Laboratory for Human and Machine Haptics: The Touch Lab

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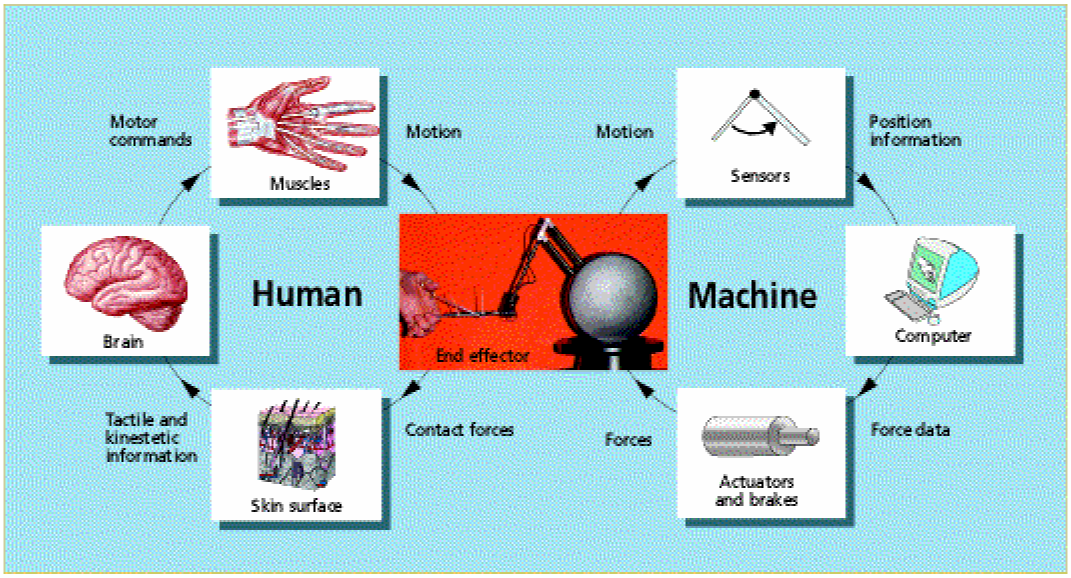
Sponsors
National Institutes of Health – Grant RO1-NS33778
Massachusetts General Hospital
Defense Advanced Research Projects Agency

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.

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.



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.

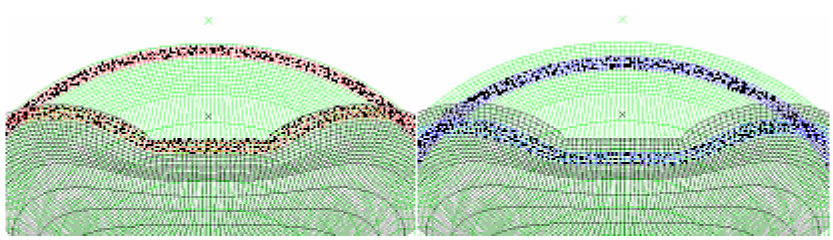
In the Touch Lab, we develop apparatus and perform experiments to measure the mechanical properties of the skin and subcutaneous tissues. In addition, we develop sophisticated mechanistic models of the skin to gain a deeper understanding of the role of its biomechanics in tactile neural response. A variety of techniques have been used in our experiments, including videomicroscopy, Optical Coherence Tomography (OCT), Magnetic Resonance Imaging (MRI), high frequency ultrasound imaging, 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.

Biomechanical Studies Based on More Precise Finite Element Models of Human Fingertips

We have continuously improved the accuracy and spatial resolution of our finite element models for both monkey and human fingertips, and we have taken into account contact mechanics of the fingerprint ridges, geometry of the inner skin layers, and viscoelastic material properties. The models are capable of predicting biomechanical variables such as skin displacement, reaction force, spatial pressure distribution, subsurface strain and stress fields that are generated when the fingerpad is loaded by various shapes of indentors. The models are improved with the aid of empirical data from Optical Coherence Tomography (OCT), videomicroscopic imaging and contact pressure measurement. Predictions from the models provide hypotheses for further experiments, helping us to gain a deeper understanding of the biomechanics of tactile perception.

