Human and Machine Haptics

RLE Group
Laboratory for Human and Machine Haptics (The Touchlab)

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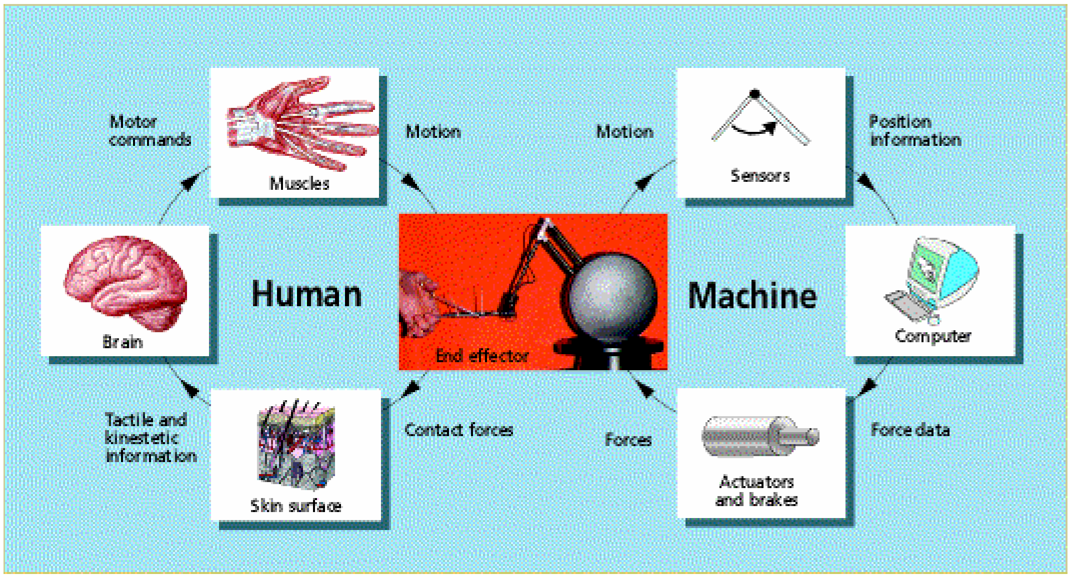
Abstract
The work in the Touch Lab (formal name: Laboratory for Human and Machine Haptics) is guided by a broad vision of haptics which includes all aspects of information acquisition and object manipulation through touch by humans, machines, of a combination of the two; and the environments can be real or virtual. In order to make progress, we conduct research in multiple disciplines such as skin biomechanics, tactile neuroscience, human haptic perception, robot design and control, mathematical modeling and simulation, and software engineering for real-time human-computer interactions. These scientific and technological research areas converge in the context of specific application areas such as the development of virtual reality based simulators for training surgeons, real-time haptic interactions between people across the Internet, and direct control of machines from brain neural signals.

Key Words
Haptics, touch, skin biomechanics, tactile neuroscience, haptic psychophysics, human-computer interactions, virtual reality, medical training, brain-machine interfaces

Introduction
Haptics refers to sensing and manipulation through touch. Although the term was initially used by psychologists for studies on active touch by humans, we have broadened its meaning to include humans and/or Machines in real, virtual or teleoperated environments. The goals of research conducted in the Touch Lab are to understand human haptics, develop machine haptics, and enhance human-machine interactions in virtual environments and teleoperation. Human Haptics is the study of how people sense and manipulate the world through touch. Machine Haptics is the complimentary study of machines, including the development of technology to mediate haptic communication between humans and computers as illustrated in the figure below.



In the figure, a human (left) senses and controls the position of the hand, while a robot (right) exerts forces on the hand to simulate contact with a virtual object. Both systems have sensors (nerve receptors, encoders), processors (brain, computer), and actuators (muscles, motors). Applications of this science and technology span a wide variety of human activities such as education, training, art, commerce, and communication.

Our research into human haptics has involved work on biomechanics of skin, tactile neuroscience, haptic and multimodal psychophysics, and computational theory of haptics. Our research into machine haptics includes work on computer haptics -- which, like computer graphics, involves the development of the algorithms and software needed to implement haptic virtual environments -- as well as the development of haptic devices. Applications of haptics that we have investigated include methods for improving human-computer interaction as well as novel tools for medical diagnosis and virtual reality based medical training. An exciting new area of research we have initiated is the development of direct brain-machine interfaces, using which we recently succeeded in controlling a robot in our lab using brain neural signals transmitted over the internet in real-time from a monkey at Duke. Another of our research results that made world news headlines recently was the first demonstration of transatlantic touch where a user in our lab and a user in London collaboratively manipulated a virtual cube while feeling each other's forces on the cube. Our current projects are described in the following sections.

1. Biomechanics of Touch

Mechanics of the skin and subcutaneous tissues is as central to the sense of touch as optics of the eye is to vision and acoustics of the ear is to hearing. When we touch an object, the source of all tactile information is the spatio-temporal distribution of mechanical loads on the skin at the contact interface. The relationship between these loads and the resulting stresses and strains at the mechanoreceptive nerve terminals within the skin, plays a fundamental role in the neural coding of tactile information. Unfortunately, very little is known about these mechanisms.

