1997 International Symposium on Experimental Robotics, Barcelona, Spain. June 1997.

Mechanical Design and Control of a High-Bandwidth Shape Memory Alloy Tactile Display

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Abstract: We have constructed a tactile shape display which can be used to convey small-scale shapes in teleoperation and virtual environments. A line of 10 pins spaced 2 mm on center are each actuated with a shape memory alloy wire. A combination of careful mechanical design and liquid cooling allows a simple proportional controller with constant current feed-forward to achieve 40 Hz bandwidth. To quantify the value of increased bandwidth, an experiment involving a prototypical search task has been conducted using the display. A digital filter limited the frequency response of the display to three cutoff frequencies: 1, 5 and 30 Hz. Subjects were able to complete the search more than six times as quickly with 30 Hz bandwidth than with 1 Hz.

1. Introduction

We are developing systems for conveying small-scale shape information in teleoperation and virtual environments. These tactile display devices consist of an array of pins that are raised and lowered against the finger tip. Our goal is to recreate skin deformations that might be produced by object features such as corners, raised edges, and surface textures. One important application area for these displays is minimally invasive surgery, where the display can reproduce tactile information sensed by instruments within the patient's body. A key example is the localization of tumors, which often appear as hard lumps embedded in soft tissues, such as the lung and the liver [1].

Recent experiments by Peine et al. [2] show that surprisingly high bandwidth is required for effective tactile display. These experiments used an optical tracking system to measure finger speeds while experienced surgeons located simulated tumors in soft rubber models. They found that maximum finger speeds for 90 percent of the population tested were approximately 120 mm/second. This measurement allows us to determine the temporal bandwidth required for effective shape display. Given a shape display that has pins spaced 2.0 mm apart, the maximum spatial frequency that can be created (in the Nyquist limit, with pins alternating up and down) is 0.25 cycles/mm. If the maximum spatial frequency is scanned across the display at 120 mm/sec, each pin must travel up and down in 33.3 milliseconds. This means that each pin must achieve a temporal bandwidth of at least 30 Hz. If the tactile display device cannot raise and lower the pins in this time interval, then the tactile information will not be correlated with the gross motion of the finger. The lack of correlation between finger motion and tactile information can make it difficult to quickly and accurately locate tactile features. Extremely low bandwidths can lead to a "move and wait" strategy where the user conducts a search using discrete motions followed by pauses to wait for the display to catch up which makes it difficult to quickly and accurately search a space.

In addition to high bandwidth, high spatial resolution is required because Johnson and Phillips [3] have shown that humans can reliably distinguish between two points that are separated by as little as 0.9 mm. This implies that pins in a shape display should be spaced as closely as 0.9 mm in order to convince users that they have a shape pressed into their fingerpad, rather than an array of pins. In addition to the small spacing requirement, Pawluk et al. [4] have found that human finger pads have a stiffness as high as 3.5 N/mm at 1.2N indentation force when indented with a flat plate. Since we are interested in displaying shape, rather than pressure, we require pins with high stiffness and high force capability. This is especially true when designing displays to be used on force reflecting devices, because the pins will need to support all of the force produced by the user's fingers during manipulation.

A number of researchers have constructed tactile shape displays [5,6,7,8]. These displays have been constructed in many configurations including single pin and multi-pin matrix displays. Unfortunately, these previous displays have all been limited by low bandwidth, low stiffness or lack of static response. Thus, in order to effectively portray small scale tactile shapes a display must have small pin-to-pin spacing, produce large forces, have high pin stiffness and extremely high bandwidth.

2. Mechanical Design

2.1. Configuration Design

Our shape display is intended to be used for virtual texture experiments as well as for use in remote palpation surgical instruments. These two applications require a compact shape display. Using a single row of pins simplifies packaging and mechanical design constraints, yet retains the functionality of a matrix of pins because textures can be easily perceived along the line of the pins. The user can also sweep the display to perceive curvature perpendicular to the line of pins. There is clearly a trade-off between perception of two dimensional curvatures and temporal bandwidth, and we have chosen to concentrate on the latter. Figure 1 shows that the line of pins runs along the finger pad rather than across it. The size of various available components limits the pin spacing to 2.0 mm on center. In order to cover the length of most finger pads, we have chosen to use ten pins.

