suspension is requested, the user program is reactivated when touch input is received or when a time-delay expires, whichever occurs first. If suspension is not requested and control is returned immediately, the user program must have some way of determining that touch input has occurred. A general input/output wait routine is available for this purpose and permits the user to request conditional or unconditional suspension until some specified I/O event has occurred. These options permit the user to exercise close control over the experimental environment. By requesting that control be returned immediately, the user program is free to continue computation or to initiate some other

I/O process. The conditional suspension option enables the user program to take some adaptive action if no touch input is received within a user-specified time period.

The other major segment of the touch control software is the interrupt processing routine. This routine is entered whenever a hardware interrupt occurs, indicating that contact has been made on the touch-sensitive screen and that coordinate information is available. After storing the proper machine registers, the interrupt routine first examines the software flag set by the request processing portion to determine if touch input has been requested. If no request has been made, a spurious interrupt counter is incremented, the machine registers are restored, and control is returned to the interrupted program. The spurious interrupt counter is maintained to facilitate debugging in the event of a hardware malfunction in the interface or touch-sensitive screen.

If the input has been requested by a user program, the interrupt processing routine reads a hardware clock to determine the time of the touch contact. An input instruction is then issued to strobe the touch coordinate data into the 18-bit accumulator register of the CPU. As was described in the previous section, this information is in the form of two 9-bit segments representing the X and Y coordinates of the point of touch contact. Since there is no hardware encoding, each bit position corresponds to an equivalent position on either the ordinate or abscissa of the 9 by 9 touch screen array. In the X-axis segment, all bits are normally in the zero state, and a bit in the one state indicates that a touch contact has been made somewhere in that row in the screen array. All bits are normally in the one state in the Y-axis segment, and a bit in the zero state indicates contact somewhere along the corresponding column.

The interrupt routine checks for error conditions prior to encoding the data and returning it to the user program. Only a single bit should be in the one state in the X-segment or zero state in the Y-segment; if not, control is returned to the user program with an error indication. If no error condition is found, each segment is encoded into a binary value in the range of 1 through 9, where the value represents the position on the axis. The X value is stored right-adjusted in the high-order 9 bits of an 18-bit word, and the Y-axis is stored right-adjusted in the low-order 9 bits of the word. These coordinates, plus the time-of-day of the original request and the time-of-day of the touch

Fig. 4. Schematic of the earlier wire-wire touch interface circuit. The inset shows the network configuration produced by a touch.

interrupt, are stored in memory locations specified by the user program. Once this is completed, the time-sharing system scheduler is notified that the user's touch input request has been satisfied.

Experience with Unit and Overall Evaluation

The wire-wire grid touch has been in daily use for 3 years and has proved to be an extremely reliable piece of hardware. It has been used primarily as a terminal device for experimental computer-assisted instruction with small children and has survived considerable abuse without loss of sensitivity. Most of what has been learned about the wire-wire grid touch relates to its effective use in various experimental applications.

Initially, there was some concern over the possibility of data loss, since information is available to the computer only for the duration of the actual physical contact with the touch-sensitive surface. In other words, it might be possible to quickly touch and withdraw from the surface before the computer could respond and read the data. To prevent this, the touch surface was given a high priority in the priority-interrupt structure so that the unit would be quickly serviced, even during periods of heavy interrupt activity. However, extensive experience with the unit now indicates that this was unnecessary. The

duration of the average touch contact is long enough to allow the computer to respond, regardless of other time-sharing activity.

A more serious problem arose from the lack of immediate feedback to a child, indicating that a touch contact was recognized and accepted. This problem does not occur when using a terminal device like a Teletype, since the depression of a key is followed by the printing of a character or at least by some audible action on the part of the printing unit. However, the

touch-sensitive screen is wholly silent and gives no indication that it has recognized a contact. This problem is particularly severe when the desired response involves sequential touch contacts. The child is given no indication until the last contact that any of the previous touch contacts were accepted. As a solution to this problem, a small audio oscillator was installed in the touch unit and placed under computer control. When a touch contact is detected, the oscillator is enabled for approximately $\frac{1}{2}$ sec, producing a soft high-pitched tone to indicate that the touch contact is recognized. This simple audio feedback is quite effective and is now regarded as an essential component in any touch-sensitive screen application.