In the Touch Lab, we develop apparatus and perform experiments to measure the mechanical properties of the skin and subcutaneous tissues. In addition, we develop sophisticated mechanistic models of the skin to gain a deeper understanding of the role of its biomechanics in tactile neural response. A variety of techniques have been used in our experiments, including videomicroscopy, Optical Coherence Tomography (OCT), Magnetic Resonance Imaging (MRI), high frequency ultrasound backscatter imaging (UBM), and computer-controlled mechanical stimulators. We use the empirical data to develop finite element models that take into account inhomogeneity in the skin structure and nonlinearities in its mechanical behavior. Analysis of these models in contact with a variety of objects generates testable hypotheses about deformations of skin and subcutaneous tissues, and about the associated peripheral neural responses. Verification of the hypotheses are then accomplished by comparing the calculated results from the models with biomechanical data on the deformation of skin and subcutaneous tissues, and with neurophysiological data from recordings of the responses of single neural fibers. We are currently engaged in a wide range of projects in this area.

1.1 Computational Mechanistic Models

To study the mechanism of transduction by the mechanoreceptors, 18 mechanical measures were obtained for the calculated stress and strain components at 9 mechanoreceptor locations under load ranges from as low as 8 gwt and as high as 50 gwt. Three sinusoidal indenters with half-cycle wavelengths of 0.45, 1.23 and 3.318 mm respectively were used, compatible to those used in the neurophysiological experiments. It was found that the spatial response profile was dependent on the lateral location of the receptor. It is implied that the population response is substantially different from the spatial response profile in general, as shown in the Figure 1.1-1. Among all the shear and strain measures, strain energy density is the best candidate since it is a scalar that is invariant with respect to receptor orientations and is a direct measure of the distortions of the receptor caused by loads imposed on the skin.

Based on the in-vivo Optical Coherence Tomography (OCT) images from fingertips of human subjects, more detailed fingerprint substructures were incorporated into the 2D finite element model for human fingertips. The epidermis was divided into two sublayers, stratum corneum and living epidermis. Spherical indentors were applied both in the experiments using OCT and the simulations, with radii ranging from 7.8 mm to 78.0 mm. The profiles of skin displacement indicated by the model agrees pretty well with the experiments at this finer level.

More investigations will be conducted to incorporate the detailed ridge information into our well-developed 3D finite element models. Moreover, corresponding experiments will be done to further improve the model.

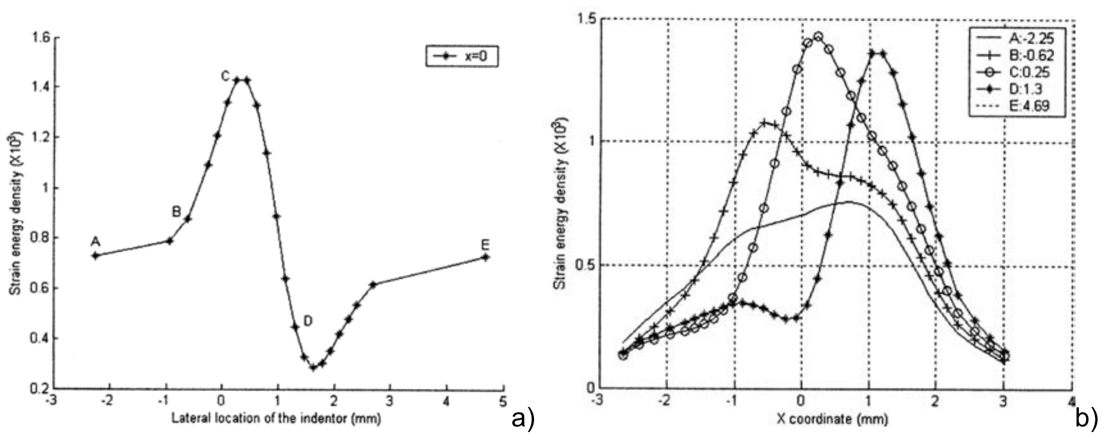


Figure 1.1-1 *Relationship between simulated population and spatial response profiles in terms of strain energy density. This example is from the case for a sinusoidal indentor with half-cycle wavelength of 1.23 mm and indented to a load of 20gwt. a) Spatial response profiles for one receptor; b) population response profiles when the indentor is located at 5 different locations.*

1.2 Investigation of Skin Material Properties using *In Vivo* Ultrasound Backscatter Microscopy (UBM)

To further improve our finite element model of the fingertip, the stiffness ratio of epidermis versus dermis was investigated using strain imaging technology. An indentation system was added to our UBM system (which was developed previously) so that the RF signal can be collected before and after compression by an indenter. Figure 1.2-1 shows a UBM image (a) of the fingerpad skin of a female subject aged 18 and the processed data of axial displacement with two straight lines fitted to it (b). The axial strain, or the slope, of the displacement curve, is about 0.0042 till depth 1 mm and 0.0343 below that, indicating a ratio of more than eight times. Ten human subjects were tested for ten times. And the average ratio of the stiffnesses of the two skin layers was shown to be 6.58, with a standard deviation of 2.21. The maximum standard deviation for a single subject is 3.13 and the minimum is 1.40.

