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HAPTAC: A HAPTIC TACTILE DISPLAY FOR THE PRESENTATION OF TWO-DIMENSIONAL VIRTUAL OR REMOTE ENVIRONMENTS

Christopher J. Hasser

CREW SYSTEMS DIRECTORATE
BIODYNAMICS AND BIOCOMMUNICATIONS DIVISION
WRIGHT-PATTERSON AFB OH 45433-7901

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FOR THE COMMANDER

Thomas J. Moore

THOMAS J. MOORE, Chief
Biodynamics and Biocommunications Division
Crew Systems Directorate
Armstrong Laboratory

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Christopher J. Hasser

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This report describes the development of a tactile display device that allows the user to "see" (feel) a two-dimensional computer-generated surface with his or her fingertip. The user places a fingertip on a tactile feedback array composed of pins that rise through a touch plate. The feedback array, affixed to a position-sensing "mouse" on a digitizer pad, slides across the digitizer pad surface when pushed by the user. As the mouse indicates the changing position of the fingertip, pins in the array rise and fall to simulate a virtual surface underneath the user's fingertip. The pins of the tactile feedback arrays used for this device are driven by shape-memory alloy (SMA) wires that contract when heated by electric current. The low bandwidth of these actuators prevents the user from moving across the virtual surface more than a few centimeters per second, but next-generation actuators with higher bandwidths should improve upon this performance. Applications include tactile perception research, teleoperation, virtual reality, aids for the blind, etc.

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PREFACE

The Human Sensory Feedback (HSF) for Telepresence Project at the Armstrong Laboratory (AL/CFBA) was founded in 1986 in what was then the Harry G. Armstrong Aerospace Medical Research Laboratory. The mission of the HSF team is to study the human interface with telerobotic systems as well as sponsor the development of human interface technology. Current work concentrates on force-reflecting arm interfaces, force-reflecting finger interfaces, and tactile feedback.

When the author joined the HSF project in 1991, there were two tactile feedback arrays in the laboratory that had been provided under a Phase I Small Business Innovation Research (SBIR) contract with TiNi Alloy Co., San Leandro CA. The devices could be used to stimulate the fingertips of a user to represent geometric patterns (shapes, letters, etc.), but the stimulators simply sat on the lab bench and the sensory stimulus felt by the user had nothing to do with any movement of the tactile stimulator. After characterizing the behavior of the array and beginning a series of stationary tactile pattern recognition experiments (with Dr Jan Weisenberger, Ohio State University), the obvious next step was to create a system in which the tactile feedback array acts as a virtual reality or teleoperator feedback device, allowing the user to move the stimulator array to receive haptic feedback corresponding to that movement. The HAPtic TACtile (HAPTAC) Display does just that. Experimental work with this system is being documented with conference papers and journal articles. This special report presents the source code for the system.

ACKNOWLEDGEMENTS

Many people assisted with the creation of the HAPTAC system and the generation of this report. Major Ron Julian and Captain Paul Whalen led the HSF for Telepresence Project and encouraged the development of the system. Monty Crabill, Todd Mosher, John Brinkman, and Jeff Logan, formerly of Systems Research Laboratories, provided crucial know-how and labor to help get the system working (not to mention answering many implementation questions from the author). Dr Jan Weisenberger and Kathy Specht offered valuable input, both as research collaborators and as technology customers. They also bore the brunt of any bugs that popped up while using HAPTAC. Marvin Roark, of Systems Research Laboratories, has helped to maintain the system and has provided the flow charts included as an appendix to this report. Marty Luka and Merry Spahr, also of Systems Research Laboratories, provided technical editing services and shepherded this report through the publication process.

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INTRODUCTION

Humans immersed in teleoperator or virtual reality systems rely on sensory feedback devices to give them a feeling of being "present" in the remote or virtual environment. Teleoperator interfaces have concentrated on feeding back visual, joint position, and joint force information. Virtual reality interfaces have concentrated on stimulation of the human visual and auditory senses.

In the development of teleoperation and virtual reality interfaces, the sense of touch provided by mechanoreceptors near the human's skin surface has not received as much attention as the other senses. Tactile feedback is vital to achieving a full sense of "presence," and to manipulating the remote or virtual environment with dexterity. Even though considerable research exists on the psychophysiology of human touch, the development of mechanical aids to stimulate this sense realistically has continued to be a serious challenge [12]. Tactile feedback requires the development of hardware displays that are lightweight, portable, and suitable for mounting in gloves or other moving strata. Kaczmarek and Shimoga have both conducted thorough reviews on progress to date in developing tactile feedback displays [8, 13, 14].

A planar haptic exploration system with a mobile tactile stimulator array has been developed at the Armstrong Laboratory. A multi-pin tactile feedback array moves over a digitizer pad, providing stimulation to the user to represent a virtual surface. Virtual surfaces have a cell resolution matching the spacing of the stimulator pins on the feedback array. The two arrays used for development of the HAPTAC system have pin spacings of 3 mm and 2.5 mm, although a display recently delivered to the Armstrong Laboratory has pins spaced 1.4 mm apart. Small design advances should allow current technology to achieve 1 mm pin spacing. The pins are actuated by shape-memory alloy (SMA) wires driven by pulse-width modulated (PWM) currents.

Characterization of the feedback array has been accomplished with a laser vibration sensor [5]. Tactile pattern recognition experiments with a stationary array are mentioned briefly, as they lay the groundwork for investigation of the haptic system with a mobile stimulator array. The planar haptic exploration system has only recently been developed, and experimental work is in the earliest stages.

PREVIOUS WORK

Boyd et al. used a Telesensory Systems Optacon II tactile display to construct a moving haptic feedback device to represent graphical user interfaces (icons, menus, windows) on a computer screen [2]. The Optacon II has a 5-column $\times$ 20-row vibrotactile array measuring 1.27 cm $\times$ 2.92 cm. With the first system, the user moved the mouse to control the portion of the screen displayed on the Optacon II. One hand controlled the mouse, and the other used the tactile display. For absolute position reference and one-handed use, the system was improved. The Optacon II vibrators were placed on a planar absolute pointing device (similar to a graphics tablet puck). Tactile enhancements included virtual buttons and tactile "ribs" on the virtual surface to enhance the user's sense of position.

Kuc also used an Optacon II connected to four microswitch motion detectors to conduct experiments on human interaction with information-bearing tactile images [10]. He focused on tactile communication rather than virtual surface representation. The first of three experiments used four human subjects to determine the maximum number of discriminable patterns for various element sizes and densities (similar style of static pattern presentation to that of Hasser and Weisenberger [5]). The second experiment determined maximum attainable data rates for different array configurations using four subjects and the patterns from the first experiment. The third experiment exposed two subjects to a bidirectional vibrotactile communication system with which they performed tasks such as switch toggling and simple vehicle control by interpreting statically presented tactile patterns on a virtual control panel and reacting with small finger motions left, right, up, and down. Finger motions were detected by four microswitches and could be used either to move to a different static display or to toggle some state in the system.

All tactile patterns presented in Kuc's experiments were static; that is, once presented they did not change until a new pattern was presented. This precluded patterns scanning across a stationary finger in the manner of Craig [4] and Hasser et al. [5]. Kuc does not report any experiments where finger motions directly affected stimuli in a manner required for haptic exploration (a limitation determined by the choice of microswitches rather than a position sensor).

Kontarinis and Howe have constructed a 9-pin SMA-actuated tactile feedback array, with stimulators spaced 2 mm apart [9]. They are preparing to mount the device to a pair of planar two-degree-of-freedom finger master controllers, with the tactile feedback arrays perpendicular to the plane of motion [6]. The master-slave testbed also has an identical pair of slave manipulators, which will enable the simulation of two-finger planar telemanipulation with tactile feedback.

