Laboratory for Human and Machine Haptics: The Touch Lab

Academic and Research Staff
Dr. Mandayam A. Srinivasan, Dr. S James Biggs, Dr. Gang Liu, Dr. David W. Schloerb, Dr. Lihua Zhou

Visiting Scientists and Research Affiliates
Dr. Orly Lahav, Dr. Donjin Lee, Dr. Jianjuen Hu

Graduate Students
Hyun Kim, Wan-Chen Wu, Siddarth Kumar,

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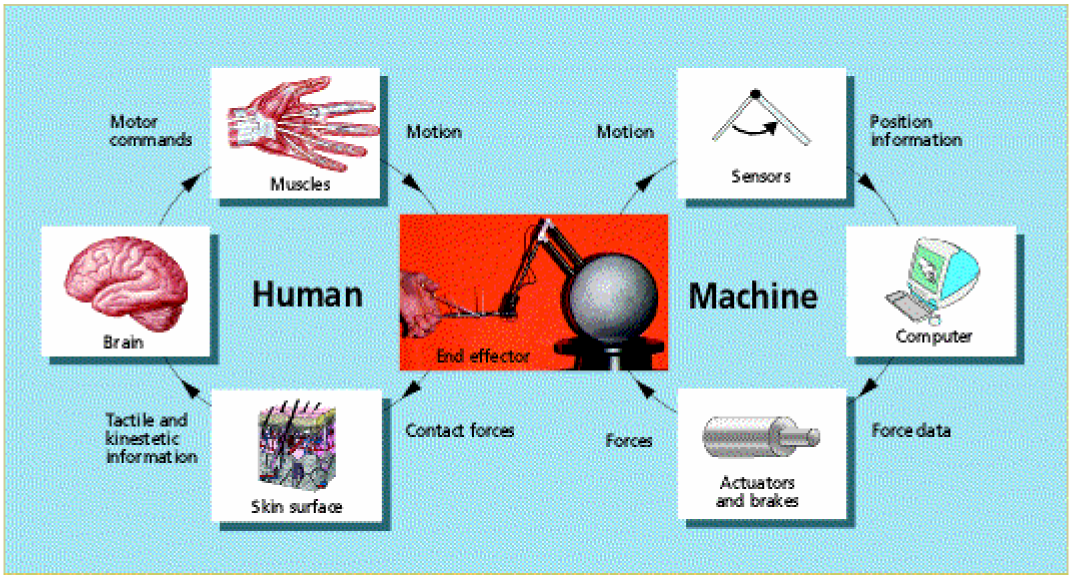
Abstract
The work in the Touch Lab (formal name: Laboratory for Human and Machine Haptics) is guided by a broad vision of haptics which includes all aspects of information acquisition and object manipulation through touch by humans, machines, of a combination of the two; and the environments can be real 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 3D Finite Element Model with ridges of Human fingertip

The three-dimensional human fingerpad model developed by incorporating both outer and inner ridges, and the stiffness ratio of the epidermis and the dermis based on the UBM strain imaging, and verified by the data from previous Optical Coherence Tomography (OCT) experiments, was simulated. Figure 1.2-1 shows a comparison of the distribution of stain energy density (SED) at the depth of the Merkel disks from the simulation results. The old model was built without the ridged structure on the skin surface and between the epidermis and the dermis, while the new model takes them into consideration with both outer and inner ridges. These two models were indented by a spherical indentor (R = 7.8 mm) from 0 to 2.5 mm. The SED distribution at different indentation stages were shown as multiple curves rising from the bottom to the top of the plot along a path of 54 elements in the middle plane. The model without any ridged structures renders a smooth distribution of SED with its maximum appearing near the center, where the indentation reaches the maximum, while the distribution of SED obtained from the new model shows multiple sharp spikes. The locations of those spikes correspond to the discrete locations of the intermediate ridges, where Merkel disks normally reside.