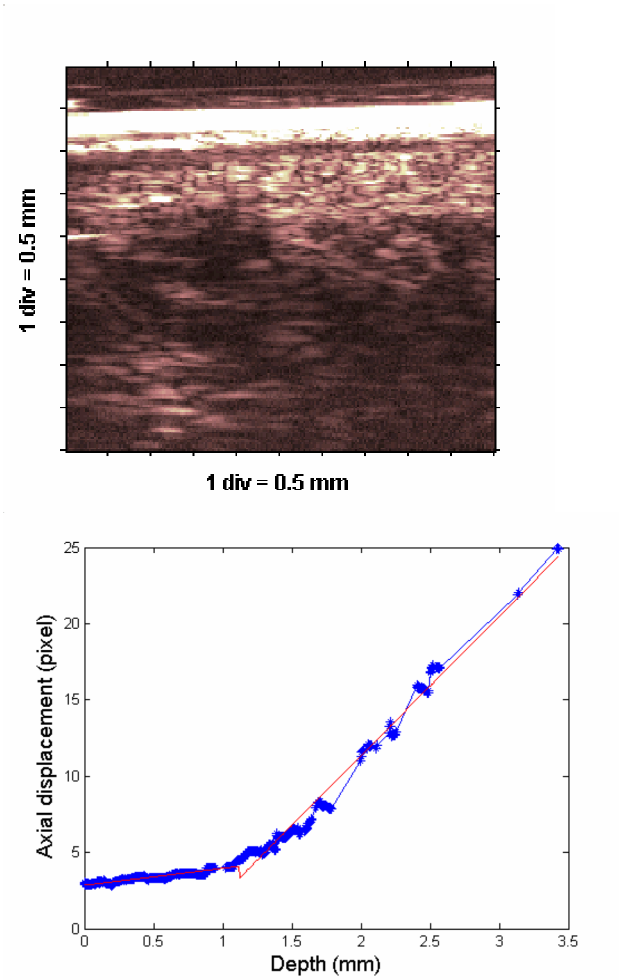


Figure 1.2-1 *A UBM image (a) in which the distance between the ticks on the axes is 0.5mm. (b) The axial displacement data of the fingerpad and its curve fitting with two straight lines.*

2. Tactile Neuroscience

Tactile neuroscience is concerned with understanding the neural processes that underlie the sense of touch originating from contact between the skin and an object. Traditional studies have focused on characterizing the response of mechanoreceptors in the skin to various stimuli such as vibrating probes or indenting sharp edges. In contrast, we have tried to determine how object properties such as shape, microtexture, and softness, and contact conditions such as slip, are represented in the peripheral neural response.

Most of our work in this area has been done in collaboration with Dr. Robert H. LaMotte of the Yale University School of Medicine. In the experiments, microelectrodes monitor the discharge rate of tactile receptors in the skin of anesthetized monkeys while the surface of the skin is mechanically stimulated. Computer-controlled stimulators press and stroke carefully designed objects on the fingerpads. Frequently in conjunction with these neurophysiological measurements, we have also performed psychophysical experiments with human subjects using the same apparatus.

2.1 Development of methods to quantify mechanoreceptor response in vivo to mechanical loading

The project aims at the development of methods to “observe” and quantify neural impulses of mechanoreceptors in vivo in response to external mechanical stimuli. Studies are being conducted on the touch receptors of the roundworm C. Elegans, where receptors similar to those in humans are more accessible for analysis using available techniques such as fluorescence microscopy. The project focuses on developing methods that can be extended to the study of human or primate fingertips. Two approaches are being followed to analyze and quantify the neural response of the mechanoreceptors of this worm,

The observation of mechanoreceptor response to mechanical stimulation by analyzing calcium transients in nerve cells through analysis of the change in emission wave length of a calcium sensitive Green Fluorescent Protein (GFP) dye administered to the mechanoreceptor of the worm under fluorescence. Analysis of the change in scattering across the axon of the nerve cells is an indication of change in neuron membrane potential and hence neural activity when the mechanoreceptor is excited by mechanical stimulation.

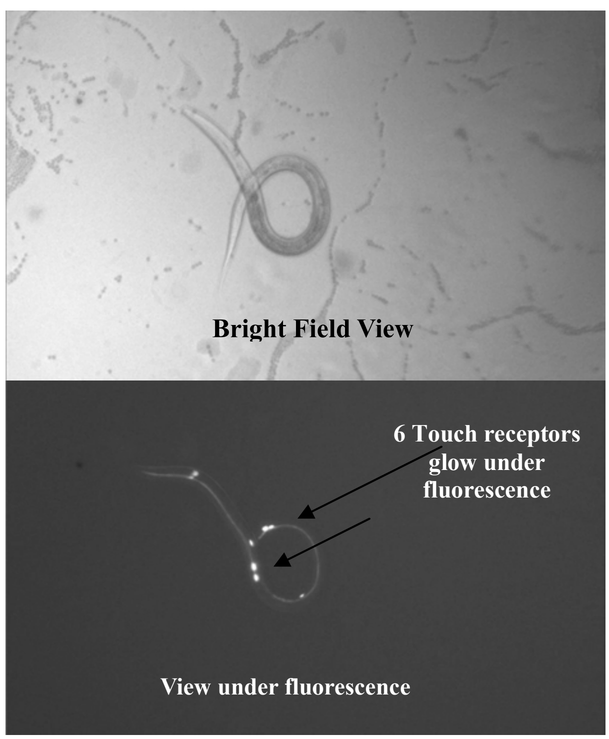


Figure 2.1-1 *Observation of GFP fluorescence in the touch neurons of C. Elegans*

The worms have been administered with a cell specific Green Fluorescent Dye targeted at the touch receptors and as a result, the touch receptors are visible under fluorescence as shown in the above figure. The response of these touch cells will be studied under mechanical stimulation, provided with a microprobe attached to a computer controlled X-Y table, by the above two mentioned approaches.