There are few reports of direct tactile array feedback in telerobotics. Browse and McDonald compared visual presentations of tactile data combined with visual scene image to simple visual scene image alone, for the ability of subjects to predict a stable grasp on various block-style objects with a parallel jaw gripper [3]. No experimentation with direct tactile feedback to the subject's fingers was included. The authors concluded that visual presentation of tactile data increased the chances that a subject would accurately predict stable or unstable grasp for their experimental setup.

Massimino used discrete piezoelectric buzzers placed in various locations on the hand to improve performance in a telerobotic peg-in-hole task, but did not investigate multi-element tactile feedback arrays [11].

Bliss et al. constructed two tactile feedback systems [1]. A 24-element airjet system fed tactile signals to each of the 24 phalanges on a human hand (excluding the thumb). The second system is more relevant to this discussion; a 4×8 array of piezoelectric bimorphs, spaced on 0.1-inch centers, was used to feed back tactile information from an on-off tactile sensor with similar resolution. The sensor was placed on a pair of gripper tongs, and a master-slave telerobotic system was used to demonstrate performance improvement with the tactile feedback array. The operator's finger is centered over the actuator array. With 12 rows on 0.1-inch centers, the array is approximately 1.2 inches long; the array extends beyond the distal phalange (finger pad) of the index finger and partially onto the medial phalange.

Bliss showed that tactile array feedback slightly reduced task completion times (by about 7%) for a complex latch-removal task, but significantly increased the percentage of tasks completed successfully (17-40% improvement). Tactile feedback became even more important when vision was obscured to varying degrees. Bliss also found that the value of tactile feedback depended on the novelty of the task, suggesting that tactile feedback is important for exploratory work where the tasks are highly variable or perhaps unknown ahead of time. Bliss' results showed that when the object is fragile, hard to find, or requires accurate positioning to be picked up, the tactile feedback system increases efficiency.

The efforts of Bliss, Kontarinis, and Kuc are most relevant to the current work. Bliss provides clear motivation to further develop tactile feedback arrays, leaving many variables open for future investigation. Kuc's trials with various array element sizes and densities may prove useful, though the absence of a position sensor made haptic exploration impossible. The Optacon II also restricted Kuc to using the single 230 Hz frequency of the piezoelectric actuators, with essentially on-off actuation. Bliss was similarly restricted by his piezoelectric actuators. The SMA-actuated array used in this work responds to a range of vibration frequencies and step amplitudes, widening the range of experimental variables. Kontarinis' device bears many similarities to the present device; however, Kontarinis uses slower, thicker SMA wires (0.75 mm versus 0.1 mm) which produce higher stimulator pin forces (1.2 N versus about 0.2 N) than the present device. Kontarinis uses relatively continuous power control generated by a digital-to-analog converter, producing a non-vibratory stimuli. The question of adequate stimulator pin force is an open one. The Kontarinis system is designed so that the stronger stimulator pins must support the force of a human finger in force-reflecting telemanipulation. The present system uses a protective touch plate (described below) that supports the finger, limiting load force on the stimulator pins.

SYSTEM DESCRIPTION

30-Pin Tactile Feedback Array

A tactile stimulator has been constructed for research into human perception of multielement tactile feedback [7]. The tactile stimulator array has 30 elements arranged in a 5×6 rectangle, 1.2 cm wide and 1.5 cm long. Element tips are evenly spaced 3 mm apart in both directions. Each element is an "L"-shaped cantilever beam, with the long leg of the beam lying horizontally under a touch surface. One end of the beam is anchored; on the other end, the short leg of the "L" protrudes through one of 30 holes in the touch surface. The human subject's finger, lying on the touch surface, feels the stimulator tips as they rise upward through the holes.

Short, thin, SMA wires which contract when heated under prestress are connected at one end to the long legs of the stimulator elements. One 15 mm long, 0.1 mm diameter wire actuates each stimulator element. The nickel-titanium SMA wire, anchored first on an insulator block above the base and again at the middle of the cantilever beam, bends the beam upward when heated by electric current. PWM signals provide the current to the actuators. Both the period and duty cycle of these rectangular signals may be varied, where the duty cycle is the percent of time the binary pulse is "on." Figure 1 shows dormant and actuated stimulator elements.

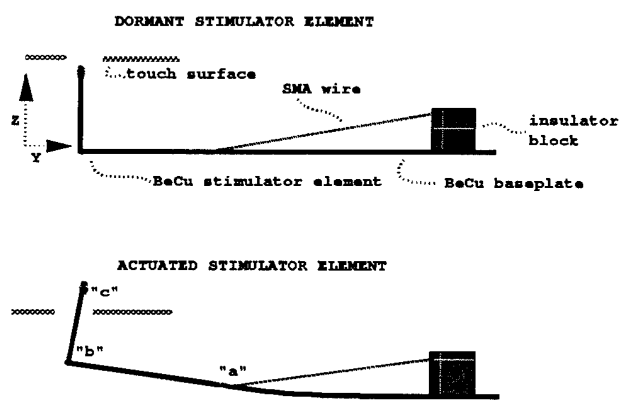

Figure 1: Dormant and Actuated Stimulator Element

In addition to the desired z-axis displacement towards the fingertip, motion at the tip has a translation component along the y-axis, as well as a rotational component. This complex motion makes displacement sensing difficult.

The 30 stimulator elements were acid-etched out of a single flat baseplate in a staggered diagonal pattern so that the upward-bent tips of the diagonally aligned elements form the rectangular array. Fifteen elements are anchored from either end of the baseplate at one of two insulator blocks. On each side, the 15 elements alternate with three lengths: short, medium, and long. Three lengths were necessary so that elements could reach to three of the six rows from each of the two base insulator blocks.

The SMA wires attach to all the elements at the same distance from the insulator blocks, regardless of element length. Geometric variability occurs because the longer elements extend farther upward when actuated. To see this, look at the actuated element in Figure 1 and extend the distance between points "a" and "b," causing point "c" to rise slightly higher. The difference in mass beyond the SMA attachment point "a" causes variability in the dynamic behavior between elements of different lengths.

Force exerted against the finger tip by an individual stimulator is on the order of 0.2 N (about 20 grams at 1 g). Data on the fully-loaded displacements and stiffnesses of the stimulator elements are not yet available.

9-Pin Tactile Feedback Array

In response to experience with the 30-pin tactile array, TiNi Alloy Co. developed a 9-pin array as an early prototype during a Phase II Small Business Innovation Research (SBIR) contract with the Armstrong Laboratory. The pins in the array are each powered by an SMA wire that extends in a "V" shape from the end of the pin opposite the finger to the mounting base. The left side of Figure 2 shows a view of the underside of the "V"-style tactile stimulator array. The right side of Figure 2 shows the mounting box sitting atop the modified digitizer pad mouse, with part of the cooling fan showing as a yellow, white, and red disc in the upper right-hand corner.

Figure 2: A View of the Underside of the 9-Pin Tactile Stimulator Array

The 9-pin array has a more forceful actuation than the 30-pin array; according to TiNi Alloy Co., it can produce a force equivalent to 60 grams, compared to 20 grams for the 30-pin cantilevered design. It has rise times closer to 50 ms, an improvement over the 170 ms rise time of the 30-pin array. The 9-pin array has a pin spacing of 2.5 mm.

Description of the Haptic Tactile Feedback System

A two-dimensional tactile haptic display has been constructed, with a tactile feedback array attached to the pointer on a Calcomp Drawing Board II digitizer board. The digitizer board provides high-resolution, absolute position information. As the user moves the tactile array across the digitizer board, the array acts like a moving window on a virtual surface described by a two-dimensional array in the software program. The digitizer can provide position but not rotation information, so the user must keep his or her index finger pointing straight towards the top of the page. A photograph of the system appears in Figure 3.

