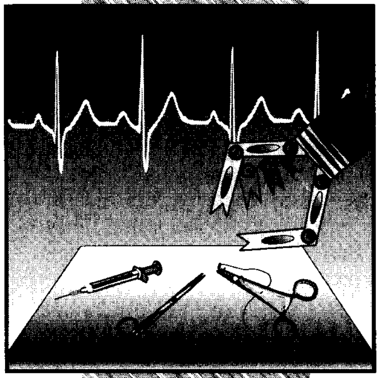

Remote Palpation Technology

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One of a surgeon's most important tools is a highly developed sense of touch. Surgeons rely on sensations from the finger tips to guide manipulation and to perceive a wide variety of anatomical structures and pathologies. Unfortunately, new surgical techniques separate the surgeon's hands from the surgical site. These techniques include minimally invasive procedures such as laparoscopy and thoracoscopy, and new techniques involving robotic manipulators. In these situations the surgeon's perception is limited to visual feedback from a video camera, or gross motion and force feedback through the handles of long instruments.

We are working to develop new technology to rectify this sensory deficit by relaying tactile information from the surgical site to the surgeon. We have developed a variety of tactile sensors that can be mounted in a probe or surgical instrument. The tactile information provided by these sensors may then be conveyed through the tactile display devices we have developed to recreate the tactile stimulus directly on the surgeon's finger tip. By using these remote palpation devices, the surgeon may regain some of the perceptual and manipulative skills present in conventional open-incision surgery.

Among the tactile feedback parameters we are investigating are force reflection [1], vibration [2], and small-scale shape. Shape information is particularly important for many surgical tasks, such as finding hidden anatomical features and locating tumors. In our system, a tactile array sensor in the remote tip of an instrument measures the distribution of pressure across the tissue contact. A computer system samples this pressure distribution and applies signal processing algorithms. The resulting signal can be graphically displayed on a video monitor, or tactually displayed using a tactile display device mounted in the finger tip contact area of the surgeon's interface. This display device consists of a regular array of pin elements or "tactors" that rest against the surgeon's finger tip. Shape memory alloy wires raise and lower individual tactors to approximate the desired surface shape on the skin. This permits the surgeon to experience the small-scale shape of the tissue at the remote site.

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 teleoperated manipulation. 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 that use tactile array sensing have employed visual feedback to convey touch information from the remote robot to the human operator [4, 5]. Previous work on medical application of tactile array sensors (e.g., [6]) was largely aimed at creating autonomous robotic palpation systems. Our system can also relay to surgeons the sort of information they would receive in direct palpation with their own fingers.

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. A few devices for presenting static (nonvibrating) shape information have been developed. The most appropriate for surgical applications include a tactile pressure distribution display implemented by Cohn, Lam, and Fearing [8]. It uses a 5 x 5 close-packed array of pneumatically-actuated pins, controlled by pulse-width modulated solenoid valves. Mounting on surgical instruments is difficult due to the large number of valves and tubes connected to its elements. Hasser and Weisenberger [9] describe a 5 x 6 array actuated with shape-memory alloy wires in a flexture design. This display provides the high density and small package required for mounting in surgical instruments, but

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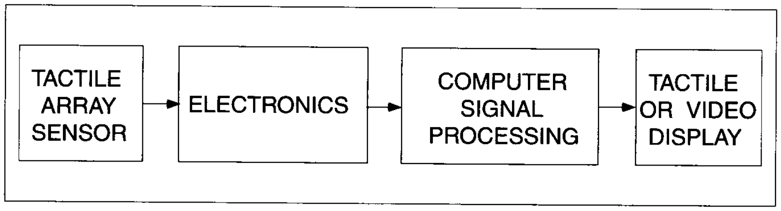


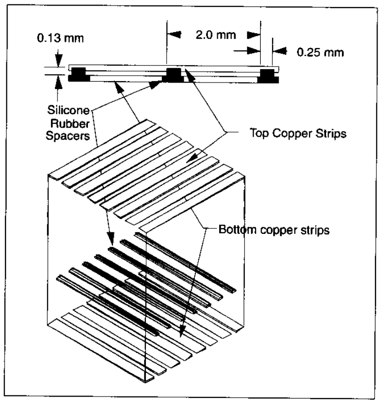
1. System block diagram.

force levels are limited to 0.2N per element, restricting the ability to represent shapes with high curvature under force reflection loads.

Human Tactile Perception

The purpose of our tactile display is the simulation of natural events on the operator's finger tips, so we briefly examine the spatiotemporal characteristics of the human 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, and so on; and tactile or cutaneous sensing, which refers to distributed sensation from the skin [10]. Kinesthetic feedback is typically determined by the surgical instrument, which will not be discussed here, since small-scale shape displays provides stimulus intended primarily for cutaneous perception.

