DESIGN AND PERFORMANCE OF A TACTILE SHAPE DISPLAY USING RC SERVOMOTORS

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ABSTRACT

Tactile displays are used to convey small-scale force and shape information to the fingertip. We describe a 6 x 6 tactile shape display design that is low in cost and easily constructed. It uses commercially available RC servomotors to actuate an array of mechanical pins. The pins deflect a maximum of 2 mm, with a resolution of 0.1 mm. The pin center spacing is 2 mm and the pin diameter is 1 mm. For the maximum deflection of 2 mm, the display can represent frequencies up to 7.5 Hz; smaller deflections lead to achievable frequencies up to 25 Hz because the servos are slew rate limited. This design is well suited to tactile display research, as it offers reasonable performance in a robust and inexpensive package.

1. INTRODUCTION

Tactile displays attempt to realistically simulate skin deformations that occur during interaction with real objects by transmitting small-scale shape information to the fingertip. The ideal tactile display implementation would provide the user with a sensation indistinguishable from direct contact [1]. Both teletaction (the sensation of touching a remote object) and virtual environments are domains where an effective tactile display can be crucial to establishing a realistic sense of presence. Lederman and Klatzky [2] have shown that when contact forces to the fingertip are not spatially distributed, spatial acuity, pressure sensitivity, orientation detection and detection of a lump by palpation are all markedly impaired. These data argue for the potential importance of displaying spatially distributed information to the skin in domains such as remote medicine, minimally invasive surgery, and virtual training applications.

The dominant tactile display design uses an array of stimulators that contact the skin to achieve a force or shape distribution on the fingertip. Because the slowly adapting (SA I) mechanoreceptors have been shown to be important in small scale shape perception [3], Moy et al. proposed a set of device specifications for an array style tactile display [4] based on the SA I's signal response characteristics. The tactile display should have a bandwidth of at least 50 Hz, an actuator density of 1 per mm^2, and a maximum pressure of 50 N/cm^2. Each actuator should indent up to 4 mm with a height resolution of 10%. While these specifications were initially targeted for teletaction, they match well to studies examining the necessary bandwidth for tactile exploration [5], and the distinguishability of two adjacent pins [6]. Other desirable features of a tactile display include small actuator size, high reliability, and low cost.

Initial tactile display research was based on sensory substitution for the blind. Piezoelectric driven pins were vibrated with varying intensity [7]. However, our focus will be on single finger static pin array tactile displays. Other approaches for displaying tactile information are vibrotactile [8, 9], electrotactile [10], shear [11-13], contact area change [14], and multi fingered stiffness change [15]. A review of current tactile display research is given in [4].

Continuing research has led to tactile displays designs utilizing various actuator technologies, with tradeoffs between bandwidth, actuator size, and actuator stiffness. Actuators styles include shape memory alloy (SMA) wires [16-20], pneumatics [1, 21, 22], solenoids [23, 24], and electrostatics [25]. A complete review of the state of the art in tactile displays can be found in [25]. No current design meets all of the requirements proposed by Moy et al. Further, most designs rely on a large number of costly actuators, causing the overall display to be expensive and unreliable [26].

We propose a tactile display design that provides reasonable performance in a robust and cost effective package by taking advantage of commercially packaged RC servomotors. The display achieves a high bandwidth, high actuator density, large vertical displacement, and firm static response. Figure 1 shows the entire system, including the latex rubber sheet that serves as a spatial low pass filter. Our display uses the servomotors to vertically actuate a 6x6 array of mechanical pins at a 2 mm spacing to a height range of 2 mm with a resolution of +/- 0.1 mm. This paper serves to fully characterize the servomotor based tactile display design previously introduced [27]. While no current tactile display device currently meets requirements specified by Moy et al. (including the design proposed here), we hope that our design establishes a platform for further tactile research by providing the appropriate tradeoff between device complexity, reliability, performance, and construction cost. We include a comparison between our design and the current state of the art in array style tactile displays using different actuation methods.

