A Tactile Shape Sensing and Display System for Teleoperated Manipulation

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Abstract

This paper presents a system for relaying distributed tactile information from the finger tips of a remote manipulator to the finger tips of a human teleoperator. Tactile array sensors measure the pressure distribution at the contact between the robot hand and the grasped object. A computer samples this pressure signal and applies signal processing algorithms. The resulting signal drives a tactile shape display mounted on the master manipulator. This device raises an array of pins against the operator's finger tip skin to recreate the object shape. This system has been tested on a force-reflecting teleoperated hand. Experiments confirm the system's ability to convey significant contact information.

1 Introduction

Dextrous telemanipulation with multifingered hands has recently become an active area of research. As with teleoperated arms, force feedback in teleoperated hands improves performance in many tasks [1], and can increase the subjective sense of "virtual presence" at the remote manipulator. However, neurophysiological and psychophysical studies have shown that human dexterity also relies on tactile information when manipulating objects directly with the hand [2]. This suggests that relaying tactile information from the remote manipulator to the operator can increase dexterity in telemanipulation.

Tactile shape information is important for both object recognition and control purposes. The local surface normal direction can be calculated from object shape data, which is important for predicting frictional behavior and rolling motions. Contact shape can also determine the overall behavior of the hand-object system. Manipulation of objects by multifingered hands can be described as a series of changing kinematic configurations involving the hand, the object, and the environment. For example, when an object is grasped between the fingers for precision manipulation, the contact areas between the object and the finger tips form temporary passive joints. Depending on the shape of the contact area, these passive joints have a different number of degrees of freedom (DOF). Visual sensing alone cannot provide the needed information, as the contact area is, by definition, occluded by the finger tip.

This paper describes a new system for investigation of the role of shape information in telemanipulation. A tactile array sensor in the remote robot finger tip measures the distribution of pressure across the contact area. A dedicated computer system samples this pressure distribution and applies signal processing algorithms. The resulting signal is sent to a tactile display device mounted in the finger tip contact area of the master manipulator. This display device consists of a regular array of pin elements or "tactors" which rest against the operator's finger tip. Shape memory alloy wires raise and lower individual tactors to approximate the desired surface shape on the skin. We have implemented this prototype system on the force-reflecting teleoperated hand system in our laboratory. Preliminary tests show that it can successfully convey contact information, and permits the operator to localize small features in the remote environment.

We begin by reviewing previous work on tactile sensing and display. Since tactile displays must provide appropriate stimulus to the human sense of touch, we also review pertinent aspects of human taction. The following section describes the design of the prototype system, including the tactile array sensor, the tactile shape display, and systems integration issues. Next, experimental measurement of the performance of both the individual components and the overall system are presented. Finally, we discuss conclusions from this research, and outline future work on the next generation of shape relay systems.

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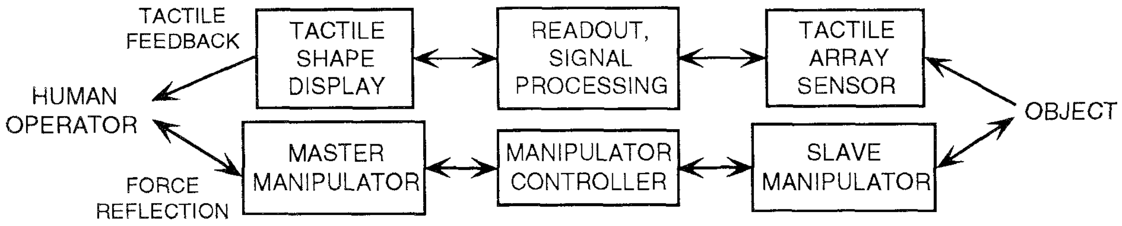


Figure 1. Block diagram of telemanipulation with tactile feedback.

1.1 Previous work

The development of a tactile relay system draws on a number of disparate areas of research, including robotic tactile sensing, human tactile display interfaces, and dextrous telemanipulation. In robotic tactile sensing research the major focus has been the development of new array sensor devices, which can measure pressure or displacement at a large number of locations across the contact area; see [3] for a recent review. In teleoperation, the few studies of tactile array sensing have used visual feedback to convey remote touch information to the human operator [4, 5]. Several workers have also investigated sensing and display of vibratory information in telemanipulation [6].