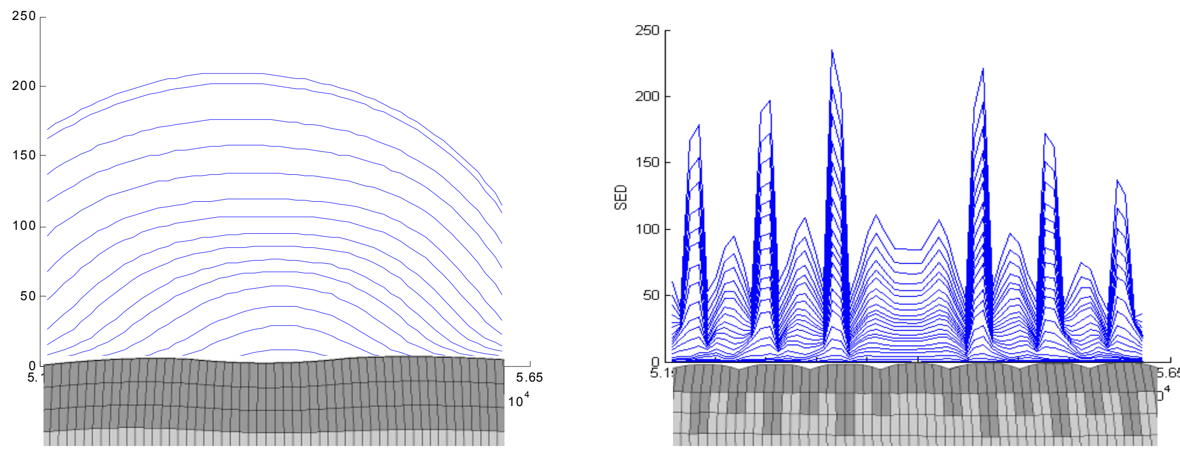


Figure 1.1-1 *SED distribution at the depth of the SA-I mechanoreceptors. Simulation from old smooth model (left). Simulation from the new model (right).*

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.

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.

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 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.

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[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.
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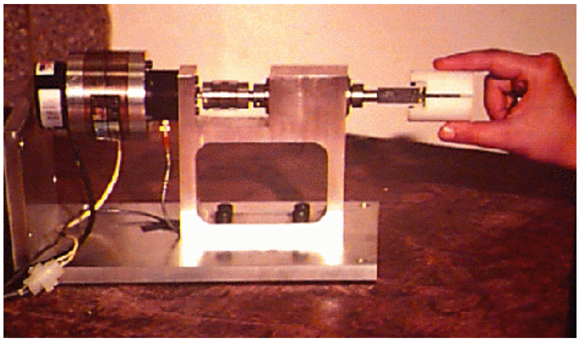

Figure 4 -1 *Instrumented Screw Driver*

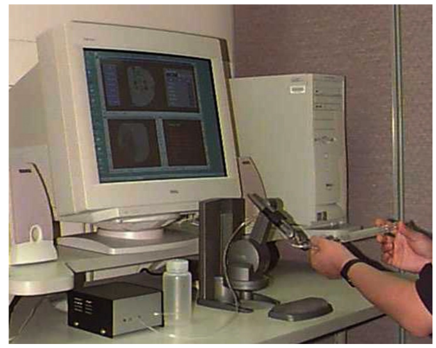

Figure 4 -2 *Epidural Injection Simulator*

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).