3. Sensorimotor Psychophysics

Psychophysics is the quantitative study of the relationship between physical stimuli and perception. It is an essential part of the field of haptics, from the basic science of understanding human haptics to setting the specifications for the performance of haptic machines. It is also quite natural to extend psychophysical methods to the study of motor control in this case, investigating the relationship between intention and physical effect, because the haptic channel is inherently bi-directional.

We have conducted pioneering psychophysical studies on compliance identification and discrimination of real and virtual objects, and determined the human resolution (i.e., Just Noticeable Difference, JND) in discriminating thickness, torque, stiffness, viscosity, and mass under a variety of conditions. Furthermore, using the virtual environment systems that we have developed, we have conducted psychophysical experiments under multimodal conditions, such as the effect of visual or auditory stimuli on haptic perception of compliance. We have also conducted a number of studies on the human ability to apply controlled forces on active and passive objects. Psychophysical experiments related to the detection of extremely fine--75-nanometer high--textures and the detection of slip have also been performed in conjunction with neurophysiological measurements. Currently we are engaged in the various tactile threshold measurements.

3.1 Perceptual Frequency Response of Human Skin

This project investigated spatiotemporal tactile perceptive characteristics and biomechanical properties of human skin and considers their implications for the design of tactile displays. Three separate experiments were conducted. First, we measured vibrotactile thresholds as a function of frequency of vibration, using a cylindrical contactor of 0.7mm diameter. The results of our experiment showed similar trends to that of previous physiological results that used a larger contactor. In the second experiment, vibrotactile spatial acuities were investigated. Two-point localization errors were measured on the tip of the index finger and on the thenar eminence as a function of frequency of vibration. The results show that human skin is sensitive to spatial differences at the frequency bands of 1-3Hz and 18-32Hz. The subjects' spatial acuities gradually decreased as the frequency of vibration increased over 50Hz. In the third experiment, impedances of human skin were measured as a function of frequency of vibration. These results have implications for designing spatially distributed tactile displays and methods for texture display.

4. Haptic Device Development

Haptic devices are used to investigate, augment, or replace human haptic interactions with the world. For example, haptic devices like the Instrumented Screw Driver (see photo) have been developed and used in the Touch Lab to investigate human performance. The Instrumented Screw Driver was used in an experiment to study a person's ability to sense and control torque.1 In the experiment, subjects held the handle of the computer-controlled device in a pinch grasp and overcame a preprogrammed resistive torque to rotate the handle. Other devices, like the

[1] Jandura L and Srinivasan MA, Experiments on human performance in torque discrimination and control, in Dynamic Systems and Control, Vol. 1, Ed: C. J. Radcliffe, DSC-Vol.55-1, pp. 369-375, ASME, 1994.

Epidural Injection Simulator (see photo), have been developed in the lab to augment medical training.2 Using this device, the trainee manipulates a syringe and feels realistic forces as he or she attempts to position the needle and inject a fluid. Another example of augmenting performance is on the development of machines that can be directly controlled by brain neural signals.3 4.

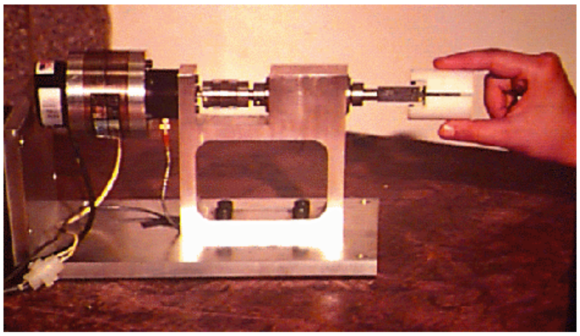


Figure 4 -1 *Instrumented Screw Driver*

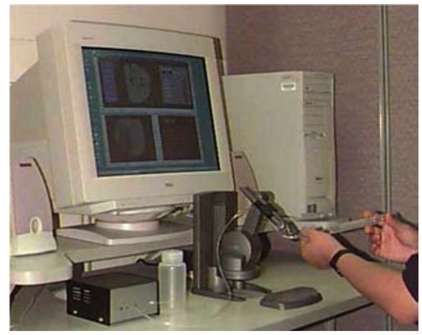


Figure 4 -2 *Epidural Injection Simulator*

Primarily, the development of haptic devices in the Touch Lab is driven by our need for new types of experimental apparatus to study haptics and its applications. Our work in this area includes the design and construction of new devices as well as the modification/enhancement of existing apparatus to meet specific needs. Our current work on haptic devices focuses on the development of tactile sensors, displays, and stimulators in connection with our projects related to Biomechanics of Touch, Sensorimotor Psychophysics, and Brain Machine Interfaces.