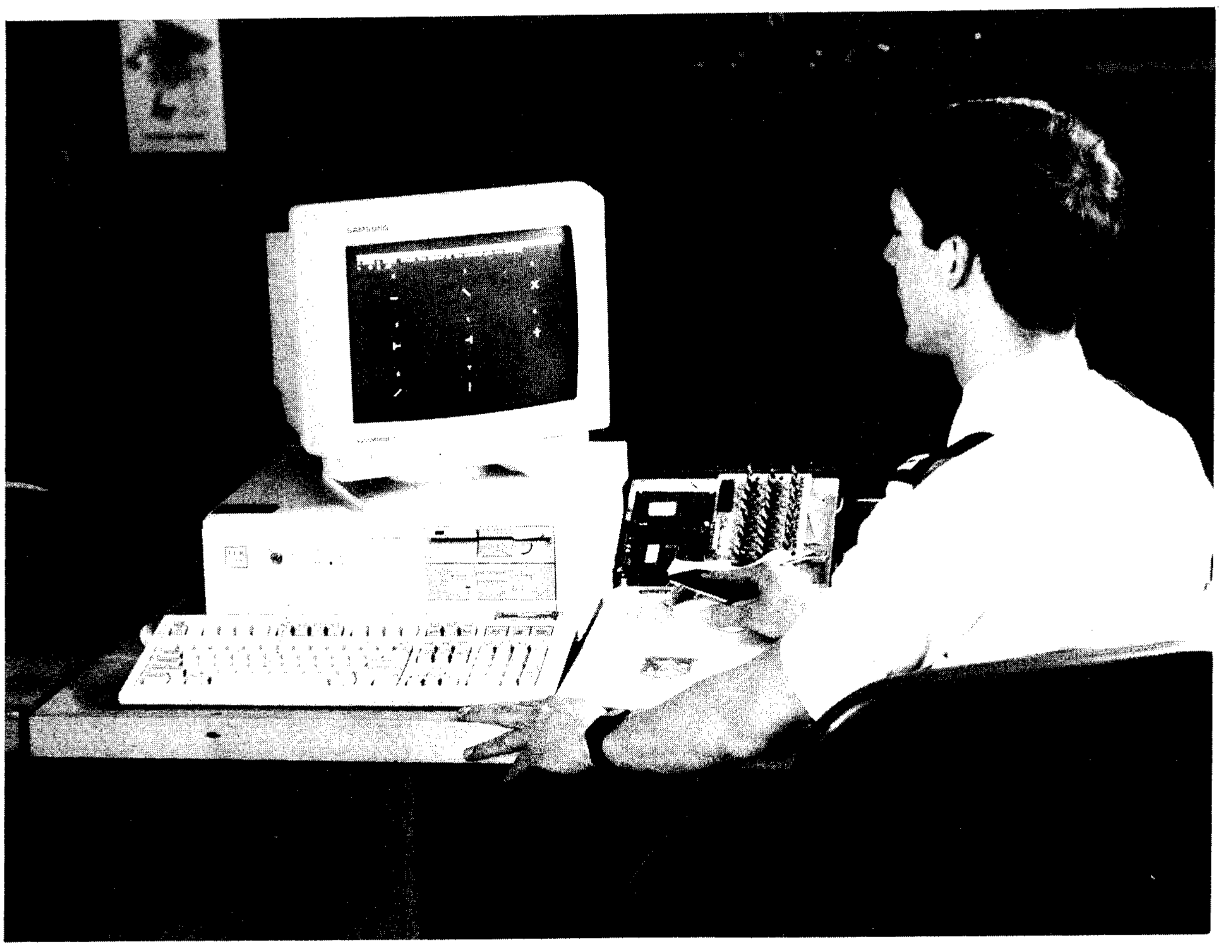

Figure 3: The Haptic Tactile (HAPTAC) System

Each cell in the virtual array corresponds to a 3 mm $\times$ 3 mm square on the virtual surface (matching the resolution of the tactile feedback device). In the simplest implementation, each cell represents either a raised feature on the virtual surface or remains a part of a featureless background.

If a tactile feedback pin passes over a "raised" cell on the virtual surface, it rises to stimulate the user's finger; otherwise, it remains dormant. Pins can also be actuated with less upward movement to represent a surface with no raised edges.

The system software presents a single virtual surface at a time; the user feels this surface while sliding the feedback array across the digitizer pad. Experimental software can present a series of these surfaces in random trials. Subjects in the random trials are prompted to enter the number of the surface they feel. Experimental variables include stimulator pin frequency, PWM duty cycle, and a mask that can disable any of the stimulator pins. The capability exists for automatic limiting or measurement of the time required to identify a virtual surface or perform a task.

INSTALLATION

Components

- Personal computer (equal to or faster than IBM 386)
- Digitizer pad
- Modified digitizer pad mouse
- Tactile feedback array with amplifier box
- HAPTAC software

Software

Load all of the software into a dedicated subdirectory (e.g. C:\HAPTAC), and create a subdirectory HAPDAT (e.g. C:\HAPTAC\HAPDAT) to store any experimental data that are created. Necessary software includes HAPTAC.EXE, CCMOUSE.COM, and any .SUR (virtual surface) files. The .SUR files use simple ASCII text (0's, 1's, and 2's) to describe virtual surfaces. Refer to Appendix A for an example .SUR file. Other relevant files include the set files (*.SET) containing sets of surfaces, and mask files (*.MSK), allowing pins to be selectively disabled.

Digitizer Pad

- Connect the digitizer pad's serial cable to COM1 on the computer.
- Connect the modified digitizer pad mouse (flat acrylic, with locator coil).
- Connect the 1/8" power plug from the wall transformer to the appropriate socket (either on the back of the digitizer pad or on the serial connector, depending on the model).
- Turn the digitizer pad "on" using the switch on the back edge.

Tactile Stimulator

- Plug the power supply into the wall.
- If the power supply is separate from the control box (depends on prototype version), connect them.
- Plug data cable into parallel port (PTR1) on computer.
- Connect tactile stimulator array to control box.
- Attach tactile stimulator array to modified mouse using Velcro.

OPERATION

Upon starting HAPTAC.EXE, the user will encounter a window offering five possible options:

Run experiment Multiple surfaces will be presented to the user, one at a time and randomly selected. The surfaces will be taken from a set of up to 10 surfaces defined by the user. Visual images of all possible surfaces will be displayed on the computer screen with a number for each surface, and the user will be prompted to enter (using the keyboard) the number of the surface he or she feels.

Demo one surface A single virtual surface will be presented to the user. In a later window, the user will select from a list of the .SUR files contained in the current directory.

Set creation This option allows the user to assemble a set of up to 10 already existing .SUR files and to give that set a name for later use in experimental trials.

EXIT Exit the program and return to DOS.

Subsequent windows will prompt the user for information (e.g. the surface to be demonstrated, or the subject's initials). One of these windows will ask the user to enter two sets of parameters for pulse-width modulation (PWM) period and duty cycle. The second PWM period **must** be a multiple of the first; this requirement results from simplifying assumptions made in the software.

Another window also provides the user with the ability to mask out certain pins. This allows experiments to be run with a smaller array of active pins, or with a particular pattern of pins disabled. Mask files are particular to the display being used (mask files for the nine-pin display won't work with the 30-pin display, and vice-versa). All mask files end in `.MSK`, and can be edited using a text editor.

Troubleshooting

- Mouse coordinates in the upper left-hand corner of the screen should change as the mouse moves. Lack of coordinates or frozen coordinates is an indication that HAPTAC is not communicating with the digitizer pad. Check connections, digitizer pad power, etc.
- Problems can often be solved by turning the digitizer pad "off" then "on," and/or restarting the HAPTAC program.
- If the logic input to the tactile stimulator array seems to be working, but the pins do not rise, make sure the "dead man's switch" is activated.
- Due to a programming bug, an experimental subject may need to move the mouse while hitting the keyboard key representing his or her desired response (if the mouse is not moving, the program may not check keyboard for input).