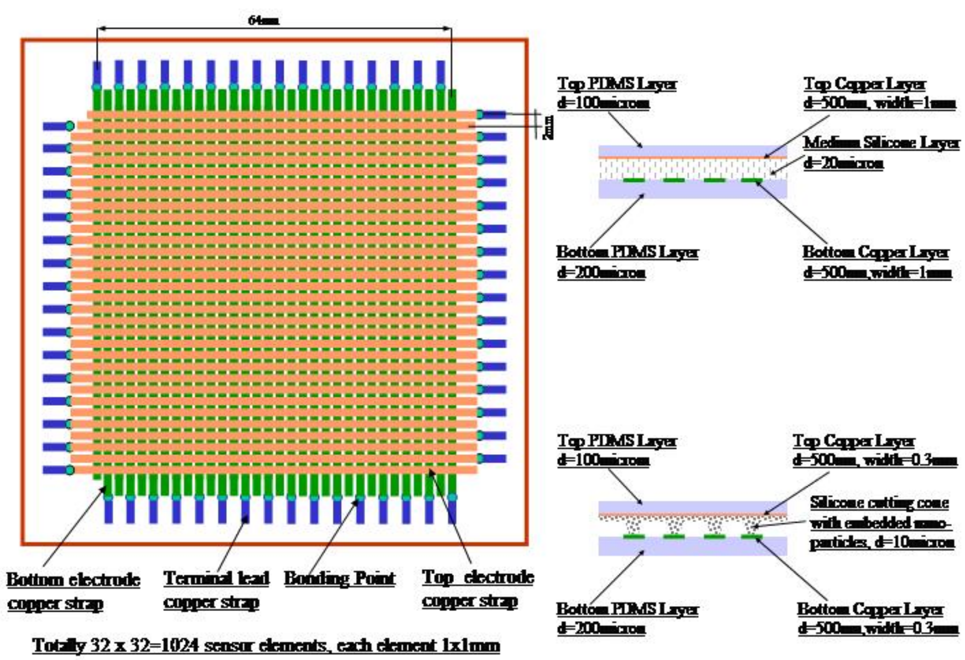

Figure 4.1-1 *Schematic illustration of pressure sensor array–overview (left) and cross-section (right).*

Finite element analysis (FEA) is being used to evaluate the behaviors of sensor during loading and testing. 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 has also been performed by using the same model. Our results show that the stress generated in copper electrode due to loading will not exceed the tensile strength of copper as long as the extra load is limited below designed limitation. While the concentration of electric field is just slightly dispersed under the assumed structural parameters.

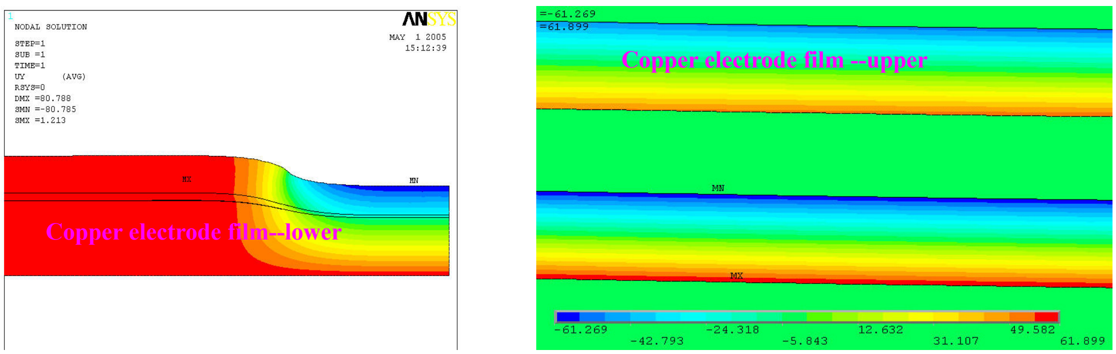

Figure 4.1-2 *Vertical displacement of 0.5μm copper electrode of sensor under a pressure of 0.06MPa. (left) The maximum tensile stress generated in the copper electrode film during loading is less than 70MPa when the displacement ratio of the electrode pair being evaluated goes up to 70%.(right)*