2. DESIGN AND CONSTRUCTION

Figure 1. The full tactile display

Figure 2. The 6x6 display showing a sine wave grating

2.1 Materials

One mm (0.041-inch) diameter steel piano wire was used to fabricate the mechanical pins. Each pin is bent at the end closest to the servo. It then passes through a hole in the plastic arm, forming a hinge by which the pin is attached to its actuating servo. The other end of the pin passes through a top plate of Delrin, chosen to reduce pin friction. The pin tip is also slightly rounded to prevent tearing of a rubber cover sheet. The grid of pins, along with the Delrin top plate, is shown in Figure 2.

The servomotors used are small, high performance ball bearing servos normally used in radio-controlled (RC) hobby applications (MX-50HP/BB, Maxx Products International, Lake Zurich, IL). Each servomotor package includes a power amplifier, DC motor, gearhead, position sensor, and closed-loop controller. The electronic interface to the servo is a simple three-wire design of power, ground, and a pulse width modulated (PWM) control signal. The servo model was chosen on the basis of its low weight, small size, and high speed.

2.2 Servo Arrangement

The servos are tightly packed to achieve a 2 mm pin spacing. A diagram of a six-servo block is shown in Figure 3, displaying how the horizontal 2 mm spacing is realized and how the rotational motion of a servo translates into vertical motion of the pin. Each servo block makes up one column of six pins.

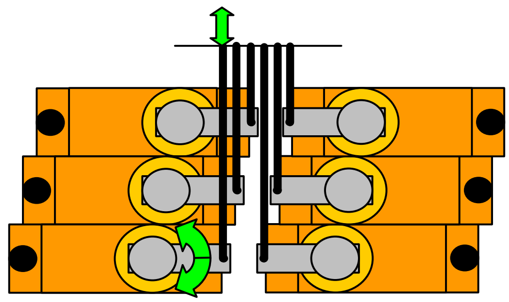

Figure 3. Configuration of six servos in a block

Figure 4 shows the vertical layout of the servos. The six blocks of six servos each are rigidly attached to an aluminum chassis at varying depths to achieve the full 6x6 array. The top plate is also affixed to the chassis.

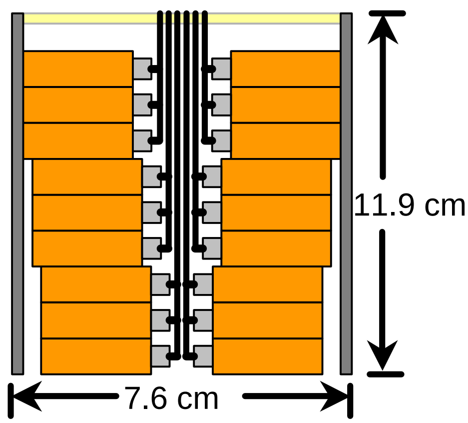

Figure 4. Vertical configuration of servos

The tactile display can be separated into two halves to simplify construction and pin maintenance (Figure 5). Each half of the top-plate is rigidly attached to the corresponding half of the chassis. When the tactile display halves are joined, the top-plate halves also connect to the opposite chassis side for stability and alignment.

Figure 5. Display halves

2.3 Control System

The height of each pin is set by controlling the duty cycle of a PWM voltage signal, which is sent to the corresponding servo. The 36 50Hz PWM waves are generated by logic implemented on Xilinx programmable gate array mounted on a parallel interface card (XS40-005XL, XESS Corp., Apex, NC). The individual PWM waves are commanded through a PC parallel port.

The servos are powered using a 300W switching PC power supply (FSP300-60BT, Aopen America Inc., San Jose, CA). A PC power supply is used to achieve the power requirement with a low cost and small package.

2.4 Active Exploration System

To allow for active tactile feedback, we mounted the tactile display on castors (Figure 6). An optical mouse is connected to the underside of the chassis to provide position information. Using this setup, we are able to provide the user with tactile information that actively changes in response to hand motion.

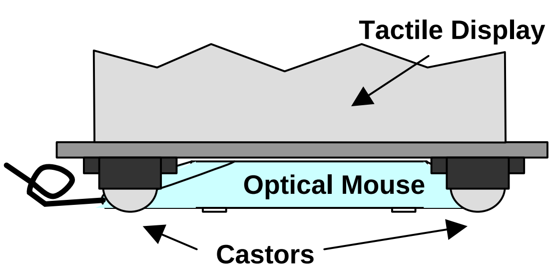

Figure 6. Active exploration addition

3. PERFORMANCE

We used a lever arm connected to a high-resolution potentiometer to evaluate the temporal response of the tactile display (Figure 7). This setup achieves 1 micron height resolution. Contact between the lever arm and a pin was guaranteed by using a 50g weight to pull down on the arm. Note that for all performance characterizations, the rubber spatial low pass filter layer was not included in order to isolate the pin effects.