4.1 Design of pressure sensor array

We are developing a new type of tactile pressure sensor arraya. As shown in Figure 4.1-1 (left), the sensor array is a 32x32 sensor matrix with overall working area of 64x64mm2. The spatial resolution of this matrix is 2mm, and the effective area of each element is 1x1mm. Each sensor element is a small capacitor formed at the overlap between the top and the bottom copper straps which are perpendicular to each other. The pressure applied on the sensor surface is indirectly obtained by measuring the change in the capacitance of each sensor element.

Figure 4.1-1 (right) shows the structure of capacitor elements and geometric parameters. It can be seen that each element consists of 5 layers, which are the bottom PDMS layer (substrate), the lower electrode layer, the medium layer, the upper electrode layer and the top PDMS layer (protective layer).

[2] Dang T, Annaswamy TM and Srinivasan MA, Development and Evaluation of an Epidural Injection Simulator with Force Feedback for Medical Training, Medicine Meets Virtual Reality Conference 9, Newport Beach, CA, January, 2001.
[3] Wessberg J, Stambaugh CR, Kralik JD, Beck P, Laubach M, Chapin JK, Kim J, Biggs SJ, Srinivasan MA and Nicolelis MAL, Adaptive, real-time control of robot arm movements by simultaneously recorded populations of premotor, motor and parietal cortical neurons in behaving primates, Nature, Vol. 408, No. 6810, pp. 361-365, 2000.
[4] Nicolelis MAL and Chapin JK, Controlling Robots with the Mind, Scientific American, 287 (4), pp 46-53, 2002.

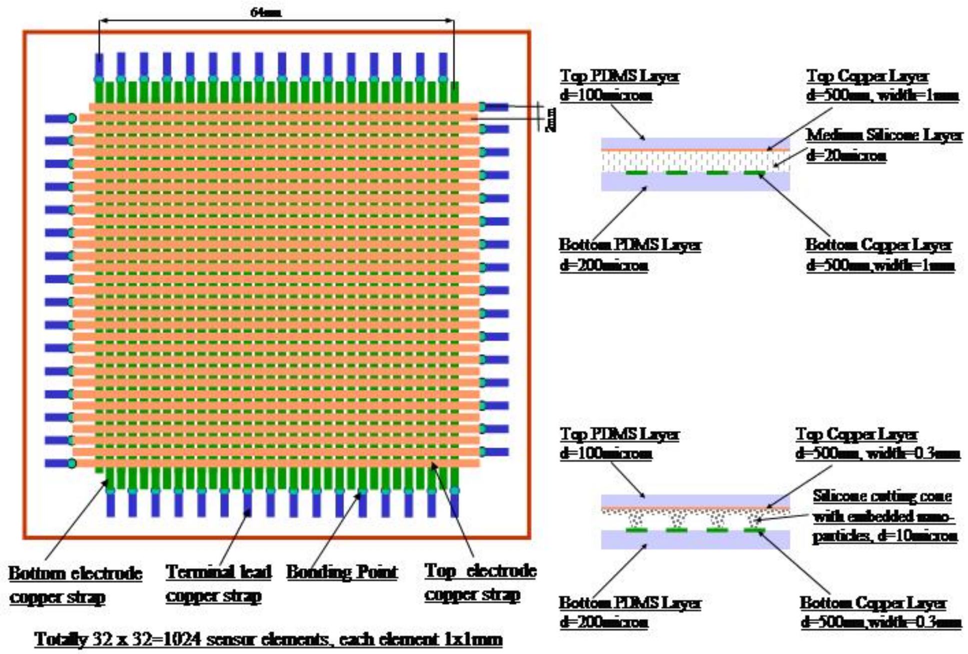


Figure 4.1-1 *Schematic illustration of pressure sensor array–overview (left) and cross-section (right).*

Finite element analysis (FEA) is being used to obtain optimal structural parameters for the sensor. An FEA model has been built up to determine the magnitude of vertical (y) displacement and horizontal (x) stress throughout the sensor after virtually applying a certain loads. Simulation of electric field properties have also been performed with the same model with an input voltage. Our results show that the concentration of electric field is just slightly dispersed under the assumed structural parameters. This should mitigate errors due to any non-linearity in the capacitors.

Figure 4.1-2 shows a photo of an initial prototype sensor array we have made. By improving the metal deposition process and adopting a new PDMS surface treatment method, we created a special deposition process which we have named floating deposition. This will benefit the sensor in two aspects. The first is to get rid of the rigidity brought about by the existence of extra copper. The second is to prevent the cracking of copper under tensile stress during bending, so the sensor array could be bent and folded to the profile of the object to be sensed.