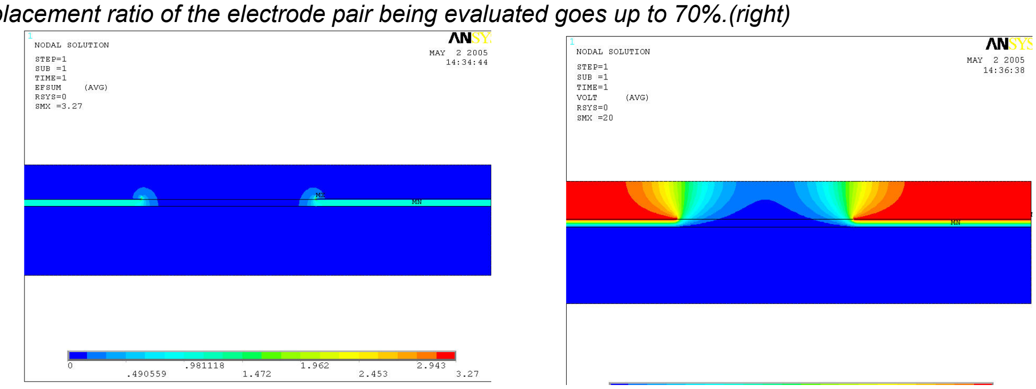

Figure 4.1-3 *Electric field in the undeformed sensor with a voltage of 20V applied(left).Electric potential in the undeformed sensor with a 20V input(right)*

In the future, we hope to modify the deposition process in order to obtain defect-free copper electrode straps. This will help to prohibit the occurrence of break. The other coming works includes hardware build-up and software development for signal processing system and the calibration of sensor array.

4.2 Development of PDMS based Optical Pressure Micro sensor for Skin Mechanics Studies.

A quantitative understanding of how spatial temporal loads, imposed on the surface of the skin, are transmitted to mechanoreceptor locations within the skin needs to be developed in order to fully understand the role of biomechanics of the skin in touch,. With the advent of imaging technologies such as the Optical Coherence Tomography (OCT) and microfabrication, we are now able to design and fabricate of an Optical Pressure Sensor Device to determine the pressure distribution on the finger pad of a Human finger.

The Optical Pressure Sensor is a PDMS based five layer device having a total thickness of 150 microns.

It consists of two layers of patterned SU-8 separated by a layer of Soft PDMS of thickness 100 microns. The top and bottom protective layers are of PDMS and have a thickness of 25 microns each. . The entire device is fabricated bottom up on a silicon wafer using soft lithography techniques and the textured pattern is imprinted onto the PDMS using photolithography techniques. Figure 1(a) depicts an OCT image of the sensor and 1 (b) depicts the sensor deformed by an unknown load. Figure 2 depicts the fabricated sensor.

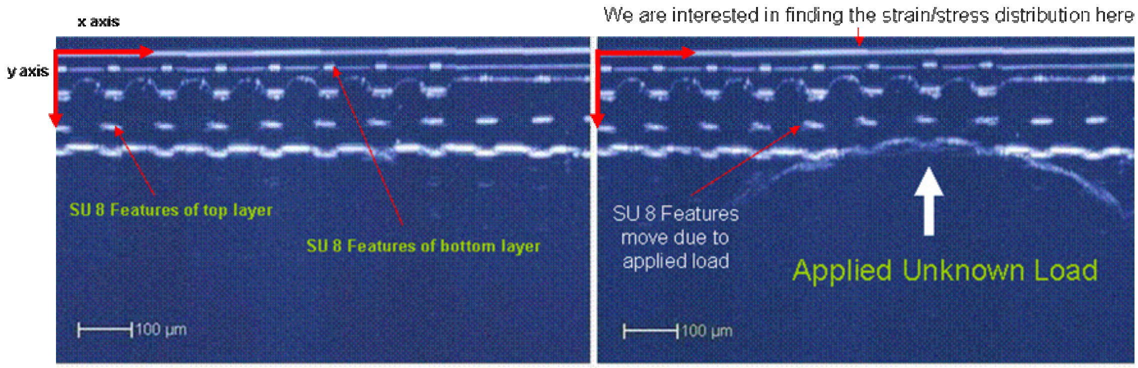

Figure 4.2-1 *OCT images of the undeformed sensor (left) and sensor deformed by an unknown load(right)*

As a result of external stimulus, the human skin along with the pressure sensor gets deformed, both these deformations are picked up by the OCT image. The deflection between the two bands of patterns is used to estimate the stress at the pressure sensor and skin interface through a continuum mechanics model. Tests demonstrate a linear relationship between the measured pressure and applied load from 0 to 3.8 M Pa. The sensor is designed to function over a working length of 1000 microns. The sensor was used to determine the normal pressure distribution exerted by a spherical indenter of diameter 125 microns, this is depicted in figure 3.