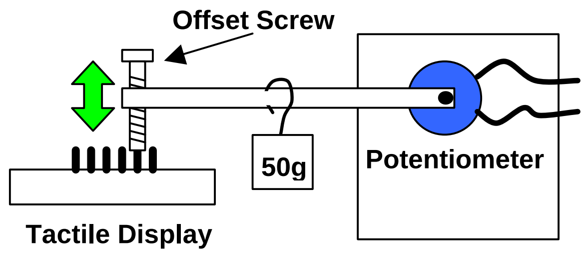

Figure 7. Setup to measure pin height

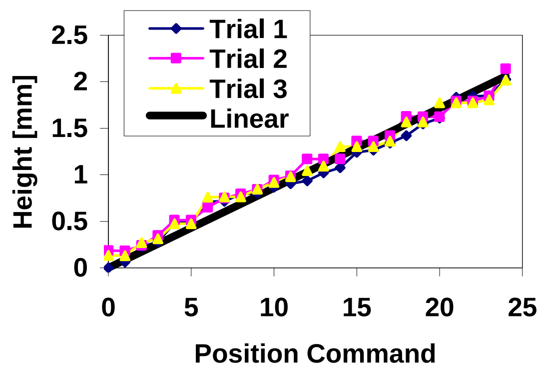

Figure 8. Commanded versus actual pin height

The resolution of a typical pin is shown in Figure 8. The control system allows for 24 incremental position commands to be sent to a servo over a 2 mm height range. However, not all position commands result in a change in pin height. To characterize the actual height resolution the same servo was given incremental position commands over three trials and the pin height was measured. The mean of the trials was found to be linear with $r^2 = 0.9925$. The maximum error between pin height and a true linear trend between height and position command was found to be 0.245 mm, while the standard deviation of the error was 0.093 mm. Thus, the tactile display can resolve heights to +/- 0.1 mm.

To determine the transient characteristics of the display, a pin was commanded to track a 2 Hz sine wave and square wave with a 2 mm peak-to-peak amplitude (Figure 9 a,b). Due to the nature of the servo, the pin motion was slew rate limited. The slew rate was found to be 30 mm per second after determining that both the 10%

to 90% rise time and the 90% to 10% fall time was 52 ms for a 2 mm displacement. Further, we observed a 40 ms delay between command and servo movement. We can then determine the maximum displayable frequency using

$$f_{\max} = \frac{v_{slew}}{2h_{\max}}$$

where t_{delay} is the delay time, h_{max} is the maximum pin height, and v_{slew} is the slew rate. Thus, for the maximum pin height of 2 mm, the achievable bandwidth is 7.5 Hz. The servo update rate of 50 Hz limits the maximum achievable bandwidth to 25 Hz for small amplitude signals. Previous studies suggest that this bandwidth is adequate for representation of tactile features in free exploration [5]. We also note the presence of some distortion of less than 0.2 mm in amplitude of the falling phase of both waveforms. This is apparently due to imperfections on the bottom surface of the offset screw attached to the potentiometer arm; these imperfections cause vertical displacements when large lateral motions occur between a display pin and the offset screw.