EXPERIMENTAL ISSUES

Since the tactile stimulator pins rise and begin vibrating when activated, the stimulus resembles a vibratory motion superimposed upon a step displacement. This type of stimulus does not directly correspond to earlier tactile perception research and devices; comparison to, and use of, previous results must be approached cautiously. Furthermore, the PWM control that causes this unique behavior is not the only successful way to drive SMA actuators for tactile feedback [9].

The development of this system leads to many questions. How will the vibratory behavior and the speed with which the pins are able to rise through the holes in the touch plate affect perception? At what rate will the subject be able to move his or her finger before there is a perceptible lag in the response of the stimulator array? What perceptual artifacts will be produced by moving too fast? The maximum finger speed with the present unoptimized system appears to be only a few centimeters per second. At excessively fast rates of motion the user seems to feel nothing, as the pins do not have time to rise before the stimulator array is positioned over different cells on the virtual surface.

The fact that the SMA wires are thermally actuated and produce waste heat may mean that surface feature density (likelihood that many pins will be actuated repeatedly) will affect stimulator behavior. The effect may be advantageous, decreasing pin rise time by increasing nominal temperature, or disadvantageous, saturating actuators with unusually high ambient temperatures.

How fast should the pins vibrate, and how high should they rise, in order to produce effective percepts? How should we define the term "effective?" Vibration frequency can easily be confirmed, but data on amplitude behavior of loaded pins (finger placed on top of stimulator pins) will likely be more difficult to obtain.

In addition to the questions relating to individual pin control, questions exist concerning the array as a whole. How do pin density and the number of pins in the array affect perception? Each of these factors could be addressed in a preliminary way by activating a reduced number of pins in the display.

The perception of touch with the SMA tactile array is complicated by the fact that this stimulator delivers sensory cues in an alien fashion, actuating some mechanoreceptors in ways that do not correspond to "real world" contacts. Learning how to use this stimulator with some normal cues absent and some alien cues present will be a challenge for experimenters.

System Sample Time and Latency

In the current configuration the computer must turn the pins on and off every time they vibrate and must also read the digitizer position. Since this is done without interrupts, the maximum rate at which the program can sample the digitizer pad location is determined by the period of the lowest frequency stimulus being used (the longest period in use). Only after the program has completed a complete on-off cycle will it check the digitizer position. Thus, for a 10 Hz stimulus (close to a worst-case scenario), the digitizer pad position would only be sampled at 10 Hz (every 100 ms). The digitizer sampling rate might be improved by moving to an interrupt-driven scheme.

Ideally, the sample period would be much less than 50 ms. Exactly how low a sample period would be useful depends on the ability of the SMA wires to respond to rapidly-changing commands. At some point, the SMA actuator bandwidth rather than the computer control rate will be the limiting factor. Indeed, this is probably the case with high frequency operation, where the computer checks the digitizer pad at 200 Hz and the magnitude of vibration of the pins begins to drop off.

System latency must also be considered. It takes a computer running a serial port at 9600 baud about 6 ms to read the six-byte packet of information from the digitizer pad. It also takes time for the nine or 30 bits of information to be fed into the register in the SMA driving hardware, but this delay is dwarfed by that of the digitizer pad. No matter how fast the control loop runs, the control algorithm will always be using somewhat old information. At some point this may become a system limitation (again, the bandwidth limitation of the SMA actuators may keep this delay from becoming apparent to the user).

OBJECT I.D. WITH MOVING VERSUS STATIONARY FINGER

The ability of subjects to discriminate the simple patterns of Figure 4 has been tested with subjects' fingers resting upon a stationary feedback array [5]. Subjects were able to identify the patterns with accuracy approaching 100%. These data provide a baseline against which to test the mobile stimulator array. Subjects were also tested for their ability to discriminate between wave-like line stimuli moving in eight different directions (up, down, left, right, and along both directions on the main diagonals) [5]. These direction-of-motion tests also yielded near 100% accuracy. In

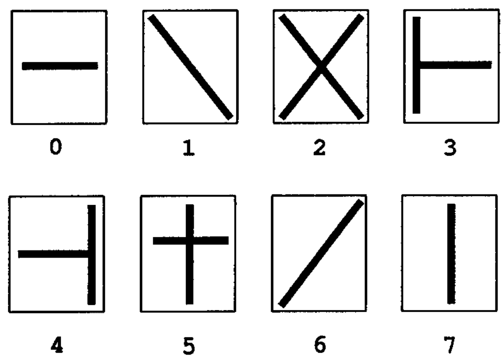

Figure 4: Static Pattern Icons Used in Perception Experiments

experiments currently underway, the patterns will be scrolled from right to left across the subject's finger as it rests passively on a stationary feedback array. In a later experiment, the patterns will be presented one at a time on the virtual surface, in random trials. The subjects will be free to move the stimulator in two dimensions to identify the pattern on the virtual surface. Preliminary experimental results indicate that identification of single-line patterns (numbers 0, 1, 6, and 7) will be extremely easy, while identification of double-line patterns (numbers 2, 3, 4, and 5) will require more training.

BASIC OBJECT REPRESENTATION ISSUES

Normal objects felt during a task do not resemble a grid of vibrating pins. Very basic choices must be made for object representation, such as whether to represent the shapes on the virtual plane by solid filled-in shapes or hollow edge-only shapes. Pins positioned over the center of a filled-in virtual rectangle would vibrate, while pins over the center of a hollow rectangle would not.

Earlier experiments with vibrotactile arrays such as the Optacon have been limited to a predetermined stimulus amplitude and frequency. Pins representing the edge of a shape and pins representing the centers of filled-in shapes behaved similarly. People clearly do not perceive edges of raised shapes in the same way they perceive the textured surfaces of the shapes. This will influence more than the outcome of the filled in versus hollow question. If people perceive edges and textures differently, should the two be represented with different stimulus parameters?

Variable Duty Cycle with Motion

When a finger is stationary on a non-vibrating object, most mechanoreceptors are not stimulated, or have adapted to the stimulus, depending on the degree of indentation of the skin surface. The situation in which mechanoreceptors are not excited by a given stimulus is referred to as "stimulus failure"; this is a misleading term, since the stimulus is simply outside the sensing envelope of the mechanoreceptor and no pathological failure has occurred.

The current system vibrates the pins whenever the array is positioned over a virtual feature. This constant stimulation may limit the realism of the percept, countering "stimulus failure" or adaptation that would be present when sensing non-vibratory stimuli. A method to mimic "stimulus failure" or adaptation by reducing the magnitude of the stimulus might be useful. It is relatively easy to detect a change in the x-y position of the mouse and activate the stimulator pins only when the subject moves his or her finger. Instead of turning off the pins when the subject remains still, the duty cycle could be dropped by 5 or 10% to keep the wires heated, producing a more subtle reduction of stimulus intensity.

This technique was implemented so that as soon as the finger stops moving, the stimulation stops. This percept was noticeably different. The first subject (BD) did not notice a great difference, but he may have been responding to the question, "Is there an object on the virtual surface when you hold your finger still?" rather than to, "Do you actually feel stimulation when you hold your finger still?" BD had been using the stimulator for quite a while; he stated that the case of constant vibration (even when finger is still) did not feel as pronounced when his finger was still. This perception could have been caused by adaptation, or by ambient-temperature induced bandwidth loss in the SMA wire, or by some unknown factor. Other subjects, PW and DN, felt that the sudden removal of stimulus when they stopped moving their finger was distracting and did not seem to mimic a real experience adequately. Less drastic reductions in duty cycle may produce a more subtle effect closer to adaptation. Further experimentation will be required to determine if this approach adds any value to the percepts.