Inaccurate slide-image registration caused by the slippage of the film chip within the slide mount, and compounded by the poor lateral slide registration characteristics of the early Kodak Carousel projectors, was another problem that occurred during the early use of the screen as a CAI response device. The projector problems have been corrected in the current "AV" series Carousels available from Kodak. The use of plastic slide mounts with molded sprocket-hole aligning tabs eliminated the film chip slippage.

THE WIRE-WIRE GRIDLESS TOUCH

Technical Description

One of the major disadvantages of the "supporting grid" design is that touch contacts are occasionally not recognized when children touch the grid divider between two 2-in. squares. In addition, it is both difficult and time consuming to machine the plastic surface. Any bow or irregularity in the surface tends to lift the wires out of

Fig. 5. Overall view of the gridless wire-wire touch screen. For clarity, the full number of wires is not shown.

Fig. 6. Sectional view of the gridless wire-wire touch screen. The support pieces are movable to adjust spacing between row and column wires. The anchor posts are part of the support pieces.

their notches, creating insensitive areas or spurious touch contacts. Because of these difficulties, a new touch screen was designed which eliminates the troublesome grid and permits easier fabrication. Since this screen will be incorporated in a new touch display terminal, the computer interface and the touch-detection logic have been extensively redesigned to eliminate the "multiple touch" and contact bounce problems and to permit remote operation of the terminal over a dataphone link.²

The gridless touch uses as a base plate .23-in. plate glass surrounded by an aluminum and acetyl plastic frame (see Figs. 5 and 6). As in the earlier design, orthogonally crossed .003-in. stainless steel wires are stretched across the screen; however, the bottom set rests directly on the plate glass and does not deflect when touched. The upper wires are supported and spaced by acetyl plastic bridge pieces located on the outer frame and are elevated about .010 in. above the lower set. The use of plate glass insures that the supporting surface is reasonably flat and that the distance between the upper and lower sets of wires is uniform. The stainless steel wire is surprisingly strong, with a breaking strength of over 2 lbs. This permits the upper set to be stretched quite tightly over the lower set so that only one or two wires make contact when pressed by a finger.

As in the grid-style surface, rows and columns are 2 in. wide and form a 9 by 9 matrix. Although an 8 by 8 matrix would permit easier and more efficient binary encoding, the original

matrix size was retained so that existing programs and slides could be used without modification on the new terminal. Wires are spaced .2 in. apart, and wires comprising a given row (or column) are all part of one continuous run of wire. As in the earlier model, the screen is covered by a Polacoat^(R) flexible lens-screen which forms both the touch-surface and the rear-projection screen.

Computer Interface

During the redesign of the touch surface, it became clear that elimination of the grid structure would increase the probability of boundary, or "multiple," touches and that a more sophisticated interface was required. In this new interface, the Y-axis wires are held at ground with TTL drivers, and the X-axis wires are gated into an X-register. Any ground level on the X-wires generates a strobe pulse which is used to gate the position into the X-register. The Y-axis drivers are then brought high; the Y-register is gated into the wires; the X-axis drivers are brought to ground; and the Y-position is strobed into the Y-register. Since the entire cycle occurs in less than $\frac{1}{2}$ microsec, the "window" for multiple touches is quite small. Furthermore, since the control sequence is contingent on data being present at the X- or Y-registers, any bounce occurring between disallow of the X-register and allow of the Y-register will simply result in the circuit's waiting until the next closure. After the Y-axis information is entered, any further input from the touch screen is inhibited until a new

"start" pulse clears the X- and Y-registers and reinitializes the control register.