Most research on tactile shape display has focused on "sensory substitution" aids for the blind. The most familiar of these, the OPTACON, is a commercially available camera-tactile display system [7]. Vibrating pins represent the intensity pattern as the device is manually scanned across a printed page. In the category of static tactile displays there are a few examples in the literature. Among the most appropriate for teleoperation is a tactile pressure distribution display implemented by Cohn, Lam, and Fearing [8]. It uses a 5x5 close-packed array of pneumatically-actuated pins. The pneumatic pressure is controlled by pulse width modulated solenoid valves connected to the display via 25 tubes, which makes mounting on a master manipulator difficult. Hasser and Weisenberger [9] describe a 6x6 array actuated with shape-memory alloy wires in a flexture design. This display provides the high density and small package required for mounting at the finger tips of a master manipulator, but force levels are limited to 0.2 N per element, restricting the ability to represent shapes with high curvature under force reflection loads.

1.2 Human taction

The purpose of tactile display is the simulation of natural events on human finger tips, so we briefly examine the spatiotemporal characteristics of the human tactile sensory system. Perception of our environment through the sense of touch is based on two modalities: kinesthetic sensing, which refers to sensation of the internal state of the limb through parameters such as joint angle, muscle effort, etc.; and tactile or cutaneous sensing, which refers to distributed sensation from the skin. In teleoperation, kinesthetic feedback is typically provided by force reflection, which has been the focus of extensive prior research.

There are four types of specialized nerve endings in the glaborous skin of the human hand which play important roles in manipulation tasks [10]. They may be categorized by two criteria: the size of their active areas and their response to static stimuli. Nerve endings with small receptive fields are called Type I units, while those with large fields Type II. Units that respond to static stimuli are denoted SA (for slowly adapting), while those with no static response are denoted FA or RA (for fast or rapidly adapting). Neurophysiological studies suggest that SA I mechanoreceptors are most important in small-scale shape perception [11], which implies that a relatively low bandwidth display may suffice in many applications. The ability to separately perceive two pointed indenters on the finger tip requires that the points be separated by 1-2 mm, providing a target specification for spatial resolution of shape display devices.

2. System Design

Figure 1 shows the block diagram of the system. In a typical task, the human operator interacts with the master manipulator to bring the remote slave manipulator into contact with an object in the remote environment. The resulting pressure distribution across the robot finger tip is measured by a tactile array sensor with associated readout electronics. A computer processes the signal to produce appropriate drive signals for the tactile shape display, which is mounted on the master manipulator. This tactile display recreates the object shape on the finger tip of the human operator. In this section we describe the components of the tactile feedback system. The following section outlines the integration of the system with the force-reflecting teleoperated hand system developed in our laboratory.

2.1 Tactile array sensor

Figure 2 shows the construction of the capacitive tactile array sensor used in this system, which is based on an earlier design by Fearing [12]. It is composed of two crossed layers of copper strips separated by thin strips of silicone rubber. As a force is applied to the surface above the point where two strips cross, the distance between the strips decreases, which increases the capacitance between the strips. By measuring the capacitance at each crossing point, the spatial distribution of pressure across the sensor can be determined.

We have devoted considerable effort to optimizing the manufacturing process for these devices. The sensor forms a thin, compliant layer which can be easily attached to a variety of slave finger tip shapes and sizes. By encapsulating the sensor in a layer of elastomer, the surface compliance of the contact area can be controlled. In this prototype system we used 8 strips at 2 mm spacing in each direction, providing 64 force sensitive elements. Special-purpose electronics scan the array to measure the capacitance at all elements in 5 msec. The noise level of each sensor element is less than 0.001 N, and the useful range extends to over 2 N at each element.

2.2 Shape Display

In contrast to previous work, our goal was to develop a tactile shape display for use in the grasping surface of a force-reflecting teleoperated master robot hand. This poses extremely difficult design challenges. First, the display must be small enough that it fits between the fingers when manipulating an object, and light enough to avoid loading the master and limiting force reflection range and responsiveness. In addition, because it is located at the point of contact between the manipulator and the operator's finger tip, it must be strong enough that the entire reflected force can be supported by the display while maintaining the desired shape. Finally, the display's spatial and temporal bandwidth should approach the capabilities of the human cutaneous system. Based on the material cited in section 1.2, we selected design goals of approximately 2 mm center-to-center element spacing, 3 mm total vertical excursion, 10 Hz bandwidth, and at least 1 N force per tactor. Our initial prototype was limited to 3x3 elements, and the second-generation display device described here has 6x4 elements.