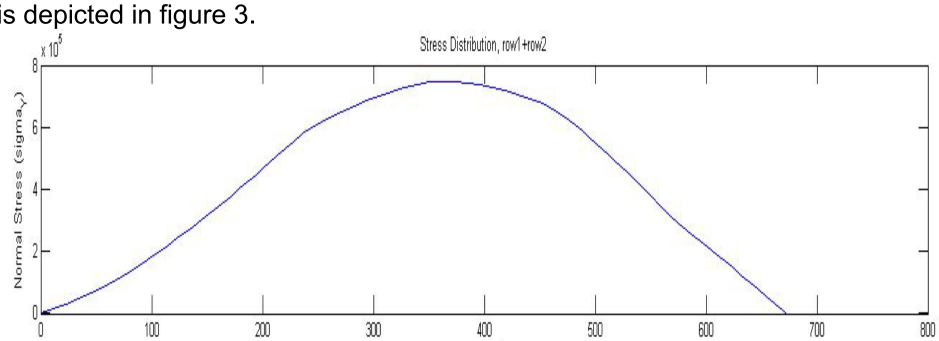

Figure 4.2-2 *Stress distribution exerted by the incidence of a spherical ball of radius 125 microns as computed by the continuum mechanics model using the sensor.*

4.3 Haptic Device Development / Back-Drivable Gripper Development for Direct Brain Controlled Grasping

During the last year we completed 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) is intended for 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 was to create a robotic end effector with performance that is comparable to and compatible with the Phantom.

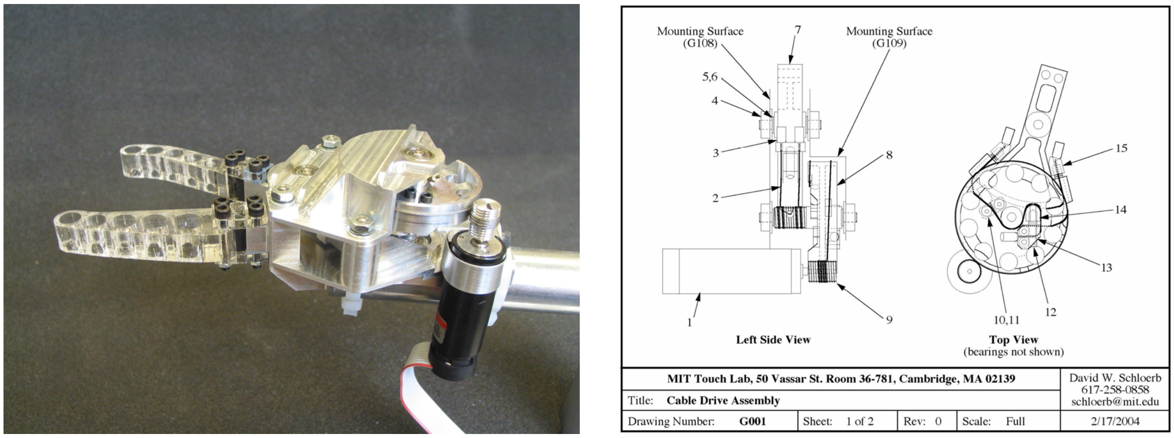

Figure 4.3-1 *Gripper illustration*

Figure 4.3-2 *Gripper system (left) and gripper mounted on 3DoF phantom arm (right)*

The photograph at left shows the completed gripper system, minus the host computer, and the photograph at right shows the gripper mounted on a large workspace Phantom. The assembled gripper is 14 cm long and weighs about 200 g.

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.

5.1 Improve Spatial Perception of blind People by using virtual environment technology.

Our work in this research area has been 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.

Over last year we start to develop an interface and a virtual reality system that includes 3D haptic and audio feedback with which blind users can interact with virtual models of real spaces that they are familiar with before actually encountering them. Lacking of visual information imposes great difficulties on blind individuals walking through unfamiliar spaces. By using this virtual environment system, we aim to explore how people who are blind explore virtual spaces, how they construct cognitive maps of unfamiliar spaces and how they activate the cognitive maps in negotiating through the real space. In this research we collaborate with the Carroll Center for the Blind.