FUTURE WORK

Recently Completed or in Progress

Early work published by this author and J. W. Weisenberger studied tactile pattern perception using the SMA feedback arrays, but did not include the ability for the user to haptically explore a virtual surface [5]. Research has proceeded more or less continuously since that early work and since the establishment of HAPTAC. Immediately after HAPTAC became operational, Weisenberger and this author studied tactile object perception on HAPTAC using the simple patterns developed for [5]. That effort also involved more complicated letter patterns perceived in static, scanned, and haptic modes [15]. In subsequent work, Weisenberger et al. studied the effect of varying the field of view (number of pins at a given spacing) on pattern perception with HAPTAC [16]. The most recent work to be published by Weisenberger et al. varies presentation time of scanned and statically presented patterns, attempting to control for some of the advantages caused by the subject's ability to repeatedly explore a pattern in the haptic mode [17].

Miscellaneous Thoughts

One future task might be to explore a "socket" on a tactile field, then to identify the corresponding "plug" on a video screen. Subjects might be asked to match triangular, square, or round "pegs" (positive images) and "holes" (negative images). Subjects could be asked to count the number of like shapes on the virtual surface, with or without interference from other shapes.

The ability to represent edges so that subjects can follow them with their fingers may turn out to be a significant strength of this system, since it can represent line stimuli so well. Subjects might be tasked to follow a complex edge with distracting edges in a confusing environment. They might try locating a virtual "D" connector socket on the back of an imaginary panel. For both shape detection and edge following tasks, subjects would be expected to show improvement in completion times with an increase in the number and density of stimulator pins.

TacGraph

A graphics display program for blind individuals has been developed by joining the HAPTAC system to the shareware graphics driver "gnuplot." The interface is essentially a special gnuplot device driver, with output being to the virtual surface rather than a printer or the screen. A copy of the virtual surface is also displayed on the screen for the sake of sighted users. Braille titles and axis labels appear on the virtual plots. Multiple frequencies of pin vibration can be used to represent different data curves. Voice synthesis using a Soundblaster board gives the user information on demand about plot title, axis labels, cursor position, magnitude ranges, and axis ranges. A patent application has been made, and an Armstrong Laboratory technical report will likely follow.

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APPENDIX A: EXAMPLE SURFACE FILE

```
SQUARES.SUR        10

00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000222222222222222000000000022222222222222200000
00000222222222222222000000000020000000000000200000
00000222222222222222000000000020000000000000200000
00000222222222222222000000000020000000000000200000
00000222222222222222000000000022222222222222200000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000222222222222222000000000011111111111111100000
00000211111111111112000000000011111111111111100000
00000211111111111112000000000011111111111111100000
00000211111111111112000000000011111111111111100000
00000222222222222222000000000011111111111111100000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000
```

Figure 5: Example Surface File: 1's and 2's Denote Features, 0's Denote Background

APPENDIX B: DIGITIZER PAD SETTINGS

The digitizer has two banks of Boolean flags that can be set using the row of buttons at the top of the digitizer pad. The settings of these flags determine the operating behavior of the digitizer pad. The Calcomp manual has some useful information, but was not designed for system developers, so this appendix records some "lessons learned."

Access the flag banks by moving the mouse pointer (the localizer coil) to the upper left-hand corner, over the button labeled "CONFIG/EXIT." With the mouse pointer positioned over the "CONFIG/EXIT" button, press the "0" button on the mouse housing (note that with the current version of HAPTAC, the mouse has been disassembled so that the coil and housing are separate). Move the pointer coil over the "A" button and notice that the "POWER" pilot light is on. This light will be used to indicate the states of various flags. Move over the "B" button and notice that the "POWER" light goes off. This means that you are currently working with Bank "A." Pressing the "0" button on the mouse housing while over the "B" button will switch to Bank "B." Move the coil over the numbered buttons 1-18, and watch the "POWER" light to see which flags are set "high." Pressing the "0" button on the mouse housing while over a numbered button will toggle the corresponding flag for whichever bank is currently activated (A or B). To exit the configuration mode and return to digitizer pad operation, toggle the "CONFIG/EXIT" button.

Considerable trial and error went into determining the proper settings. The Calcomp user's manual was moderately helpful, as was Calcomp technical support. The Human Sensory Feedback group owns two versions of the digitizer pad: Digitizer Pad II and Digitizer Pad III. The manual for Digitizer Pad II may actually contain more detailed formatting information. Most recently, the settings that have been used are:

Bank:	Flags that should be set high:
A:	1, 2, 4, 6, 9, 10, 12, 14, 15, 16, 18
B:	3, 4, 10, 14, 17, 18

Unfortunately, these settings do not always work. There is a program, CCMOUSE.COM, that was shipped with the digitizer pad. These are the default settings used by that program. In a recent experiment, manually setting the flags failed, but running and then exiting CCMOUSE.COM set the flags to the states listed above, and the digitizer pad worked as expected. Although manual setting does seem to set flag states (as indicated by the checking with the mouse and "POWER" light), seemingly identical state settings had different behaviors, depending on whether they were manually loaded or set using CCMOUSE.COM. This situation arose while this author was programming HAPTAC to use the "proximity" indicating option of the digitizer. This option indicates whether the pointer coil is on or off the digitizer pad.

APPENDIX C: LIST OF SUPPLIERS

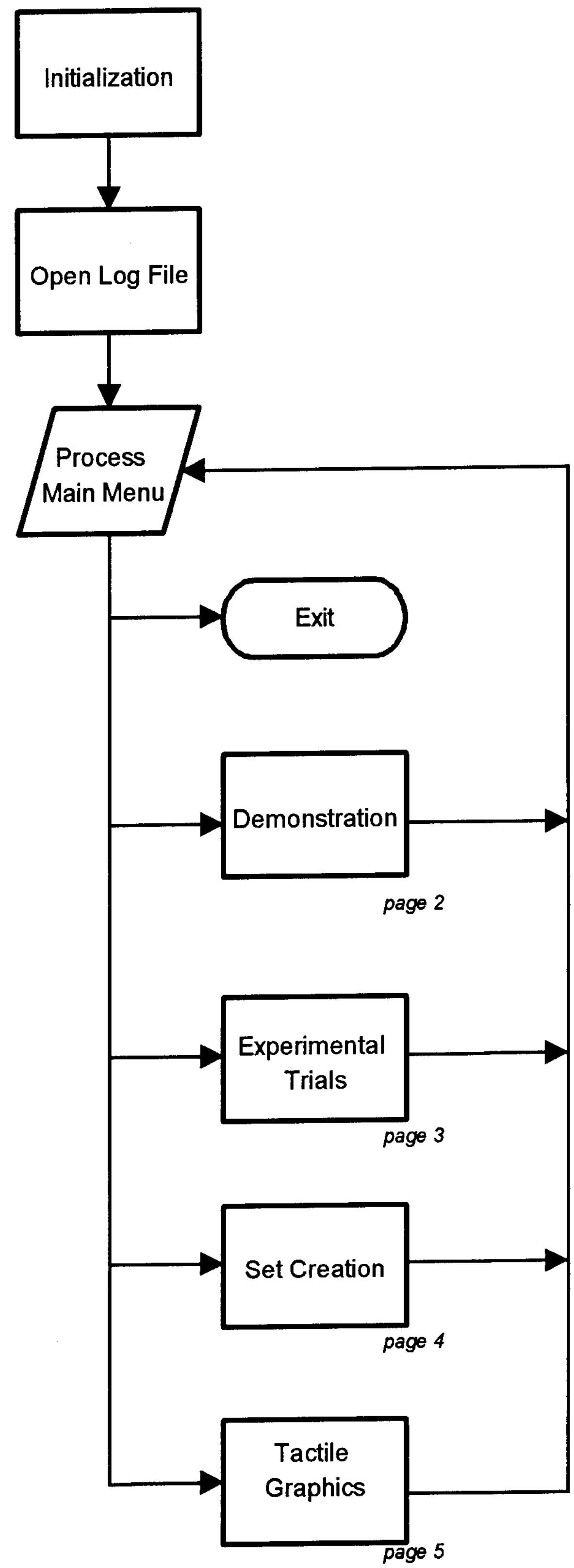
BORLAND INTERNATIONAL
P.O. BOX 660001
1800 GREEN HILLS ROAD
SCOTTS VALLEY CA 95066-0001
PHN: 408-438-5300
supplied C compiler