The shape display raises pins against the human finger tip skin to approximate the desired shape (Figure 3). We selected shape memory alloy (SMA) wires as actuators because of their very high power-to-weight, power-to-volume, and force-to-weight ratios. The mechanical design of one element of the shape display is shown in Figure 4. A length of SMA wire is attached to a rigid frame at one end and to a small lever at the other. A spring connected between the lever and the frame keeps the wire in tension and provide a restoring force. The SMA wires are actuated by heating with an electric current. The elevated temperature results in a material phase change which increases the tension and/or shortens the length between the ends of the wire. This causes the lever to rotate about a fixed shaft. The other end of the lever then forces up a pin which rests against the tip of the operator's finger. The levers provide a 3:1 reduction in force and amplification in displacement. The wires used here are 30 mm long and 0.075 mm in diameter. The shape display consists of four layers, each layer having six actuators. The center-to-center spacing of the tactors is approximately 2.1 mm.

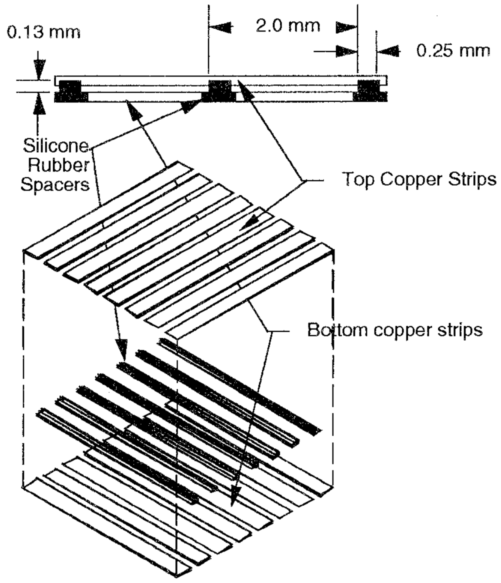


Figure 2. Tactile array sensor. Top: side view of two elements; contact occurs on the upper surface, which is covered by a layer of rubber. Contact pressure compresses the silicone rubber spacers, forcing top and bottom copper strips closer together and decreasing capacitance. Bottom: exploded view showing sensor construction.

The phase change responsible for the SMA action is accompanied by hysteresis, directional asymmetry, and other non-linear effects which pose difficult challenges to effective control. One primary problem is the slow thermal response times. There is a significant delay between an increase in input current and the appearance of a force increase at the pin due to the integrating effect of the thermal mass of the wire. On the descending phase, the delay is due to the slow cooling rate, so that the temperature drops more slowly than the cur-

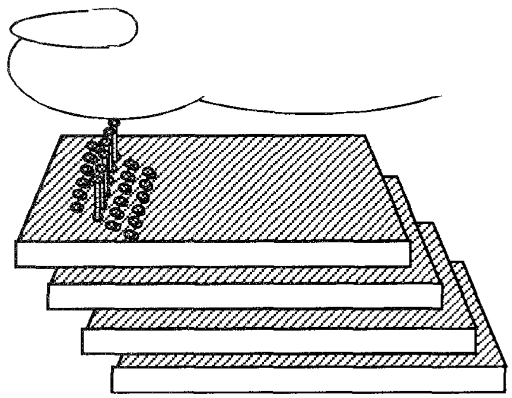


Figure 3. Shape display, showing 6x4 array of pin elements, and human finger tip. The display consists of four layers and each layer contains six actuators.

rent. Thus proportional control results in a bandwidth less than a tenth of the desired value of 10 Hz. We have addressed these problems by adding a large derivative term to the control law, and by using forced-air cooling of the wires. The resulting performance approaches the desired 10 Hz bandwidth for the system (Figure 5).

Another significant problem with SMA actuators is hysteresis. Our experiments show that a simple PD position control loop reduces this problem to an acceptable level. In addition, this control scheme reduces the variability between elements (and thus the need to calibrate each element of the display), and decreases sensitivity to variations in human finger tip stiffness. For the 6x4 element display we have designed optical emitter-detector position sensors for each element. Additional details of the display design and performance may be found in [13].