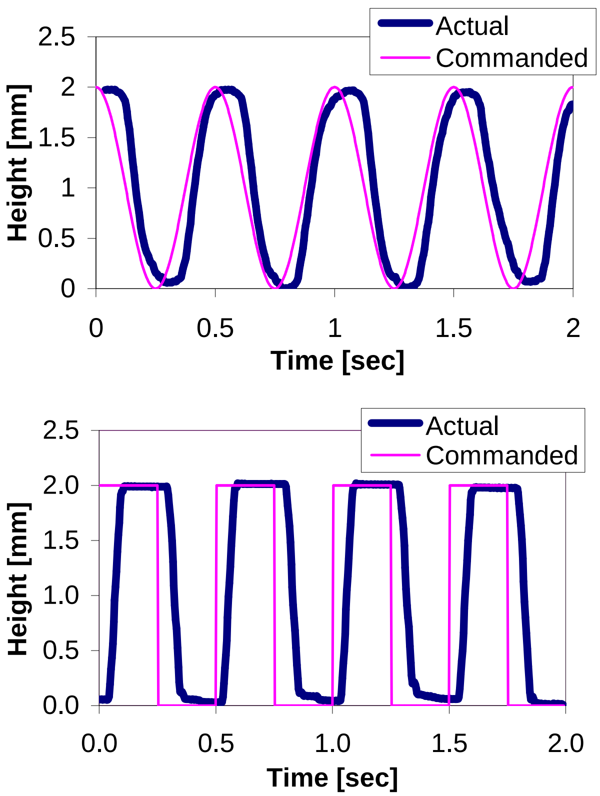

Figure 9 a,b. 2 Hz sine wave and square wave tracking

The force displacement characteristics of several pins were measured using a force sensor mounted to a vertical stage. These measurements are influenced by the stiffness of the pin wire and the active position control of the servo. Because the force displacement characteristics might also be dependent on the length of the pin wire between the top plate and the servo, three pin wire lengths were tested. A force of 10N of was shown to cause a 2 mm displacement in pin height for all wire lengths, with a mean stiffness of 5,000 N/m (Figure 10). Because the pin stiffness is high with respect to the stiffness of the finger, this display can be used as a position display.

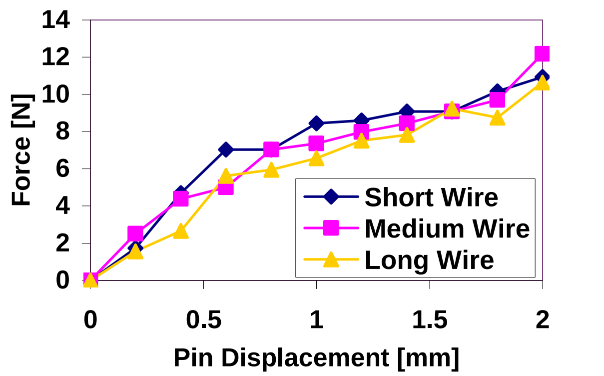

Figure 10. Force versus distance pressed for 3 pins

Because of the digital nature of the servo position controller and servo commands, the servo rotates in discrete steps. These steps manifest as high frequency noise in the motion of a pin, both audible and tactile. Additionally, the servo gearing mechanism introduces high frequency vibrations. The audio noise is usually not a concern for research applications as subjects are sound isolated using headphones.

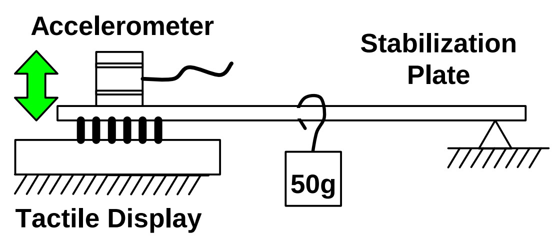

Figure 11. Accelerometer setup to measure high frequency noise

To characterize the high frequency tactile noise content, an accelerometer was placed on top of a stabilization plate resting on all 36 pins (Figure 11). A bias weight provided a 0.25 N force to maintain contact between the pins and the plate. The pins were commanded to simultaneously track a 2 Hz vertical sine wave. The magnitude of the vibrations versus frequency is shown in Figure 12, along with the threshold for tactile perception [28]. Peaks in the signal occur at 50 Hz and 60 Hz, along with associated harmonics. All vibrations above 60 Hz are within an order of magnitude of the measured tactile threshold under ideal quiet laboratory conditions. Low frequency harmonics of the 2 Hz command signal are also observed. Subjectively, these vibrations were small with respect to low frequency motions.