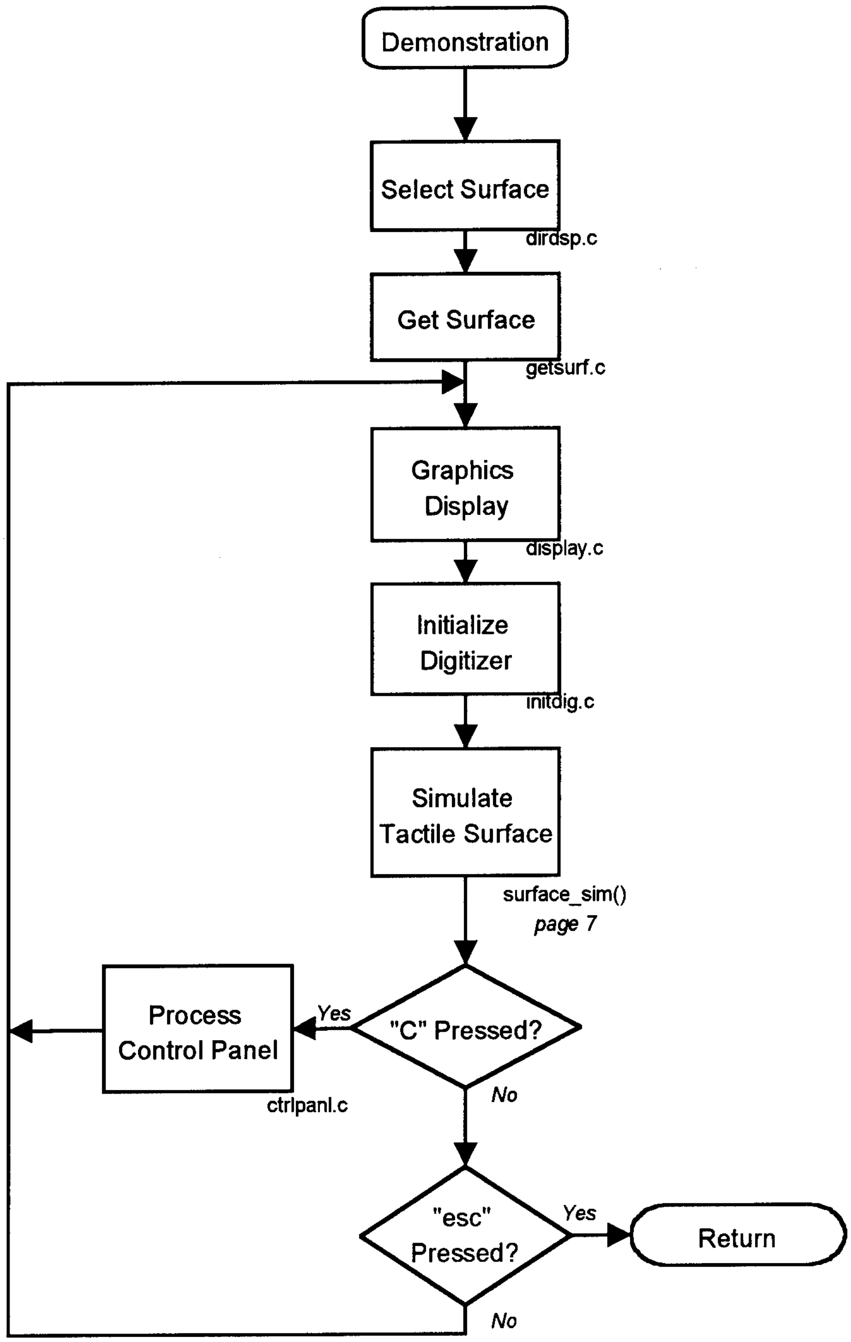
CALCOMP
DIGITIZER DIVISION
14555 N 82ND STREET
SCOTTSDALE AZ 85260
PHN: 800-458-5888
FAX: 602-948-5508

TINI ALLOY COMPANY
1621 NEPTUNE DR
SAN LEANDRO CA 94577
PHN: 510-483-9676
FAX: 510-483-1309
Email: tini1@holonet.net
Email: tini@aol.com