2.3 System integration issues

Because the display's SMA actuators have a higher passive stiffness than the human finger tip, and because the display's controller is based on position feedback, the display intrinsically creates shapes on the human finger tip. On the other hand, the tactile array sensor measures strains (i.e. fractional displacements) at some distance beneath surface of the slave finger tip. The precise relationship between this measured quantity and the contact pressure and object shape is complex, and a solid mechanics analysis of the contact interaction is required for a satisfactory explanation. Signal processing algorithms are thus required to transform the sensor signal to a suitable drive signal for the display. Fearing [12] has addressed some of the issues of deriving shape information from tactile array sensor data. Among the problems are finding surface pressure distribution from sub-surface strain measurements, and inferring shape from the surface pressure and the known mechanical properties of the sensors.

For these initial experiments, we have avoided the need for this type of signal processing by limiting the thickness of the rubber layer overlying the tactile sensor in the slave finger tip to less than 1 mm. This means that the surface of the sensor conforms to the shape of objects pressed against the finger tip, an the sensor thus records shape information directly. One limitation incurred with this approach is that the sensors has a limited compliance range, and can only conform to a limited depth. This scheme has proved sufficient, however, for successful identification of small tactile features in the experiments described in the next section.

Another important systems-level issue is the partitioning of feedback function between the shape display and force reflection. A simple example of the problem can be seen when the slave finger presses against a flat surface. This produces a uniform pressure at each point on the array sensor. If the array sensor output from each element is simply used as the commanded position for the corresponding element of the shape display, then all the pins of the display would be raised an identical amount. This, however, is not an appropriate use of the shape display, since force reflection alone will produce the same net result (identical pressure at each point), without a shape display. Our approach to this problem is to subtract from each element the smallest value for the entire array. This "baseline subtraction" allows force reflection to supply the spatially non-varying part of the contact information and the shape display to supply the spatially varying part.

3. Experiments

Two experiments were conducted to establish the functionality of the system. The first experiment confirms that the shape display can communicate fundamental contact information. The second experiment, which used the entire shape relay system on a force-reflecting teleoperated hand, confirmed that the system can be used to convey useful information in telemanipulation.

3.1 Shape discrimination

To demonstrate the tactile display's function, we performed informal psychophysical tests of shape perception. Subjects rested their index finger tip on the display, and a pattern was generated by the display. In the first test, subjects were asked to classify the pattern as a point (one tactor raised), a line (three tactors in a row), or a plane (all tactors). In a second test, they were asked to distinguish between four different orientations of lines. The success rate for all subjects in both of these elementary tests was 100%. In each case the "on" tactors were

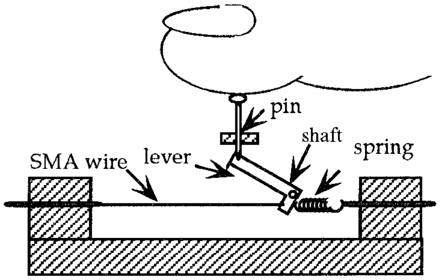


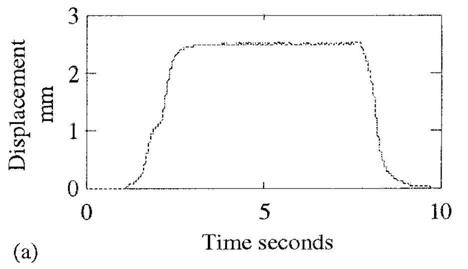
Figure 4. Side view of one display element, showing SMA wire actuator which pulls a lever to raise a pin against the human finger tip.

driven to their maximum excursion (3 mm), and the "off" tactors were not energized. Thus these results do not provide quantitative measures of the display's ability to convey spatial information, although they do provide initial confirmation that the display is capable of generating recognizable spatial patterns.

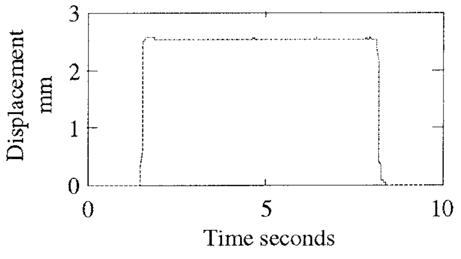
3.2 Feature localization in teleoperation

To demonstrate the ability to localize tactile features using the system, subjects were asked to locate a hard rubber cylinder inside a block of foam rubber. This task simulates the key aspects of medical procedures wherein tumors are localized with palpation. Dario [14] investigated autonomous robotic execution of this task, but here we perform the task using teleoperation, with a human in the tactile loop. This experiment uses the force-reflecting teleoperated hand system developed in our laboratory for the study of tactile sensing and display [15]. This is a non-exoskeleton system which trades a limitation on the number of degrees of freedom for a clean and simple mechanical design, which results in good control of fine forces and motions. The system is designed to execute tasks that humans usually accomplish with a precision pinch grasp between the thumb and index finger. For most tasks the operator's wrist rests on the table top and the operator makes contact with the master only at the tips of the thumb and index finger (Figure 6).