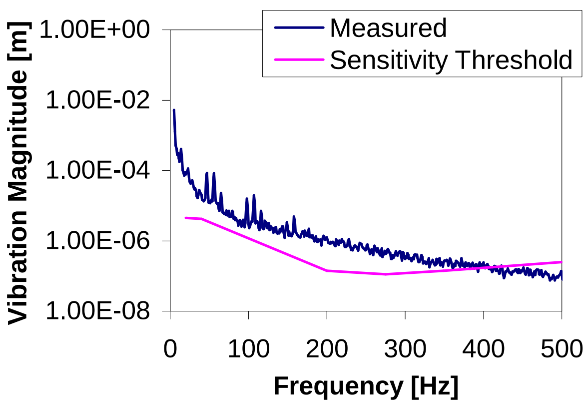

Figure 12. Vibration content of display

4. DISCUSSION

The current tactile display design has high force capabilities, reasonable dynamic range, and good bandwidth, yet is relatively simple and inexpensive to build. The platform enables unprecedented rapid development and execution of experiments on distributed tactile feedback. The design is easily scalable with respect to size and performance in addition to being robust and maintainable. Our current implementation of a 1.1 cm by 1.1 cm array of pins is reasonable for coverage of a typical single fingertip.

The number of pins in the design can be increased by simply increasing the number of servos used. Additional servos can be added to each servo block to increase the number of rows and servo blocks can be added to increase columns. These additions come at the cost of increasing the overall system's width and height.

The performance of the current display design is also scalable, as performance is largely dependent on the choice of servomotor packages. The servos used in our design were chosen to maximize performance while maintaining a small footprint. Larger servos can be used to increase performance and/or decrease cost while sacrificing overall system size. Newer servo technology, such as digital servos, will also improve display performance.

We compare the current implementation of our design with the state of the art in tactile displays utilizing different actuator technologies (Table 1), as done in [25]. The comparison focuses on array style tactile displays that display forces normal to the skin. Note that no current tactile display meets the specifications set by Moy et al.

Reference	Goal	Ours	[21]	[1]	[16]	[20]]	[23]	[24]
Actuator	N/A	Servos	Pneum.		SMA		Solenoid	
Array Size	10x10	6x6	4x4	5x5	1x10	8x8	8x8	20x20
Tactor Spacing [mm]	1	2	3.75	2.5	2	3.2	5	0.5
Temporal Bandwidth [Hz]	>50	7.5/25*	11	5	30	0.1	n.s.	40
Max Pin Force [N]	0.5	2	3	0.2	2	2.5	n.s.	1.3
Max Pressure [N/cm^2]	50	100	80	8	100	78	n.s.	260
Max Pin Height [mm]	4	2	5	0.6	3	3.5	1	2.5
Height Resolution [mm]	0.4	0.1	n.s.	n.s.	0.1	n.s.	0.25	n.s.

*Bandwidth is amplitude dependent

Table 1: Comparison of tactile displays (n.s. = not stated)

While our tactile display design does not outperform all other displays, ours in the only one to utilize low cost, commercially available actuator technology for a robust and cost effective design.

An important feature of any tactile pin display is the spatial low pass filter layer between the pins and the finger. If the rubber is viscoelastic, then the layer can act as a temporal low pass filter also. We have not included the rubber layer in our performance characterization because the mechanical properties of the optimum rubber layer for all applications are not clear [29]. This issue will be addressed in another paper [30].

Several factors serve to reduce tactile display performance. The main problem, pin friction, is one common among tactile pin displays. Friction between the top plate and the pin wire reduces achievable and repeatable height resolution (Figure 8) and increases transient response time. To counteract these effects, we used oversized top plate holes with respect to the pin wire and applied lithium grease at the pin/hole contact. Another source of error comes from the discrete nature of the servomotor's position controller. Because the position is adjusted at 50 Hz, we observe (and thus feel) high frequency noise associated with those discrete position jumps.

The complex electronics needed to generate the large number of individually controlled PWM voltage waves is a drawback to this design. We used custom logic implemented on an inexpensive Field Programmable Gate Array (FPGA) to allow control of the individual servos through the PC parallel port. Other options exist, however, including commercial microcontroller boards that have the ability to output large numbers of PWM voltage waves.

A final drawback of the display is that the large number of servos results in a package that is too bulky to be portable. The optimal tactile display would be small enough to be used with several fingers at once in a large range of positions and orientations. However, due to the difficult nature of this engineering task, our hope is that this simple and inexpensive design will stimulate more research in the area of tactile feedback. With a fuller understanding of the parameters involved in tactile display interaction, we hope that a more efficient tactile display can be designed and built.

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