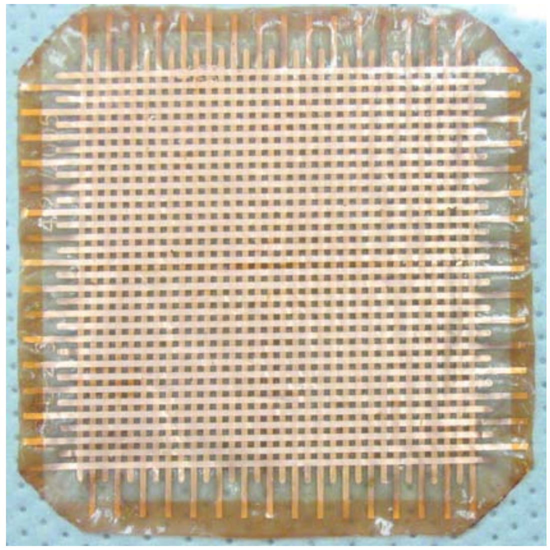


Figure 4.1-2 *Prototype sensor array fabricated in the Touch Lab*

The medium layer, acting as the dielectric layer between the two copper straps of each pair of electrodes, has been made of supersoft silicone material with the hardness as low as 50 Shore 00. This has made output amplitude of each sensor element to be at 50% even at a load of only 10g.

In the future, we hope to modify the deposition process in order to obtain nano-crystalline copper electrode straps. This will help to prohibit the occurrence of fatigue failure. We also plan to develop additional hardware and software for signal processing and calibration of sensor array. Finally we plan to in use this sensor array in experiments to understand the mechanisms of human tactile sense.

4.2 Compact Broadband Tactile Display

We have developed a tactile display which offers flexible stimulating frequency in wide range (static to ~325Hz) with a normal displacement (~700μm) large enough to feel even at low frequencies. The additional importance of this tactile display is that it is small enough to mount on existing force feedback devices. Figure 4.2-1 shows the contact interface of our tactile display. The frame is 40mm x 20mm x 23mm. Some of the parts were fabricated by stereolithography (SLA), others by laser cutting. The 30 stacked actuators are piezoelectric bimorphs (40-1055, APC Int. Ltd., PA) driven by 150 VDC bias. The maximum deflection is over 0.7mm and the blocking force is 0.06N. The size of a bimorph is 35mm x 2.5mm and the thickness is 0.6mm. The 30 pins, which lie on 1.8mm centers, were made by SLA. Efforts to minimize the weight of the materials and wiring produced a design with a finished weight of only ~11 gram. For control system of the tactile display, we used a 32-channel analog output card (NI PCI-6723, National Instruments, TX).

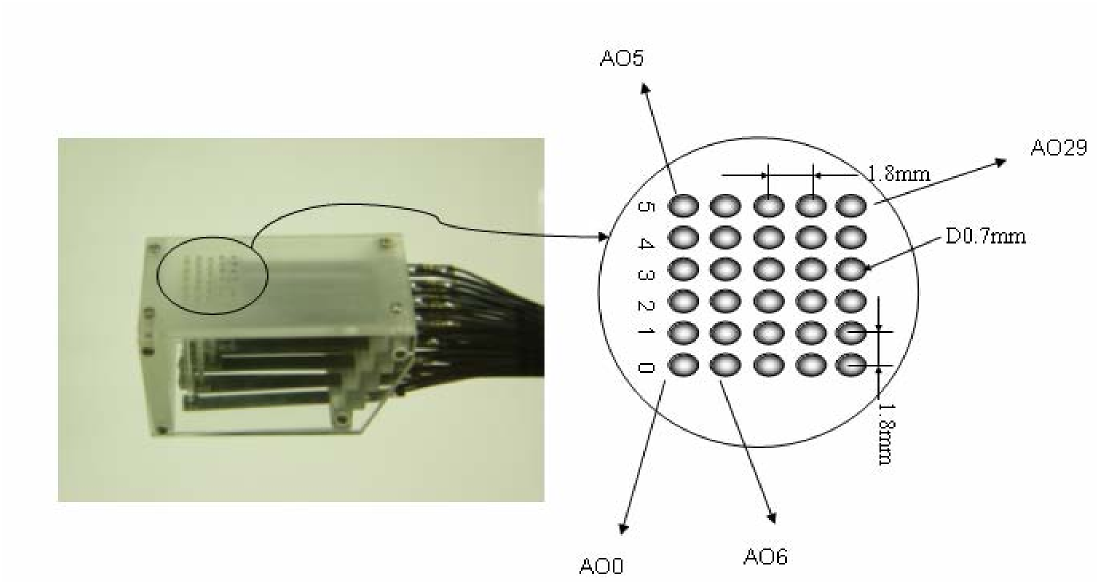


Figure 4.2-1 *The tactile display and D/A card connection configuration*

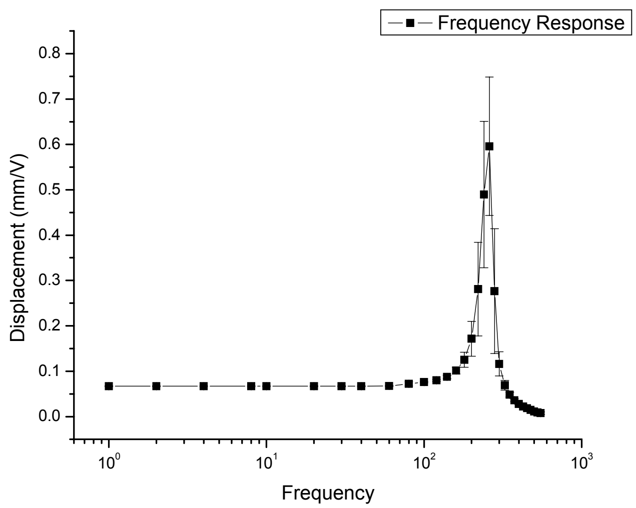


Figure 4.2-2 *Frequency Response of the tactile display*

4.3 Research on Wearable Tactile displays

Over the last year, we have developed two new types of wearable tactile displays. The first, (Figure 4.3-1) is based on shape memory alloy. It makes use of a novel bistable mechanism. Manufacturing techniques were developed to integrate the actuators, multiplexing electronics, wiring, transmission, and insulation into a conformable flex cable. Robust electronics and software for driving arrays of 8 to 120 actuators were also developed. A patent application is pending[5].