The small pin-to-pin spacing, compact size and the extremely high force and stiffness requirements, led us to choose shape memory alloy (SMA) wires to actuate each of the pins. This material is more suited to this task than electromagnetic actuators because of its high force-to-weight ratio and high intrinsic stiffness. It also provides much larger displacements than piezoelectric or magnetostrictive materials. There is a price to be paid for these benefits and SMA has its own set of design challenges which must be addressed.

Shape memory alloy shortens when it undergoes a phase transition from the Martensitic to the Austenitic phase. This reversible phase transition can be produced by heating the wire above its transition temperature using electric current. It is well known that SMA exhibits hysteresis when cycled through this transition [9]. It is also a relatively slow process because it can take a long time for the wire to cool and lengthen. Previous authors have suggested that it is possible to increase the bandwidth and account for the hysteresis by developing a model of the process and incorporating this in the controller [10,11]. While this undoubtedly will work to some degree, we have chosen to increase the bandwidth through careful thermal design and have minimized the hysteresis through position feedback control of the display.

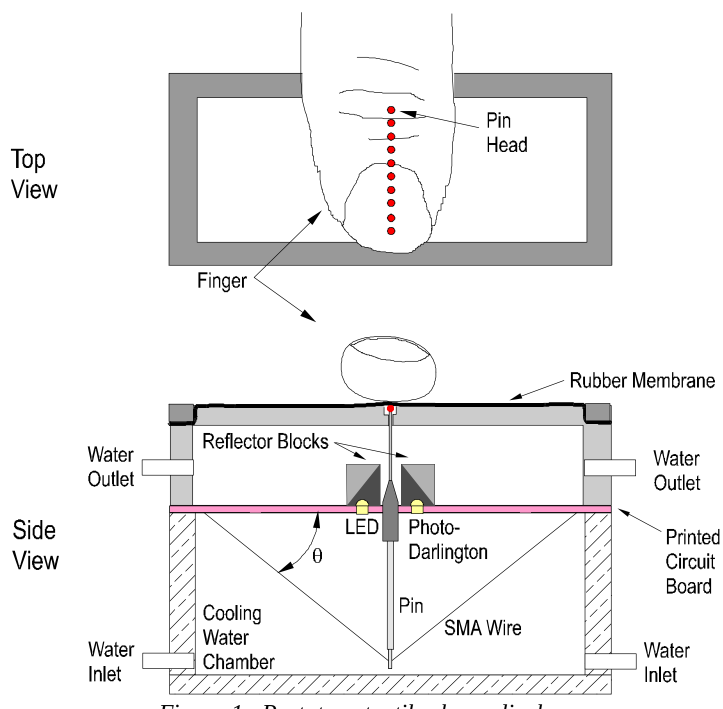

Figure 1. Prototype tactile shape display.

2.2. Mechanical Design

SMA typically undergoes less than 5% strain during the phase transition. In order to compactly package the display we have configured the wires in a V shape [3], as shown in Figure 1. Kinematic analysis reveals that if the original length of the wire is 2L then the displacement of the pin, δ, is

$$d = L\sin(q) - \sqrt{L^2 \sin^2(q) - \left\{1-(1-g)^2\right\} L^2} \quad (1)$$

where γ is the maximum strain of the wire. The stiffness of the pin, K, is related to the angle, *q*, also shown in Figure 1, and the stiffness of the wire, K_w, by the equation

$$K = 2\sin^2(q) K_w \quad (2)$$

K_w is a function of the phase of each wire, its length and its diameter, which should be chosen to maximize heat dissipation. These two equations make it clear that there are trade-offs between compactness, the displacement of each pin and the stiffness of each pin. Thus, they can be solved to determine the required wire length to produce a minimum stiffness, displacement and desired compactness.

In order to facilitate the construction of the display, it uses a layer based modular design that includes all electrical connections on a single printed circuit board. This also minimizes the number of parts that are required and makes for an overall size of 78 mm by 35 mm by 57 mm. Preliminary testing revealed that nickel-titanium shape memory alloy wire can be cycled at 4.8% strain with a 2N load for tens of thousands of cycles with no appreciable loss in performance. Thus, as an extra margin of safety, we chose to limit the SMA to 4.5% strain, which provides the required 3mm displacement when each V in the display is 60 mm wide by 20 mm deep. The usual number quoted to achieve millions of cycles is 2% strain. We have sacrificed life-span for compactness in this prototype.