We have recently obtained high-resolution in-vivo OCT images of human fingerpads, and derived from it such information as the thickness of the layer stratum corneum, the boundary between stratum corneum and living epidermis, the profiles of the ridges on the outmost surface and along the boundary between stratum corneum and living epidermis. This data have been incorporated into our finite element models of the human fingertip. Simulations have been done when the indentors are of various shapes such as sphere, bar, and plate. The size of the indentor ranged from 250 microns to 77.8 mm in diameter. The simulated results match well with the in-vivo images.

More complicated simulations have been done based on the 3D finite element model for monkey fingertip. The effect of larger contact forces, as high as 300 gwt, has been investigated. The stress and strain fields in skin and subcutaneous tissues have been studied when the external force is 8, 20, 30, 40, 50, and 100 gwt. The validity of the simulations has been tested by comparing with data from our experiments done before.

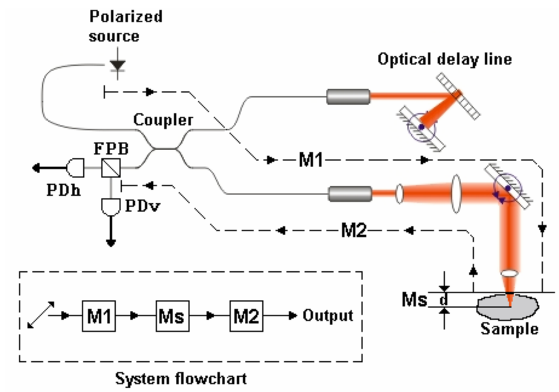


Stratum corneum (shaded, left) and living epidermis (shaded, right) before and after deformation (superimposed).The fingertip is indented by a rectangular bar with width = 4 mm and load = 306 gwt. Depth of indentation = 2 mm.

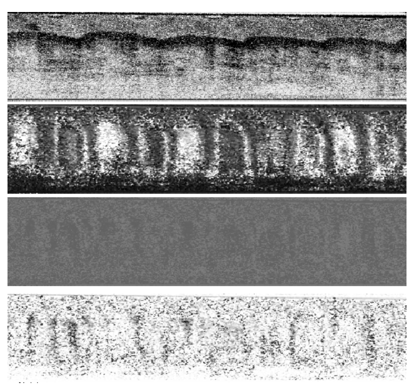
Optical Coherence Tomography (OCT): Optical Polarization Measurement System Based on Only One Incident Polarization State Using Similar Jones Matrix.

There are several limitations to existing optical polarization measurement methods based on both Jones and Mueller calculi. A major one is that multiple distinct input polarization states required: For example, the existing methods based on Jones calculus requires three incident states, oriented at 0, 45, and 90 degrees. The final result is related to the true Jones matrix still by a multiplicative complex constant C that has to be determined by other methods [1]. The methods based on Mueller calculus requires four different incident states, oriented at 0, 45, 90, and 135 degrees to determine Mueller matrix [1-2]. We have developed a new method that is based on Jones calculus with similar Jones matrix that can easily determine the Jones matrix with only one incident polarization state [1]

The method is simple, fast and explicit for optical polarization calculation and measurement. Because It requires only one incident polarization state, the polarization measurement system can be simplified and the associated hardware and software costs are reduced. And this method can be used in the case where the boundary conditions on the tested component are unknown. We have used this model to polarization-sensitive optical coherence tomography (PS-OCT) which is shown below.



Using the proposed method, we have obtained the sample image shown below.



PS-OCT images of in vivo human fingertip skin (5 x 1.2 mm^2) from top to bottom: I, δ, θ and P.

We gratefully acknowledge Johannes F. de Boer, B. Hyle Park and Mark C. Pierce of the Massachusetts General Hospital for their kind help in conducting these experiments and for stimulating discussions.