Several refinements have been made in this basic circuit to facilitate operation in a computer-assisted instruction environment. Since children often touch the screen at inappropriate times or maintain contact with the screen after a response, a circuit was added to delay "allow" of the touch screen until .1 sec has elapsed with no touch data present on the X-axis. This forces the child to remove his hand from the screen surface before a legal touch will be recognized. Secondly, since the touch screen and controller are part of a terminal which will be controlled through a dataphone link over voice-grade telephone lines, data output is encoded and condensed prior to transmission. The X- and Y-touch positions are binary-coded before the X- and Y-registers, and the two 4-bit binary coordinates are further encoded into a 7-bit binary value, which uniquely defines the square touched.

Controlling Systems Software

This gridless touch screen has been incorporated into a new student terminal configuration designed to be Teletype-compatible. As was discussed in the previous section, touch coordinate data is encoded by local logic in the terminal into a 7-bit binary value, which, along with a single parity bit, can be transmitted in a fashion similar to a Teletype character. Although this increases the unit's cost and complexity, no special data channel or systems software is required, and the terminal may be operated off any system supporting Teletypes.

OTHER TOUCH-SENSITIVE SURFACE CONCEPTS

A number of other touch-sensitive surfaces employing different design concepts have been constructed by LRDC and other organizations, although as far as the authors are aware their use has been largely limited to demonstrations. Several of these will be described briefly.

At LRDC, and elsewhere, there has been considerable interest in the use of transparent conductors. Although this was tried in an analog-output device described below, a suitable material that is both transparent and flexible has not been found. A digital-output touch screen has been constructed, however, which uses only one set of wires over Nesa-coated glass.³ Conductive strips were formed by scribing the Nesa coating with a piece of Polacoat covering the screen as in other versions. This unit has been tested and functions reliably but has

not been incorporated in a terminal since the high resistance of the Nesa coating makes direct interface to the new controller more difficult.

A second solution to the problem of producing a completely transparent touch screen is to eliminate conductors completely and use orthogonally crossed light beams, which are interrupted by a finger when the surface is touched. A small prototype photoelectric touch of this type has been constructed at LRDC and appears promising, particularly as a response device placed in front of a CRT screen. However, as a direct replacement for the large, rear-projection touch screen, the photoelectric touch would be significantly more expensive. Also, it is not at all clear that a large touch screen must be completely transparent if used as a rear-projection surface.

Although all of the touch-sensitive devices above are of the digital-output type, a number of analog-output devices have been proposed and designed. One of these, constructed by the Westinghouse Research Laboratories for LRDC in 1966, was based on the familiar voltage-pen graphical input device. The touch surface was constructed from a piece of Nesa-coated glass, which served as the lower conductor, with a flexible sheet of Mylar held slightly above it in an acrylic frame. The inner side of the Mylar was partially silvered to provide a conductive coating. When in operation, a voltage was presented alternately across the X- and Y-directions on the Nesa-glass. A touch contact on the Mylar caused the metallic coating to contact the Nesa-glass, creating a voltage divider, with the output from the Mylar fed into an A-D converter and stored in the appropriate register.

Two serious problems prevented the satisfactory operations of the device. The extremely fragile and uneven metallic coating on the Mylar resulted in "voids" where the coordinate output was wildly erratic, and variations in finger pressure caused corresponding variations in contact area, thus altering the output of the voltage divider. Both problems can be eliminated, given an improved top conductor material and a fast A-D converter; however, the potential advantages of higher resolution and the elimination of visible conductors do not appear sufficiently attractive to justify the development effort and the much higher interface cost.