The cutaneous sensory system consists of a variety of mechanoreceptor nerve endings. The four most important types for manipulation can be classified according to their temporal frequency response and size of their receptive fields [11]. Cutaneous mechanoreceptors are described as slowly adapting (SA) or fast adapting (FA), according to their frequency response, particularly to static stimuli. The other criterion is receptive field size: Type I units have small receptive areas and well defined boundaries, while Type II units have large receptive areas with poorly defined boundaries. Type I receptors (both SA and FA) are located close to the surface of the skin, where the deformations and induced stresses are more pronounced. Neurophysiological studies suggest that SAI mechanoreceptors are most important in small-scale shape perception [12], which suggests that a relatively low bandwidth display may suffice in many applications. The ability to perceive separately two pointed indenters on the finger tip requires that the points be separated by 1-2 mm, and humans perceive a surface as textured rather than perceiving each small surface feature individually if the features are less than about 1 mm in extent.



2. Tactile array sensor. Top: side view; tissue contact occurs on upper surface, compressing silicone rubber and forcing top and bottom copper strips closer together. Bottom: exploded view showing sensor construction.

System Design

Figure 1 shows the block diagram of the system. In a typical task, the surgeon will bring the tip of the instrument into contact with the tissue at the surgical site. For minimally invasive procedures, this involves manually positioning the instrument through a trocar at the entry point, while robotic applications require moving the robot's end effector to the point of interest. The resulting pressure distribution across the instrument tip is measured by a tactile array sensor with associated readout electronics. A computer processes the signal to produce appropriate output for visual display on a monitor, or tactile display against the surgeon's finger tip. Below, we describe the components of the tactile feedback system.

Tactile Array Sensor

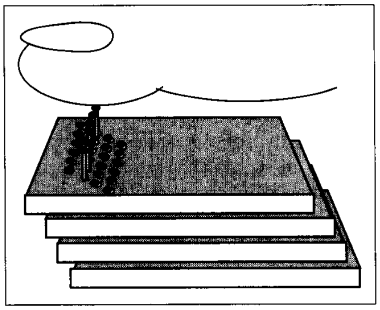
Figure 2 shows the construction of the capacitive tactile array sensor used in this system, which is based on an earlier design by Fearing [13]. The array is composed of two crossed layers of copper strips separated by thin strips of silicone rubber. As a force is applied to the surface above the point 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, we can determine the spatial distribution of pressure across the sensor.

We have devoted considerable effort to optimizing the manufacturing process for these devices. They are made with an inexpensive photolithography/etching process and are thus economically disposable after a single use. The sensor forms a thin, compliant layer, which can be easily attached to a variety of probe 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 use 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 ms. The noise level of each sensor element is less than 0.001N, and the useful sensing range extends to over 2N at each element.

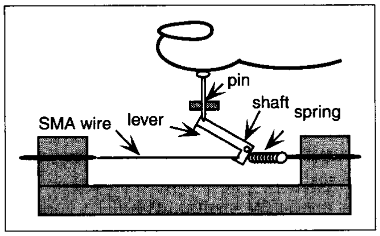
Shape Display

Our goal was to develop a tactile shape display for use in the handle of a surgical instrument or a surgical robot controller. This poses extremely difficult design challenges. First, the display must be small enough so that it fits between the fingers when manipulating an object, and light enough to avoid limiting responsiveness and the range of forces that can be applied. In addition, because the display is located at the point of contact between the manipulator and the surgeon's finger tip, it must be strong enough to support the entire force applied by the surgeon, 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 the section on human tactile sensing above, we selected design goals of approximately 2 mm center-to-center element spacing, 3 mm total vertical excursion, 10 Hz minimum bandwidth, and at least 1N force per tactor. Our initial prototype was limited to 3 x 3 elements [14], while the second-generation display device described here has 6 x 4 elements.

The shape display raises pins against



3. Shape display showing 6 x 4 pin elements and surgeon's finger tip.



4. Side view of one display element. Electric current causes the SMA wire to heat and contract, which rotates the lever to raise the pin against the surgeon's finger tip.

the human finger tip skin to approximate the desired shape (Fig. 3). We selected shape memory alloy (SMA) wires as actuators because of their very high power-to-volume, power-to-weight, and force-to-weight ratios. Their nonlinear behavior, hysteresis, and slow time response can be overcome by appropriate control schemes. The mechanical design of one element of the shape display is shown in Fig. 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 provides 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 effect causes the lever to rotate about a fixed shaft. The other end of the lever then forces a pin upwards against the tip of the operator's finger. The levers provide a 3:1 reduction in force and the same amplification in displacement. The wires we used are 30 mm long and 0.075 mm in diameter. The shape display consists of four layers, each having six actuators. The center-to-center spacing of the tactors is approximately 2.1 mm.