During assembly, the SMA wires are first electroplated[*] with copper over a small portion of their length, soldered to the board at one end, and then passed through the pins and the board, where they are tied off. Each knot is electroplated and then soldered to the board to complete the electrical connection. This electroplating and soldering process produces high strength, high-conductivity connections to the SMA wires, which is a difficult challenge.

The position of each of the pins is measured using an infrared light-emitting diode (LED) and photo-Darlington transistor pair. As can be seen in Figure 1, the pair is mounted in the printed circuit board, and the light from the LED is reflected past the pin to the photo-Darlington by a pair of specially designed reflectors. Dividers separate each pin to prevent crosstalk. Each pin is shaped so that the amount of light it blocks varies with its position, which causes the collector current in the photo-Darlington to vary as a monotonic function of pin position.

The circuit board also serves as a bearing surface for one end of each pin, while the top block on the display provides the second bearing surface. Together these constrain the pins to move linearly with minimal side loading. The top of each pin is recessed into the surface of the top block to provide a nearly flush surface for the user's finger tip to press against. Finally, the necessary spring return force for each pin is provided by a latex rubber membrane which also serves as a seal.

2.3. Thermal Design

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[*] We use a solution of water and copper sulfate mixed in a 25:1 (H_2O:$CuSO_4$) ratio by weight, and a 5 mA plating current per wire being plated. Each wire is plated for 5 minutes.

In this application, the phase transition of SMA is thermally driven, and because it is always possible to apply more electrical current to cause the wire to contract faster through resistive heating, the fundamental limitation is cooling. Because the rate of heat transfer depends on the ratio of surface area to volume, we use two small (75 micron) wires rather than one larger one to actuate each pin. We also use SMA wire with a transition temperature of 90 °C because the rate of cooling is linearly related to the temperature difference between the wires and the cooling medium.

In previous work, we found that ambient air cooling resulted in a bandwidth of perhaps 1 Hz, while forced air cooling increased this to 5-6 Hz [7]. To obtain the required 30 Hz bandwidth, the present design uses a slowly recirculating bath of water[**]. Water has been chosen as a cooling fluid because of its high thermal conductivity and tremendous heat capacity which allows for a low recirculation rate within the display. This ensures more uniform cooling of all of the wires in the display, and thus more uniform pin-to-pin performance.

3. Controller Design

Because of the success of the mechanical and thermal design of the display, a simple linear controller has proved adequate to drive each pin. To obtain maximum performance, it is desirable to always keep the wires operating between the minimum transition temperature and the maximum transition temperature. We use a proportional controller with a constant offset current. The current offset is used to heat the wire to near the transition temperature and its magnitude and the gain are determined experimentally. For the experiments reported here they were 0.5 amps and 4 amps/mm, respectively.

In order to achieve maximum performance, the desired position of each of the pins is always kept slightly more than zero to be sure that their temperature remains at approximately the transition temperature. In addition heating the wires to more than their highest transition temperature has no effect on their length, but does require more heat to be dissipated before expansion begins, which slows the response of the display. Therefore we restrict the maximum displacement of the pins to 4.5% strain. Finally, current is limited to 2.5 amps per pin in the display to ensure that wires will not be destroyed by overheating.

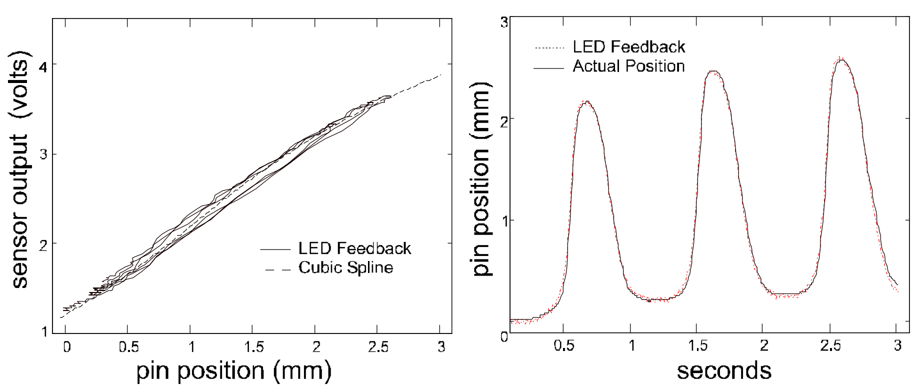
4. Display Performance Characterization

The optical sensors were calibrated by placing a potentiometer with a lever arm attached to it on top of each pin. A 50 gram weight was placed on the lever arm and a triangular current wave drove each pin. A cubic spline was used to linearize the feedback for each pin. Figure 2 shows the results of the calibration for a representative pin.