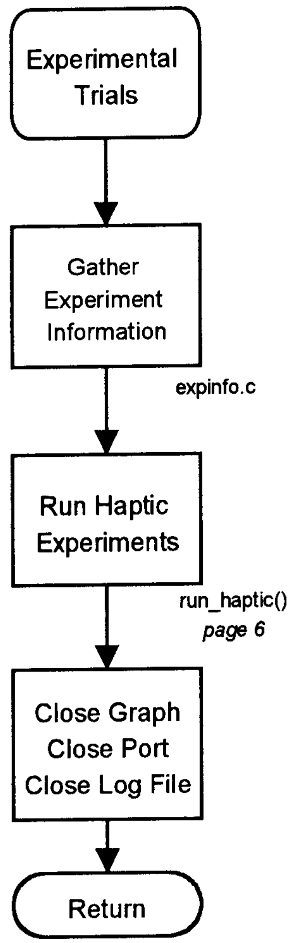
APPENDIX D: FLOW CHARTS

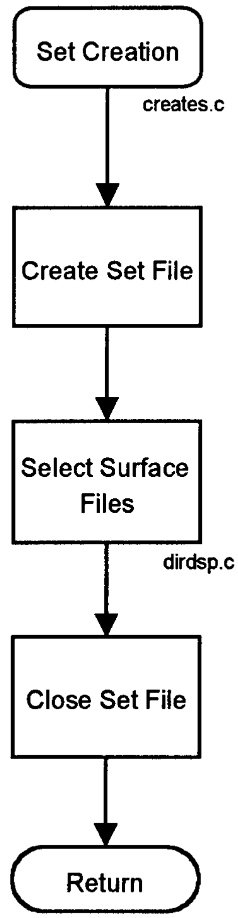
HAPTAC2

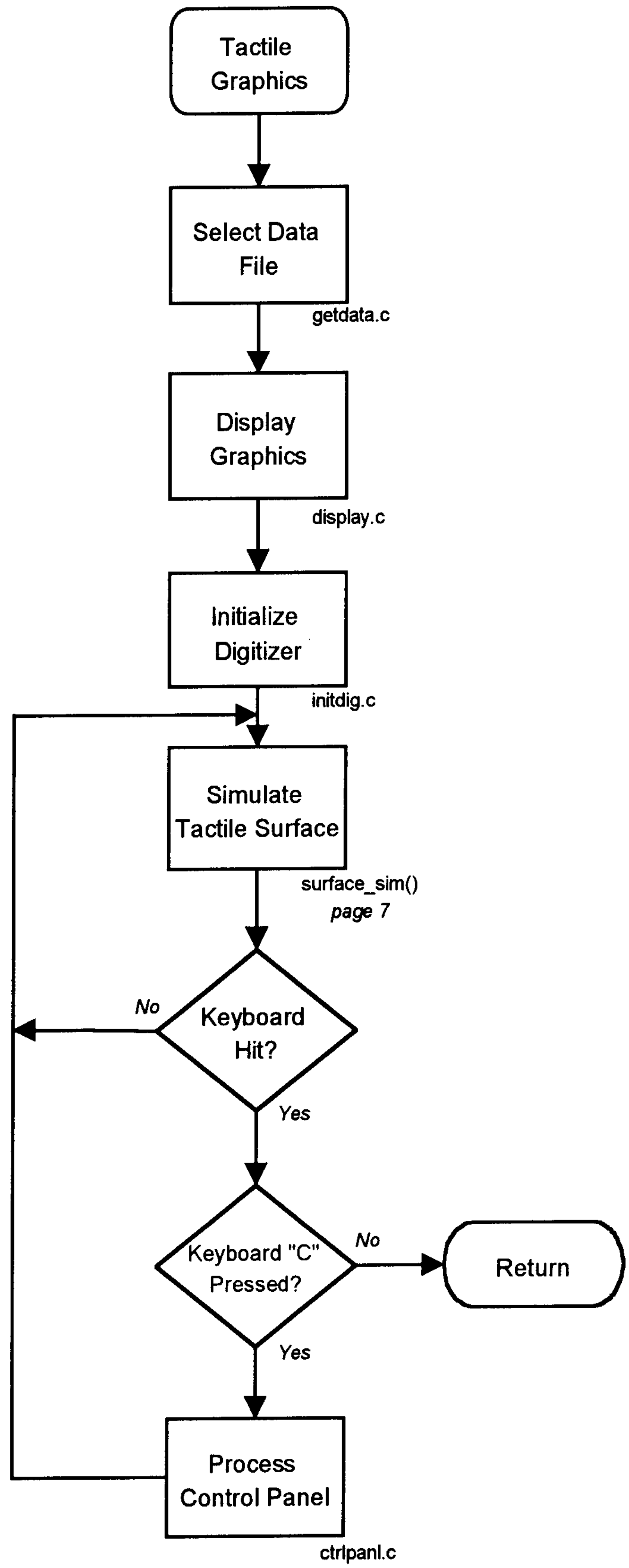

Initialization
Open Log File
Process
Main Menu
Exit
Demonstration
page 2
Experimental
Trials
page 3
Set Creation
page 4
Tactile
Graphics
page 5



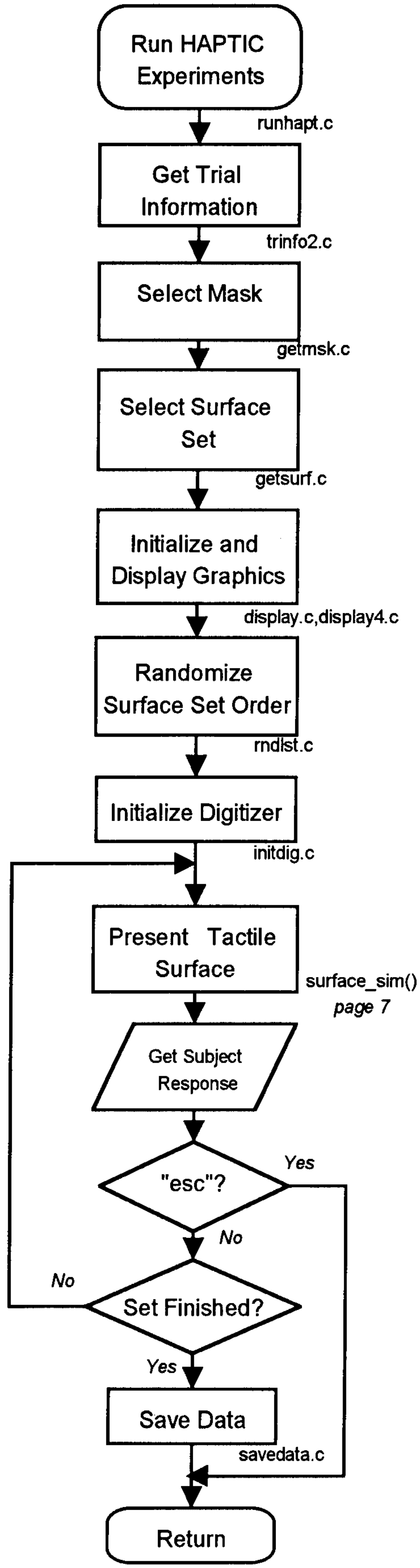
Demonstration
Select Surface
dirdsp.c
Get Surface
getsurf.c
Graphics Display
display.c
Initialize Digitizer
initdig.c
Simulate Tactile Surface
surface_sim()
page 7
"C" Pressed?
Yes
No
Process Control Panel
ctrlpanl.c
"esc" Pressed?
Yes
No
Return


Experimental
Trials
Gather
Experiment
Information
expinfo.c
Run Haptic
Experiments
run_haptic()
page 6
Close Graph
Close Port
Close Log File
Return

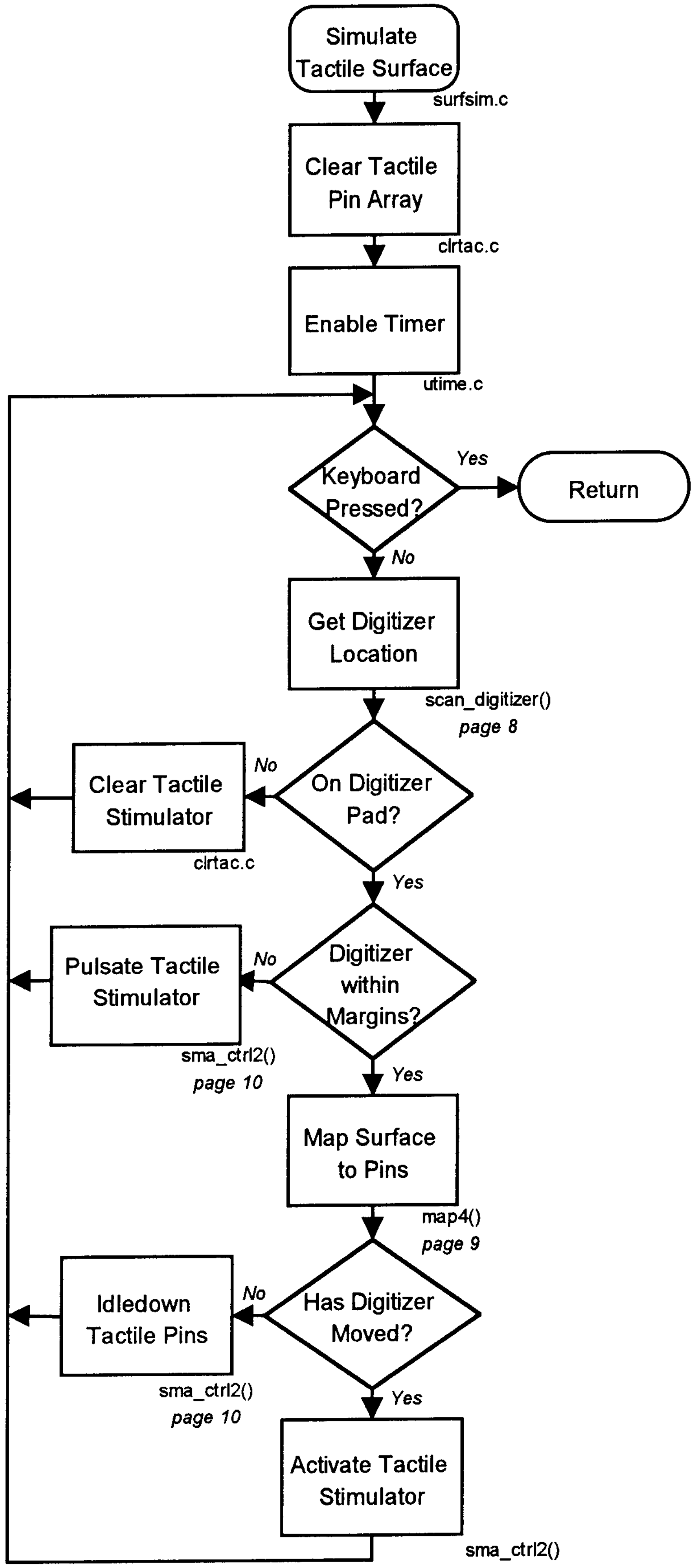

Set Creation
creates.c
Create Set File
Select Surface Files
dirdsp.c
Close Set File
Return