The phase change responsible for the SMA action is accompanied by hysteresis, directional asymmetry, and other nonlinear effects, which pose difficult challenges to effective control. (See [15, 16] for a more complete discussion of SMA properties and function.) We have addressed problems of slow thermal response time 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. 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 6 x 4 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 [14, 17].

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 of the copper strips) at some distance beneath the surface of the sensor. 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 [13] 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 sensor. In general, this is an ill-posed inversion problem; several techniques, including regularization [18] and neural networks [19], have been proposed.

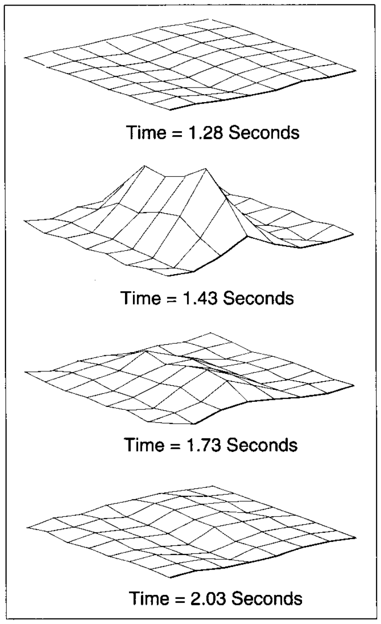
For these initial experiments, we have avoided the need for this type of signal processing by limiting the thickness of the rubber layer overlying the tactile sensor to less than 1 mm. This means that the surface of the sensor conforms to the shape of objects pressed against the finger tip, and the sensor thus records shape information directly. One limitation incurred with this approach is that the sensor 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, as shown in the experiments described below.

Artery Localization

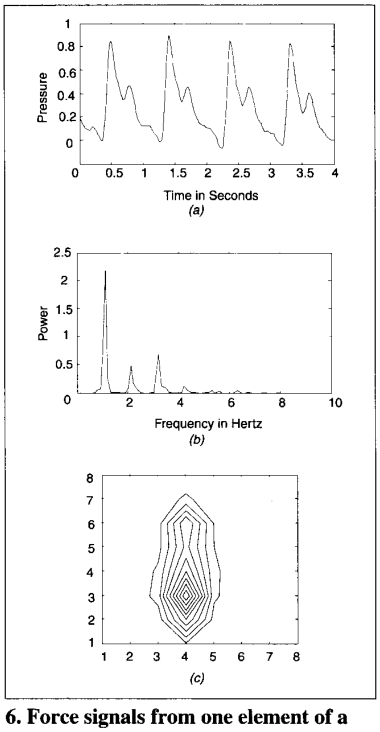
As an initial application of the technology described above, we are investigating its use in finding hidden arteries. The location of arteries beneath opaque tissues at the surgical site must be carefully ascertained to prevent unintended rupture and life-threatening exsanguination. In robotic or minimally invasive surgical techniques, this localization requires slow and painstaking dissection with clumsy tools, making these procedures time consuming and tedious. Our system permits artery localization through tactile detection of pulsatile pressure variations. The approach is modeled after the surgeon's ability to locate arteries through palpation in conventional open-incision surgery.

To use the system in a typical laparoscopic procedure, the surgeon would press a probe containing a tactile array sensor against the tissue of interest within the patient's body. A computer captures this information and processes the signal to find the periodic pressure variations due to the pulsatile arterial blood flow. The results are then displayed on a video monitor or tactile display for the surgeon's use.

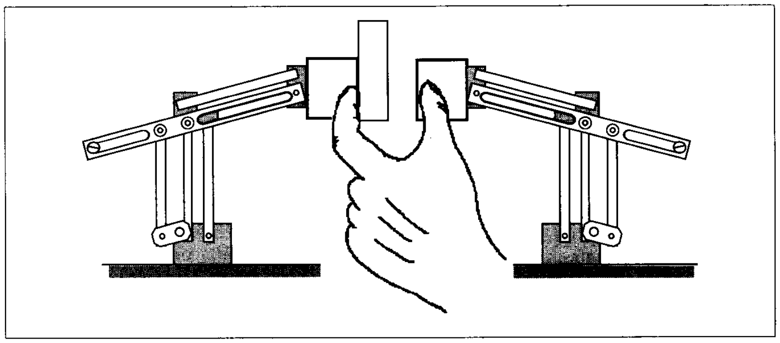
One important design problem is determining the optimum compliance of the sensor surface to maximize signal amplitude. As noted above, solution of this problem requires analysis of the mechanical interaction between the sensor and tissue. The artery is essentially an elastic tube, with the blood pressure contained largely by the strength of the arterial wall. To detect arterial pressure through contact, the sensor surface must deflect the wall of the artery and thus assume some of the pressure load. In the simplest case, the artery is modeled as a perfectly flexible membrane, and the force due to the arterial pressure on a flat indenting sensor surface is



5. Data showing time sequence of pressure distribution across the sensor due to arterial blood pressure variation.



6. Force signals from one element of a tactile array sensor located over an artery. (a) Force variation with time. (b) Power spectrum. (c) Contour plot display showing inferred artery location based on harmonics in power spectrum; axes refer to sensor element numbers.