TOUCH-SENSITIVE SURFACE APPLICATIONS IN A LABORATORY ENVIRONMENT

Although at LRDC the touch-sensitive screen has been used

primarily as a CAI response device, many other interesting applications are possible in a laboratory environment. One of the earliest non-CAI applications at LRDC was to use a small touch surface as a pigeon key in response-generalization studies. A 1 x 10 in. rear-projection key was constructed with 10 horizontal response sectors which were indistinguishable to the pigeon. The first version of the key used an acrylic plastic frame, which supported sets of horizontal and vertical .003-in. stainless wires spaced .1 in. apart, with the horizontal wires adjustable to any desired clearance under the vertical wires. A sheet of Polacoat covered the wires and provided a pecking surface. It was discovered that when the wires were sufficiently close to allow the required 15-25 g of activation force, vibration in the long horizontal wires produced spurious closures. To solve this problem, a new key was designed with longer (3 in.) vertical wires. A piece of ¼-in. Nesa-glass replaced the horizontal wires. The spacing between the wires and the Nesa-glass was made adjustable so that screen sensitivity could be varied. To permit its operations with relay circuitry, the outputs of the key were fed into pulse-lengthening relay drivers. A gate-out circuit inhibited the operation of more than one driver at a time to eliminate multiple contacts produced by a peck on a sector boundary. With the exception of the Polacoat covering, which eventually becomes scarred by pecking and must be replaced, this version of the pigeon key has been quite reliable and has seen heavy use.

Another interesting application in animal learning experiments is to use a touch-sensitive surface to directly read out an animal's position on the floor of an experimental chamber or maze. A "touch-sensitive" floor of this type has been constructed at LRDC for use in pigeon experiments. The floor consists of a gridless, wire-on-wire touch surface with a vinyl covering. The animal's weight causes a touch contact to be made, from which the animal's position can be ascertained.

Experience with the unit has been limited due to other difficulties; however, the concept seems viable and the potential uses are intriguing. When used as the floor of a maze, a touch-sensitive surface could output data directly to a computer, eliminating stopwatches and photocells, while maintaining a detailed record of activity. The walls of the maze could be separate from the touch floor and spaced 1/8 in. above it. One touch floor could be used in a wide variety of experiments, with different mazes or experimental

chambers. Although flexibility would be greatest with computer-driven experiments, the device and its controller could easily be used with simpler control logic. Gates could be added to detect any desired coordinates or coordinate change, and the data could be output to paper tape or some other recording media. For very large floors, a wire-supporting grid would be required to compensate for sag in wires and covering.

A touch-sensitive surface can also be used as a device for rapid data entry. In a recent experiment at LRDC, a human S was asked to recall and pronounce a list of words which would then be presented by the computer in an order contingent on the S's prior order of recall. The problem was to find a method by which the E could quickly and silently reinput the words to the computer as they were pronounced by the S. A Teletype or some other keyboard device was clearly not suitable, since Ss would often recall words at a rate exceeding ½ sec. In the method finally adopted, the alphabetized word list was photographed on a single slide and displayed on the touch-sensitive screen. During a recall period, the E merely touched the appropriate word on the screen as it was pronounced by the S. The method proved satisfactory, and the E had no difficulty inputting the words without data loss, even during periods of rapid recall.

CONCLUSION

Of the touch-sensitive surfaces that have been constructed and used experimentally at LRDC, the basic wire-on-wire design has been the most successful, particularly in the gridless configuration. The units are inexpensive to construct and are reliable in operation. The first wire-wire touch surface constructed at LRDC has been in daily use for over 3 years without a serious hardware failure. The coarse 2-in. resolution of the surface has been found to be adequate for most human response applications; the size of the human finger and the limits in registration accuracy of the slide projectors make finer resolution unnecessary. Although there was some initial concern over the visible conductor wires, experience with the unit has indicated that complete transparency is not essential. The .003-in. wires are only faintly visible and do not obscure the slide image or distract the user. The photoelectric and analog designs, which offer wholly transparent screens, are significantly more expensive to produce and lack both the reliability and ruggedness required in CAI applications with young children.

Because this wire-wire gridless touch performs satisfactorily, no further research and development on touch-sensitive surface is being planned at LRDC. Development efforts are being directed towards touch-sensitive surface applications and the design and construction of new student terminals incorporating touch-sensitive screens.