[5] Biggs-SJ, Daverman-RD, Thin, flexible actuator array to produce complex shapes and force distributions. Utility Patent Application to the United States Patent and Trademark Office. (filed March 11, 2005).

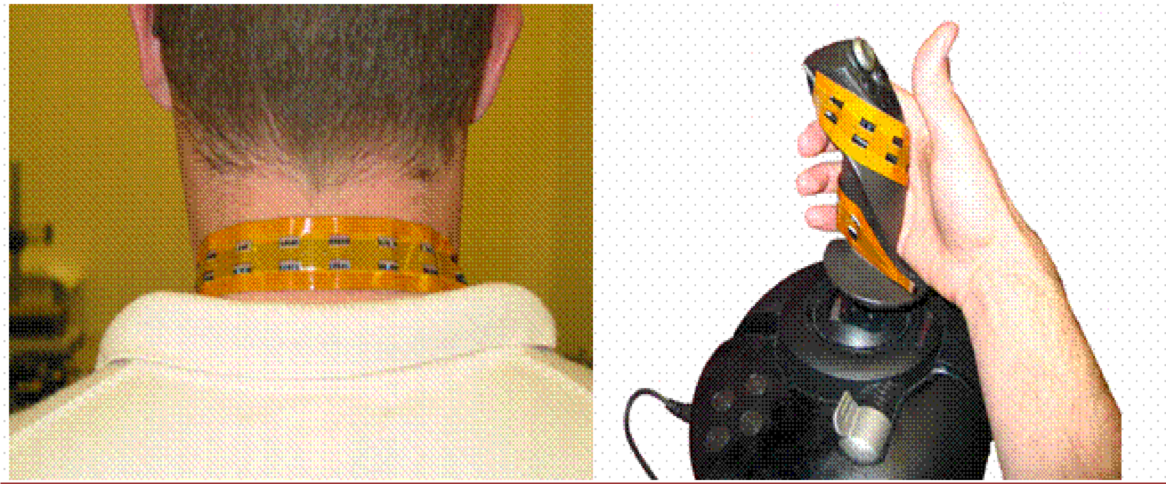


Figure 4.3-1*Conformable tactile array based on shape memory alloy*

The second new type of wearable tactile display we developed over the last year is based on dielectric elastomer actuators (Figure 4.3-2). A novel fiber-elastomer laminated composite was developed for this project, in order to give the device the wearability of clothing. Initial tests show that the actuator has sufficient bandwidth to render the full temporal range of touch sensations (0.1-250 Hz). Development is ongoing.

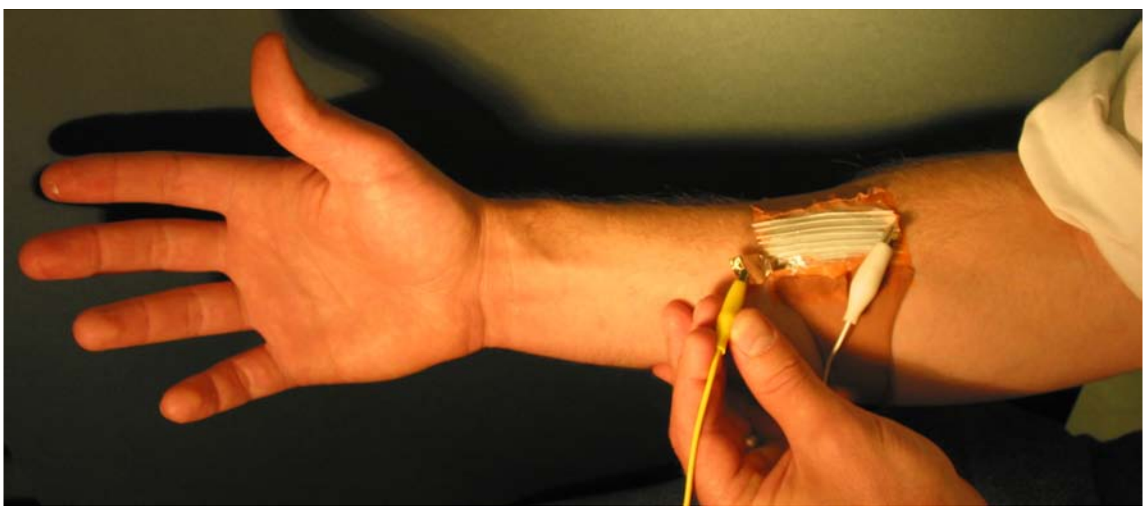


Figure 4.3-2 *Conformable tactile array based on dielectric elastomer actuators*

4.4 Back-Drivable Gripper for Direct Brain Controlled Grasping

During the last year we continued the development of a small, high-performance robotic gripper to be used in brain-controlled grasping experiments. The 1 degree-of-freedom (dof) back-driveable gripper is designed to be mounted on the end of a Phantom 3.0 (Sensable Technologies)--a 3 dof backdriveable robot that is normally used as a haptic interface--and the combined 4 dof robotic manipulator (gripper + Phantom) will be used in reaching and grasping experiments in which the robot is controlled by neural signals from electrodes implanted in a monkey's brain. These experiments require a high performance manipulator and our goal in the gripper development is to create a robotic end effector with performance that is comparable to and compatible with the Phantom.