[1] Wan S, Wu W.C. and Srinivasan MA, Generalized model of optical polarization measurement based on similar Jones matrix and its application to polarization-sensitive optical coherence tomography, Physical Review, (submitted)

Tissue-Independent Robust Deconvolution of Ultrasound Images

Tissue-independent robust deconvolution of ultrasound images was developed in the past year, which is based on higher order spectral analysis (HOSA) and wavelets.[2]

1. Tissue-Independency of the System Function

Ultrasound images are blurred in both the axial and lateral directions due to the convolution of the tissue reflectivity function $x(n)$ with a system function $h(n)$:

$$y(n) = h(n) * x(n) + \eta(n) \qquad (1)$$

where $y(n)$ is recorded echo signal, and $\eta(n)$ is additive noise. Deconvolution methods seek to extract $x(n)$ from measurements of $y(n)$. The bispectrum $C_y(z_1, z_2)$ of the third order cumulant of $y(n)$ is defined as follows:

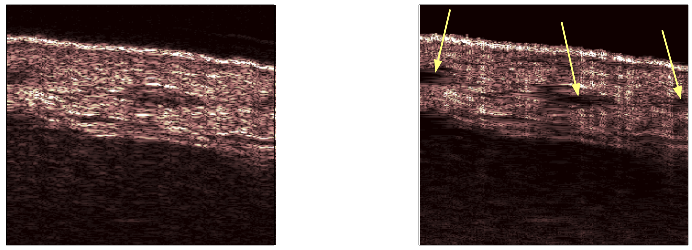
$$C_y(z_1, z_2) = \gamma_x H(z_1) H(z_2) H(z_1^{-1} z_2^{-1}) \qquad (2)$$

where $\gamma_x = E\left[x^3(n)\right]$ is a constant and $H(z)$ is z-transform of $h(n)$. In Eq. (2), $h(n)$ and $x(n)$ are completely decoupled, as the effect of $x(n)$ appears only as a multiplicative constant. This means that the estimated system pulse $h(n)$ is theoretically independent of the tissue being used to determine it. Based on this we choose a unique scale to measure individual tissue, that is for a given system we estimate a unique system function and use this function to all subjects as long as the subjects are measured using the same system.

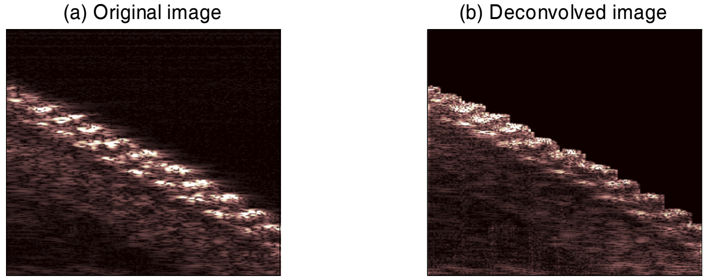
2. Wavelet-based deconvolution

A regularized deconvolution technique based on wavelets was used to estimate tissue signal $x(n)$ once $h(n)$ is obtained. In wavelet domain, due to the localizations both in time and frequency, and the flexibility in the choice of bases, various image structures such as ridges and boundaries in fingertip skin can be selectively characterized and more accurately recovered. We applied this method to images obtained from tens subjects by using ultrasound backscatter microscope systems that were upgraded in 2001. The resolutions and contrasts in all the images are significantly improved. Two samples are shown below:

[2] Wan S, BI. Raju and Srinivasan MA, "Robust deconvolution of high-frequency ultrasound images using higher order spectral analysis and wavelets", *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.* Vol. 50, pp.1286-1295.



An image of the skin at the thigh region of a 30-year-old male subject obtained using transducer I before deconvolution. The field of view is 5 mm wide by 4.5 mm (b) The same image after axial and lateral deconvolution. The hypoechoic structures (arrow marks) are possibly hair follicles, and are better displayed in the deconvolved image than in the original image.



An image of a fingertip skin of a 31 year male old subject obtained using transducer I before deconvolution. The field of view is 5 mm wide by 4.5 mm deep (b) The same image after axial and lateral deconvolution. The fingerprints on the surface are appear better in the deconvolved image in that they appear more continuous.