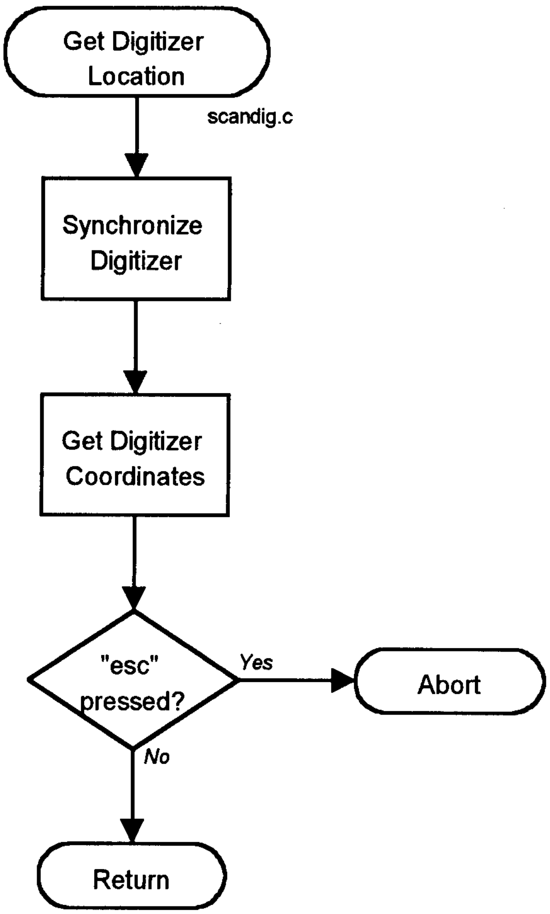

Tactile Graphics
Select Data File
getdata.c
Display Graphics
display.c
Initialize Digitizer
initdig.c
Simulate Tactile Surface
surface_sim()
page 7
No
Keyboard Hit?
Yes
Keyboard "C" Pressed?
No
Return
Yes
Process Control Panel
ctrlpanl.c

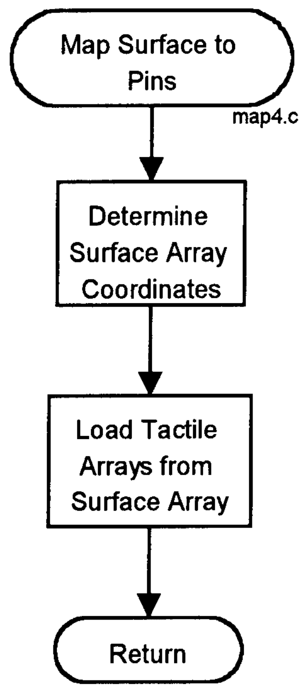
Page 5

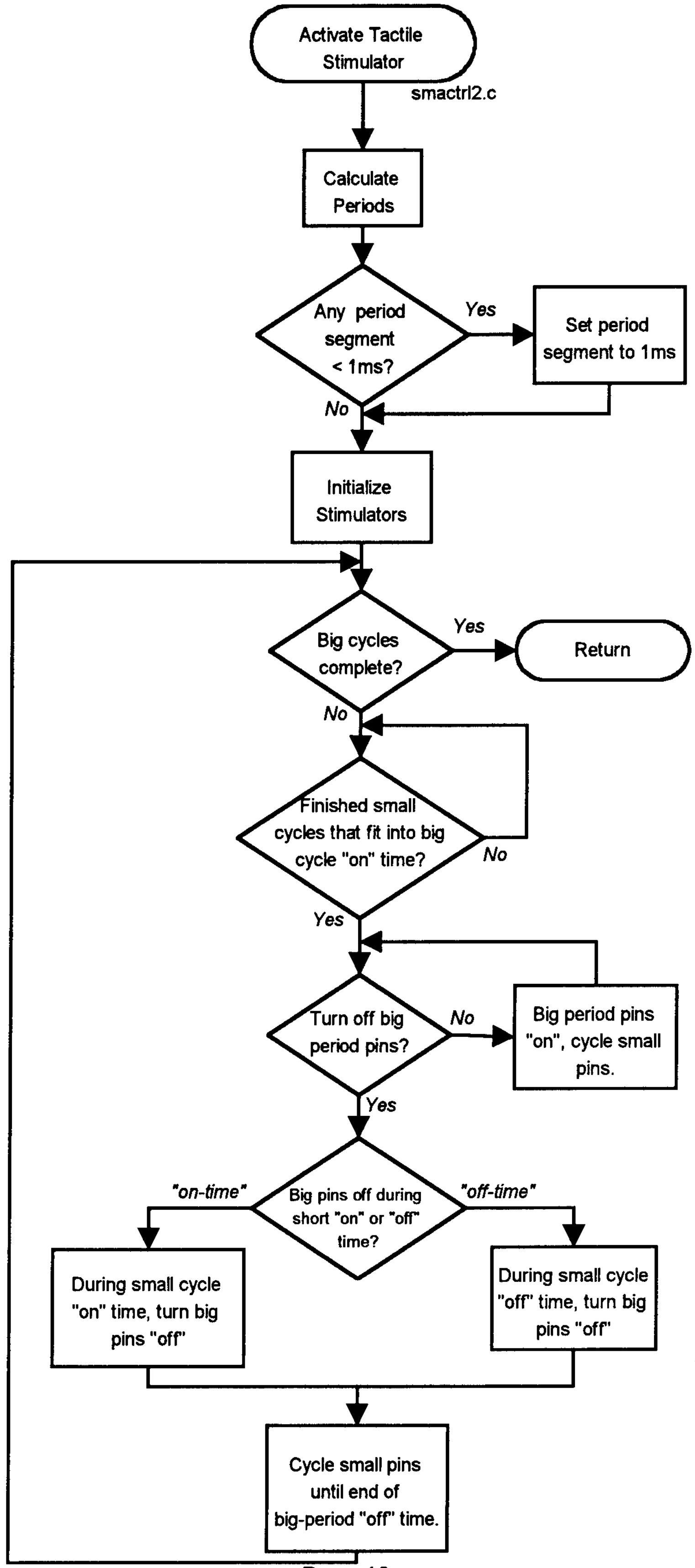

Run HAPTIC Experiments
runhapt.c
Get Trial Information
trinfo2.c
Select Mask
getmsk.c
Select Surface Set
getsurf.c
Initialize and Display Graphics
display.c,display4.c
Randomize Surface Set Order
rndlst.c
Initialize Digitizer
initdig.c
Present Tactile Surface
surface_sim()
page 7
Get Subject Response
"esc"?
Yes
No
Set Finished?
No
Yes
Save Data
savedata.c
Return

Page 6


Simulate Tactile Surface
surfsim.c
Clear Tactile Pin Array
clrtac.c
Enable Timer
utime.c
Keyboard Pressed?
Yes
Return
No
Get Digitizer Location
scan_digitizer()
page 8
On Digitizer Pad?
No
Clear Tactile Stimulator
clrtac.c
Yes
Digitizer within Margins?
No
Pulsate Tactile Stimulator
sma_ctrl2()
page 10
Yes
Map Surface to Pins
map4()
page 9
Has Digitizer Moved?
No
Idledown Tactile Pins
sma_ctrl2()
page 10
Yes
Activate Tactile Stimulator
sma_ctrl2()
page 10


Get Digitizer Location
scandig.c
Synchronize Digitizer
Get Digitizer Coordinates
"esc" pressed?
Yes
Abort
No
Return


Map Surface to Pins
map4.c
Determine Surface Array Coordinates
Load Tactile Arrays from Surface Array
Return



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