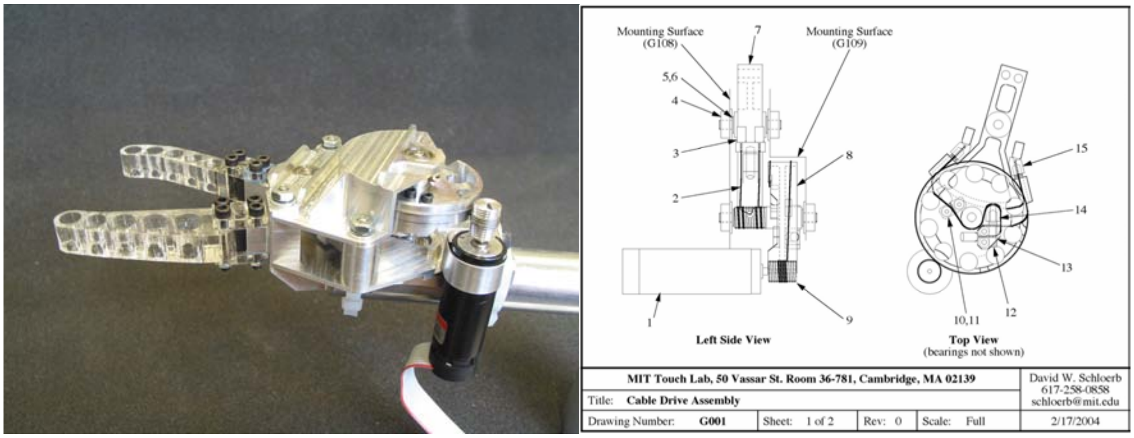


Figure 4.5-1 *Gripper illustration*

The photograph (Figure 4.5-1, left) shows the assembled gripper, minus its protective outer cover, and the drawing (right) shows assembly details of the gripper's 43:1 speed reducing cable drive. The drive is similar to the one used on the Phantom except that it has two stages and a higher speed ratio. The assembled gripper is 14 cm long and weighs 184 g (as shown). The mass with the outer cover is expected to be about 200 g, or two times the original design goal. Each finger is attached to the gripper with a mechanical fuse made out of two 3 mm thick acrylic plates. Precise cutouts, made using a laser cutter, ensure that the fingers will snap off before the cable drive is damaged when excessive loads are applied.

To date, the final electronic have been assembled and preliminary demonstrations have been performed using the gripper mounted on one of the Touch Lab's large-workspace Phantoms. Software for integrating the gripper into Phantom/Ghost applications has been written and implemented as a C++ class. The remaining work on the project involves performance testing, evaluation of the gripper, and preparation for operational use.

5. Human Computer Interactions

An important general application of our research is the use of haptics to improve communication with, or mediated by, computers. Just as the graphical user interface (GUI) revolutionized human computer interactions (HCI) compared to earlier text-based interfaces in the early 1980's, adding haptics has the potential of significantly expanding the communications channel between humans and computers in a natural and intuitive way. Specific goals range from the development of a standard haptic user interface (HUI) for a single user to improved virtual environment and teleoperation systems with users who collaborate over large distances.

Some of our work in this research area has focused on fundamental issues related to the development of haptic interfaces, such as quantifying human users' abilities and limitations in performing haptic tasks with or without the accompaniment of visual and/or auditory displays. An interesting application we have studied is the interaction of multiple users in a shared virtual environment, described below.

6. Medical Applications

Touch Lab research has a wide range of medical applications. On a fundamental level, our investigations of human haptics offer insights into the functioning of the human body that should ultimately lead to improved medical care. Many of the experimental techniques and apparatus developed in these studies also have specific clinical uses that are explored in collaboration with various medical researchers. The lab's primary medical focus, however, has been to develop machine haptics and other virtual environment technologies for specific medical needs. The major thrust to date has been the development of virtual reality based medical simulators to train medical personnel, similar to the use of flight simulators to train pilots.

We have developed an epidural injection simulator and a laparoscopic surgical simulator with novel real-time techniques for graphical and haptic rendering. The epidural injection simulator, developed in collaboration with Dr. Thiru Annaswamy of UT Southwestern Medical Center, Dallas, TX, has been tested by residents and experts at two hospitals. It is currently exhibited at the Boston Museum of Science where the general public can experience the feel of performing a needle procedure without any risk to a patient. Another project we have pursued has been on developing haptic and graphical rendering techniques in the context of laparoscopic esophageal myotomy (Heller myotomy).

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S. Meghani, B.S. Dept. of Mechanical Engineering, MIT May 2004.