Both master and remote slave manipulators are identical two-fingered hands with two degrees of freedom in each finger, so finger tip position or force can be controlled within the vertical plane. The mechanism uses a direct-drive, parallel linkage design, which minimizes friction, backlash, and moving mass. Two-axis strain gauge force sensors measure finger tip forces on both master and slave hands. The controller uses a conventional bilateral force reflection control scheme. The measured slave position bandwidth is 18 Hz and the master force reflection bandwidth is greater than 80 Hz. Further details of the manipulator system design and performance are presented in [1, 15].



(a)



(b)

Figure 5. Display element step response with: (a) no compensation or cooling; (b) feedforward compensation and cooling.

Tactile array sensors in the finger tips of the remote manipulator measured the shape encountered during task execution, and the shape display relayed this information to subjects operating the telemanipulation system. The phantom used in these experiments consisted of a cylindrical piece of hard rubber 4 mm in diameter embedded 5 mm beneath the surface of a foam block. A linear translation stage was used to change the vertical location of the phantom between trials to random locations within a 20 mm range. Subjects were asked to probe the phantom with the teleoperated hand until they located the tumor. The experimenter recorded the difference between the actual position of the tumor and the subject's reported location. For the initial planar experiments reported here, only one row of the tactile array and one row of the shape display were used to relay shape information. During the tumor localization task, full force reflection was available but no visual feedback was allowed. Subjects performed the task both with and without the shape feedback to determine the effectiveness of the shape relay system.

Figure 7 shows the results for a total of 60 trials by three subjects. Using tactile feedback, subjects were able to locate the tumor with an error of 1 mm or less in over 50% of the trials, and with an error of 3 mm or less 95% of the time. When the shape feedback was not available, the mean absolute error was over 13 mm. In the absence of tactile information subjects often guessed at the tumor location, or based their responses on spurious force signals due to interaction of the edge of the slave finger tip with the phantom. These results dem-

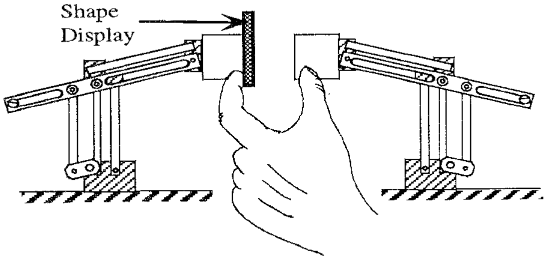


Figure 6. Master manipulator and operator's hand; slave manipulator is kinematically identical.

onstrate that tactile feedback can provide information not available with conventional force feedback. Combined with the results of the line orientation experiments, we have demonstrated the capability to sense and display significant shape features during telemanipulation.

4. Conclusions

We have developed a prototype system which can relay small-scale tactile shape information from a remote manipulator to the fingers of the operator of a telemanipulation system. Experiments confirm the ability of the system to convey important features and localize objects. Future work will be devoted to improving the performance of the shape display and implementing appropriate signal processing algorithms to transform array sensor measurements to drive signals for the shape display. Further experiments will aimed at increasing our understanding the role of shape information in dexterity.

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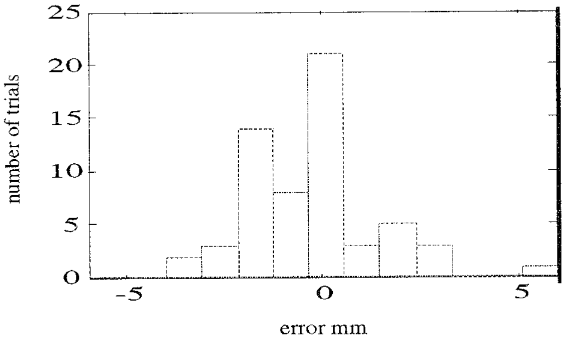

Figure 7. Histogram of errors in localization task.

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