[**] Actually, we use something of a witch's brew for cooling. A mixture of water and ethylene glycol mixed 8:1 by volume increases the boiling temperature of the water to 110 °C. We also mix in less than 0.02% by weight of Surfynol 75, a fumed silica surfactant manufactured by Air Products, Inc. to promote the migration of bubbles out of the display enclosure.

Figure 3 shows the response of a representative pin to a 1 Hz triangle wave command with 3 mm of displacement. Figure 3(a) shows the response under two loading conditions: no load, and when the experimenter was pressing on the entire display with finger tip force of at least 10 N. This data is replotted in Figure 3(b) to show the relationship between commanded and actual position; the hysteresis is well under 0.1 mm. Figure 3(c) shows the controller current required for each load. In the loaded case, peak current approached 2 Amps while in the unloaded case the current reached a more modest level of 1.6 Amps. Together, these figures show that the simple proportional controller ensures good performance across the entire range of anticipated load impedance.

Characterizing the bandwidth of this nonlinear system is problematic because the fall time is effectively slew rate limited by the wire cooling rate. One useful performance measure is the output amplitude at each frequency, in response to a triangle wave command at the maximum static displacement. Figure 4 shows the frequency response of the display when driven with a 3 mm triangle wave position command for one second with a finger pressed firmly (total force approximately 5 N) against the display. The frequency at which the output amplitude is 3 dB below the commanded input amplitude is approximately 40 Hz. Although the maximum frequency shown in the figure is 100 Hz, output can be felt at frequencies approaching 150 Hz, suggesting that the display can be used for vibrotactile feedback [12,13] as well as shape feedback. Figure 5 is a table summarizing the design targets and measured performance of the display.



(a) *(b)*

Figure 2 - (a) Output of the optical feedback plotted against the actual position of a pin; (b) output of the optical sensing after fitting cubic spline (dotted line) and actual position (solid line).