7. Master manipulator of teleoperated hand system, showing the shape display for operator's index finger tip. Slave manipulator is a kinematically identical mechanism with a tactile array sensor on the corresponding finger tip.

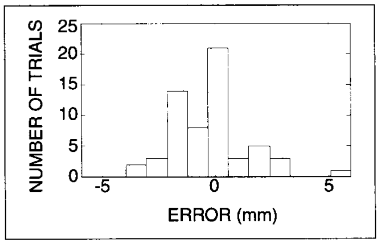
$$F(t) = \frac{\pi}{2} \Delta H \, p(t)$$

where ΔH is the distance the artery is compressed from its initial diameter and $p(t)$ is the time-varying blood pressure. According to this relation, the measured sensor signal will increase as the artery is compressed (up to the point that flow is restricted). This suggests that a rigid sensor is preferable since it will most effectively compress the artery and surrounding tissue. However, some compliance in the sensor surface is useful as it permits the sensor to conform to geometric and elastic irregularities in the sensed region. The compliance of the sensor surface should thus vary with the physiology in the target tissue region, and sensor surface compliance can be optimized for a particular application.

Figure 5 shows a time sequence of sensed pressure distribution with the sensor pressed against the wrist immediately above the radial artery. The pulsatile pressure variation is immediately apparent. Figure 6a shows the pressure response of a single element located over an artery. Signal processing routines find locations where pulsatile pressure variations are present, as well as the relative magnitude of that signal. Our current algorithm begins by examining the frequency content of each of the 64 elements; and Fig. 6b shows the power spectrum of an arterial pulse signal. Since the sensor probe is manually pressed against the area of interest, low frequency noise can obscure the signal in Fig. 6, particularly when the sensor is not centered over the artery. To lessen the effects of these perturbations on the signal of interest, we use the large-amplitude harmonics of the fundamental frequency of the pulse, which range from about two to five Hz for a typical pulse around one Hz. The power in the harmonics is summed at each element, and the relative power in comparison to the other elements is displayed as a two-dimensional contour plot on a video monitor. A more elaborate signal processing scheme now under development takes a trigger signal from an external pulse monitor, and correlates the anticipated pulse waveform with each sensor signal. Advantages of this approach include faster response, better noise rejection, and rapid adaptation to variations in pulse rate.

Localizing Tumors

We have combined the tactile aray sensor with the shape display to create a system for localizing tactile features. In our first proof-of-concept experiments, subjects were asked to locate a hard rubber cylinder inside a block of foam rubber. This task simulates the key aspects of medical procedures where tumors are localized with palpation. Dario [6] 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 (Fig. 7) [20]. This is a nonexoskeleton system that 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.



8. Histogram of position errors in tumor localization task.

Both master and remote slave manipulators are identical two-fingered hands with two degrees of freedom in each finger, and thus 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, 20].

Sensors in the finger tips of the remote manipulator measure the shape encountered during task execution, and the shape display relays this information to subjects operating the telemanipulation system. The phantom used in these experiments consists 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 is used to change the vertical location of the phantom between trials to random locations within a 20 mm range. Subjects are asked to probe the phantom with the teleoperated hand until they located the tumor. The experimenter records 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 are used to relay shape information. During the tumor localization task, full force reflection is available, but no visual feedback is allowed. Subjects perform the task both with and without the shape feedback, to determine the effectiveness of the shape relay system.

Figure 8 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 percent of the trials, and with an error of 3 mm or less 95 percent 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. The provision of small-scale shape information clearly permitted successful localization of the simulated tumor.

Conclusions

The results of these of preliminary experiments demonstrate that a tactile sensing and display system can convey important small-scale shape information from an inaccessible location to the surgeon's finger tips. Important questions remain to be addressed in the areas of hardware development, signal processing, and systems integration. The bandwidth and dynamic range requirements for specific tasks is not clear at this point, and a better understanding is required for proper specification of system performance. Another important area of future work is the integration of the tactile feedback system with surgical instrument design for minimally invasive procedures, and with robotic controllers for telesurgical applications. We are also investigating the combination of shape with vibratory information for improved perception of texture and transient events.

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