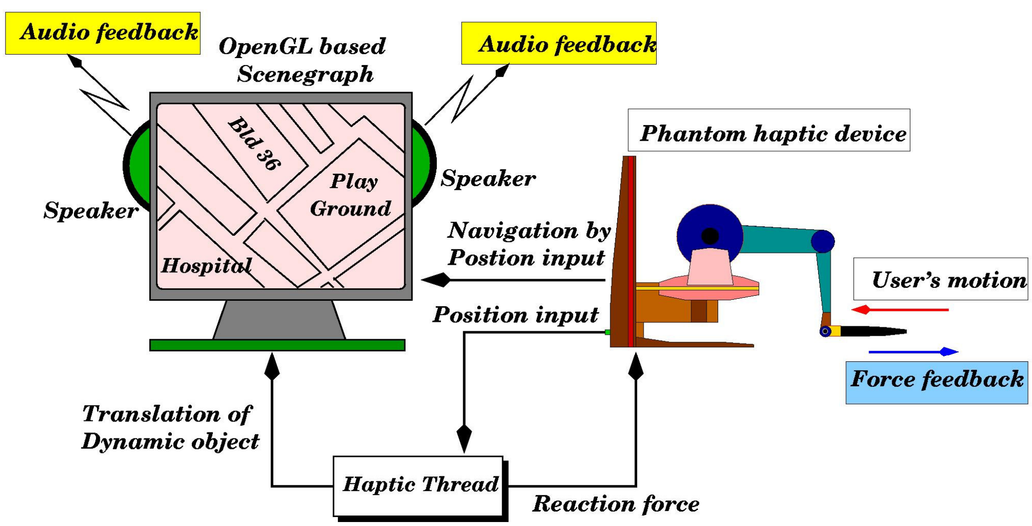

Figure 5.1-1*Schematic diagram of hardware of virtual environment system for blind spatial exploring study*

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).

Publications

Journal Articles, Published

Lahav, O, “Using Virtual Environment to Improve Spatial Perception by People who are Blind” *CyberPsychology and Behavior* 9(2):174-177(2006).

Journal Articles, Submitted for Publication

Lahav, O. and Mioduser D, “Blind Persons' Acquisition of Spatial Cognitive Mapping and Orientation Skills Supported by Virtual Environment,” submitted to *International Journal on Disability and Human Development*.

Siddarth Kumar, Gang Liu, Mandayam A. Srinivasan, “ A PDMS based flexible micron-scaled Pressure optic sensor for Biomechanics studies ", to be submitted to *Sensors & Actuators: A. Physical.*

Wan-chen Wu, Mandayam A. Srinivasan, “ Development of a 3-D Finite Element Model of Human Fingertip Based on OCT and Strain Imaging Data,” submitted to *Journal of Biomechanics Engineering*

Wan-chen Wu, Mandayam A. Srinivasan, “ Using Oct as a tool to investigate the Mechanical Behavior of human fingertip skin,” submitted to *Journal of Biomechanics Engineering.*

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Meeting Papers, Published

Lihua Zhou, Balasundar I. Raju, Mandayam A. Srinivasan, “Relevant Stimuli and Their Relationships to Primate SA-I Mechanoreceptive Responses Under Static Sinusoidal Indentation”, *The 2006 International Conference on Modeling, Simulation and Visualization Methods (MSV'06)*, Las Vegas, Nevada , June 26-29, 2006.

Lahav, O, “Using Virtual Environment to Improve Spatial Perception by People who are Blind,” IWVR, The 4th International Workshop on Virtual Rehabilitation, Catalina Island, California, September 2005.

Theses

Siddarth Kumar, *Design and Fabrication of an Optical Pressure Micro Sensor for Skin Mechanics Studies*, S.M. thesis, Dept. of Mechanical Engineering, MIT, June 2006.

Wan-Chen. Wu, *Tactile Sensing of Shape: Biomechanics of Contact investigated using Imaging and Modeling,* Ph.D. dissertation, Dept. of Mechanical Engineering, MIT, August 2005.