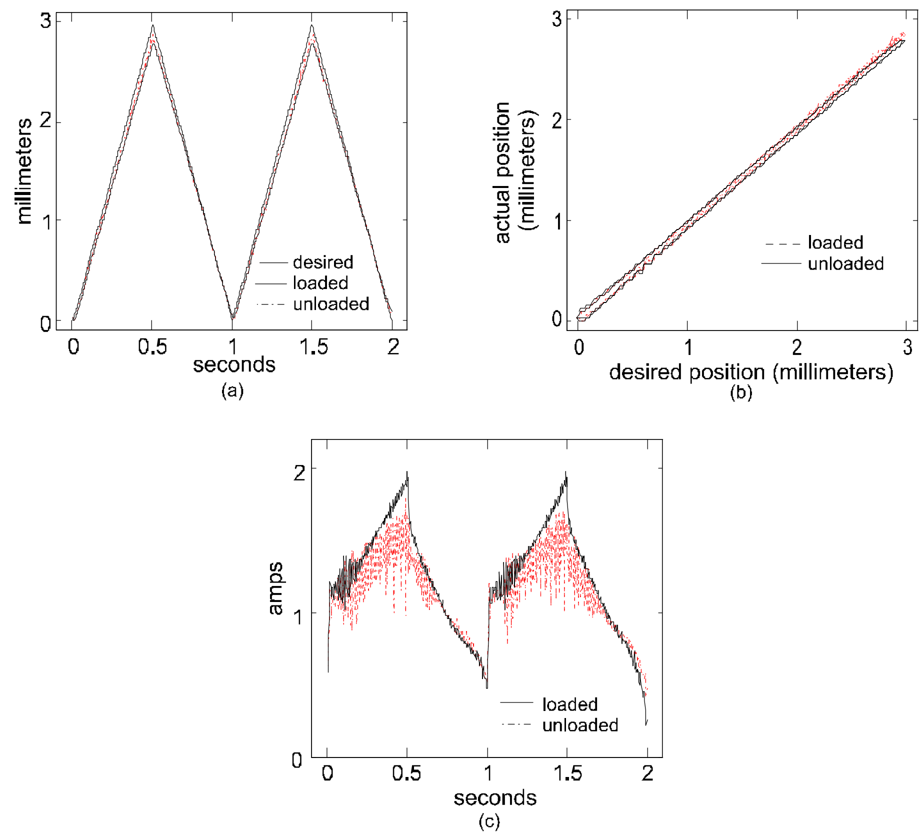


Figure 3 - (a) Desired and actual position of a representative pin under unloaded and loaded (finger pressing at 10 N total force) conditions, (b) the same data plotted as desired versus actual position (note lack of hysteresis) and (c) the current required under loaded and unloaded conditions.

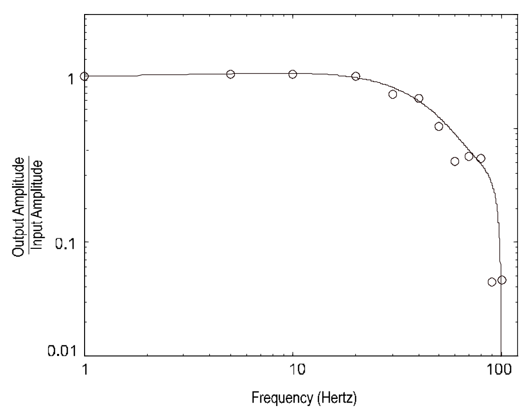


Figure 4 - Frequency response of the shape display.

Parameter	Design Goal	Achieved Performance
Pin Displacement	3.0 mm	3.0 mm
Pin Force	1.2 N	>1.5 N
Pin Stiffness (at maximum displacement)	Rigid	>35 kN/mm
Pin-to-pin Spacing	0.9 mm	2.0 mm
Frequency Response	30 Hertz	40 Hertz (-3dB point)

Figure 5 - Design targets and measured performance of the shape display.

5. Effect of Bandwidth on Performance

To quantify the effect of high bandwidth of the shape display on task performance, we asked subjects to perform a prototypical search task while a digital filter with a cutoff frequency of 1, 5 and 30 Hz was applied to the commanded positions for the display. These frequencies were chosen because they correspond to approximately the frequency response reported for shape displays cooled with still air, forced air and water respectively.

The display was mounted to the mouse pointer of a digitizing tablet. Subjects grasped the display with the dominant hand and rested the index finger tip on the pins. The tablet measured finger position as subjects moved within a test area. The computer sampled the display location and raised and lowered the display pins to represent virtual small-scale shapes at fixed locations. Subjects were asked to search a 150 mm diameter circle as quickly as possible to find two small dots (3 mm diameter by 2 mm height cylinders). They were asked to locate each dot in the search space and center the display on the dot and press a button. Once they found both dots, they were asked to press a second button to end the experiment. The time subjects took to search the space and their average velocity while searching were recorded.

Five subjects (three male, two female, 24 to 29 years of age) were asked to search each of eight virtual environments with two randomly placed dots as described above for the two highest bandwidths, and four virtual textures for the slowest bandwidth. Each subject was presented with the same eight (or four) virtual textures as the other subjects, and these were presented in random order. Subjects were told only that some of the parameters of the display had changed when the frequency bandwidths were altered. Each subject was allowed two, three-minute practice periods each time that the frequency response of the display was altered in order to minimize the effect of practice on the results. They were given a maximum of three minutes to complete the search, although this limit was only reached during testing with the 1 Hz filter.

Figures 6 and 7 show the results of the experiment. The average search velocity more than doubled, going from 18 mm/sec to 55 mm/sec when the filter cutoff frequency was increased from 1 Hz to 5 Hz. The effect of going from 5 Hz to 30 Hz was somewhat less pronounced, as the velocity only increased to about 90 mm/second. The search times showed a steady decrease from approximately 150 seconds, to 50 seconds, to 25 seconds when the filter cutoff frequency was changed from 1 to 5 to 30 Hz, respectively.