The total cost of the units constructed is somewhat difficult to estimate since they were constructed as prototypes in our own shops. The cost estimates used internally for the units are:

Wire-Wire Grid Touch

Materials \$ 50

Labor and overhead 600

TOTAL \$650

Wire-Wire Gridless Touch

Materials \$150

Labor and overhead 650

TOTAL \$800

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NOTES

1. Polacoat flexible Lenscreen Type LS60FM is available from Polacoat, Inc., Blue Ash, Ohio 45242. The price is \$2.50/sq ft.

2. This terminal is described in more detail in a technical report entitled, "An advanced touch sensitive display terminal," currently in preparation.

3. NESA-coated glass is available from PPG Industries, 632 Fort Duquesne Boulevard, Pittsburgh, Pennsylvania 15222. The price, for small quantities, is approximately \$30/sq ft for the 1/4-in. thickness.

Two-voice music programming system: The PDP-9 as an automatic electronic organ

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A small computer was programmed to translate two-part musical scores into tables of numbers which were then used in the execution of the music through an amplifier and loudspeaker. The objective was to create sets of tape recordings to be used in psychophysical testing of the discriminabilities and preferabilities of music played on different pitch scales. The close tolerances in the timing of events in such stimulus materials demand special programming techniques and hardware components. The working system is described, and recommendations are made concerning the main features of an improved system.

A small computer has many uses in a psychological laboratory, and it may seem curious that valuable computer time would be used to play music. Our purpose is to prepare stimulus materials for research on the discriminabilities and preferabilities of different musical scales. A particularly interesting question for such research is whether or not people with and without musical training can tell the difference when the same musical composition is played on two particular scales: the just-intonational scale and the equal-tempered scale. For definitions and discussions of these and other scales, we refer to the classic and still highly relevant source, Helmholtz's *Tonemphindungen*, and especially the translation by A. J. Ellis (1930), with copious annotations and appendices. Under conditions where these two scales are discriminable, the question becomes: which is preferable?

In the experimental design for the investigation of these questions, a single stimulus presentation needs to be a sequence of several notes at least,

and the esthetic question really becomes interesting only if the sequences are "pieces" of music self-contained in the sense of a song, a verse, or a movement from a larger composition. Initially, we intend to hold the sequence length and the nominal pitch pattern constant for the most part, while varying, as the main independent variable, the actual pitches slightly about those of the "standard" (just intonational) scale. This entails something like the experimental determination of a psychometric function in the space of 11 dimensions, since it is possible to vary 11 of the 12 pitches independently relative to the others. In many simple pieces of music, however, the dimensionality would reduce to 6, corresponding to the seven natural notes of the major scale. Moreover, these 6 variables are each restricted essentially to a small region in the positive half range of real numbers, since they can be mapped to the six intervals between the successive pitches on the 7-point scale. Nevertheless, the investigation would

be extremely ambitious if carried out by the classical individual psychophysical methods associated with signal detection theory, for example. Therefore, the initial experiments are planned as group experiments in which data are collapsed over individuals as well as trials. From those results, perhaps it will be clear that the detuning of any given pitch in the scale has essentially the same amount of effect as the detuning of any other, and that the effects are additive or combinable in some other way. If so, it should then be possible to define a new single independent variable accounting for the effects of the original 11 or 6. If not, then the particular interaction patterns would be of great interest.

Thus, the experiments would be conducted somewhat in the manner of group audiometry, but with some practice exposure to the sequence played on the standard scale, and with the experimental trials being of the two-alternative forced-choice type. But problems emerge in the control of extraneous variables and even of the primary variable of interest. Ordinary musical instruments are not well suited for changing from one musical scale to another. Even with instruments where such changes are possible, it probably is a rare musician who can adhere precisely to a given musical scale and shift at will from one to another. A computer can be programmed to do these things on command, and it has other obvious advantages for this kind of research. These advantages stem from the exact reproducibility of a sequence of events, and the controllability of changes from one sequence to another.

THE PDP-9 PROGRAMS

The system of programs for the