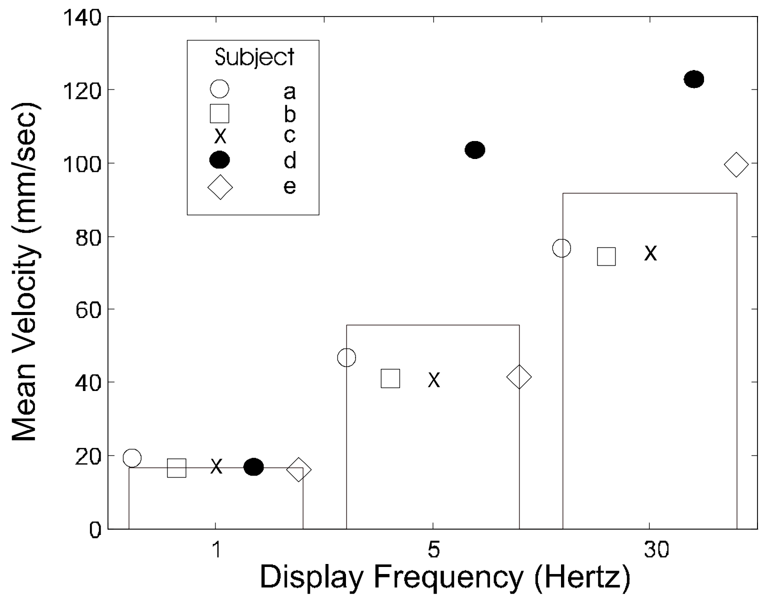


Figure 6 - Mean finger velocity during search for all trials at each test frequency (bars) and mean search velocities for each individual subject for each test frequency (symbols).

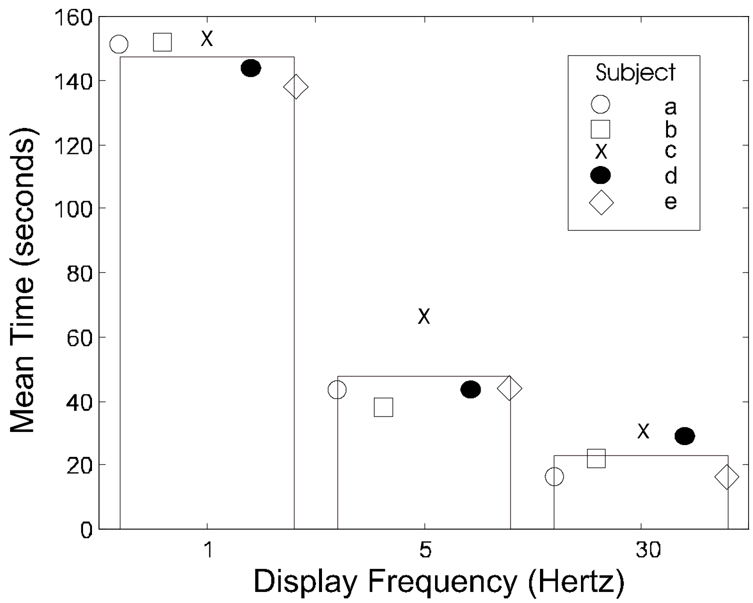


Figure 7 - Mean search time to find both dots (bars) and the mean search time for each of the subjects (symbols).

6. Discussion

This prototypical experiment shows, that at least for some tasks, high bandwidth is essential for good task performance. Subjects described "extreme frustration" when using the display to search the space with the filter set at the lowest cutoff frequency. It is interesting to note that although subject d moved at a much higher average velocity than any of the other 4 subjects during the 5 Hz frequency trials she took nearly the same amount of time to complete the task as the other subjects. This suggests that she did a large amount of wasted searching at high speeds when the display could not move the pins up and down quickly enough. During experimentation she was observed to pass directly over the top of the dots apparently without noticing on more than one occasion. This is a real concern in tasks like tumor localization where finding tumors accurately and quickly is a priority, because it will be very difficult to maintain a regular search pattern and ensure that no tumors will be missed. Thus, it is important that any tumors that may be encountered are felt the first time.

An interesting subjective result of our first studies with this display is that it is relatively easy to perceive curvature along the line of the display, but extremely difficult to perceive curvature perpendicular to it by sweeping the display. This may be because it is necessary to compare two points on the finger pad at the same time in order to have an impression of curvature. A future experiment will ask subjects to evaluate differences in curvature along the line of the display, and perpendicular to it to determine if this has an effect on performance.

7. Acknowledgments

This work was supported by a Whitaker Foundation Biomedical Engineering Research Grant and the Office of Naval Research under grant number N00014-92-J-1887.

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