2. Sensorimotor Psychophysics

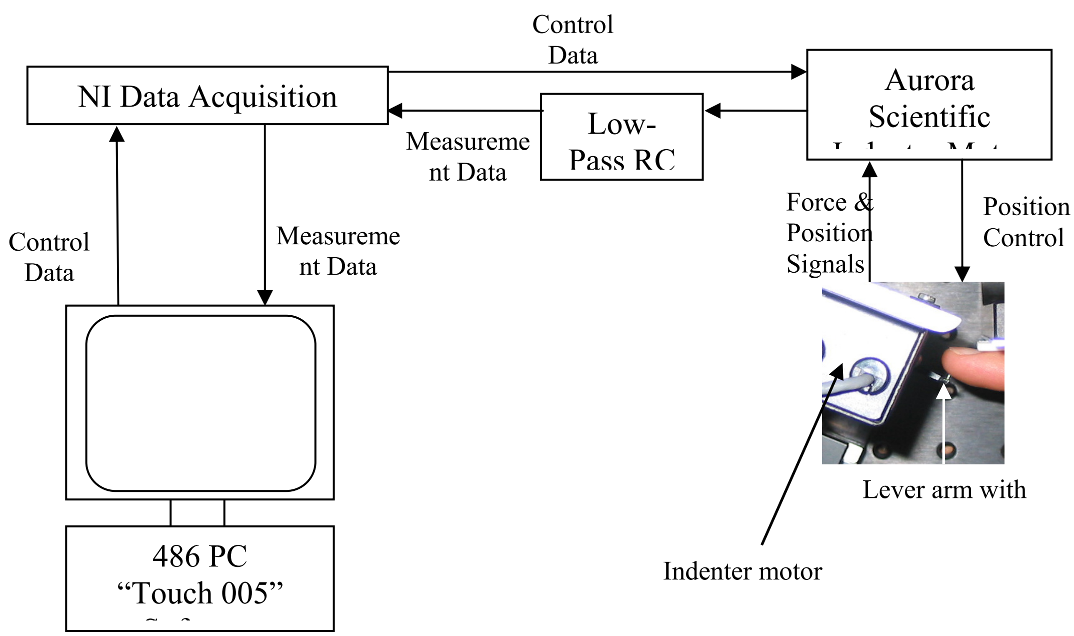
Psychophysics is the quantitative study of the relationship between physical stimuli and perception. It is an essential part of the field of haptics, from the basic science of understanding human haptics to setting the specifications for the performance of haptic machines. It is also quite natural to 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.

Tactile Perception Threshold Measurements

The goal of this project is to determine the limits of perceptual resolution for various kinds of vibratory tactile stimulation at various body sites. Two novel features of the experiments are (1) precise control of the stimuli via computer and (2) simultaneous measurement of both position and force applied to the skin. During the last year we continued one-point threshold tests and we began two-point localization tests related to the spatial resolution of human touch.

In the one-point tests, tactile thresholds were observed in humans at three different body sites (index finger, wrist and forearm) by applying sinusoidal vibration stimuli to the skin surface with a flat-ended 0.5 mm diameter cylindrical probe. Five subjects were tested at each body site. The work repeats a preliminary experiment performed in the MIT Touch Lab using the same apparatus which was reassembled and calibrated for the present tests (see Figure). A literature search was done to consider alternative methods, but none were found to improve on the approach used in the preliminary experiment. The tactile threshold was explored at 8 different frequencies (2, 4, 8, 16, 32, 64, 128 and 256 Hz), but reliable data for the index finger could not be obtained above 8 or 16 Hz due to limitations of the apparatus. Results showed that power at threshold is relatively constant with frequency at the lowest frequencies tested (below about 16 Hz) for all of the body sites. At the higher frequencies tested, the power at threshold appears to increase with frequency for both the wrist and forearm, but not for the finger. [3]



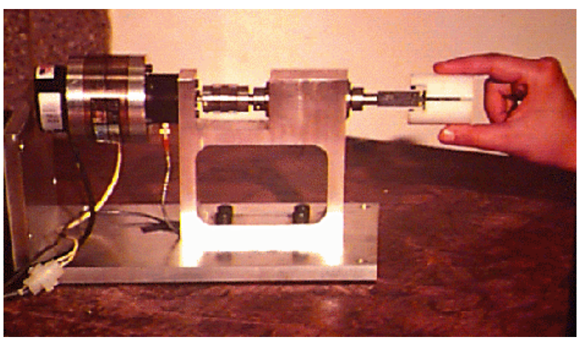
Skin Dynamics Test Apparatus used in one-point threshold tests.

[3] Herkt, M. Human tactile threshold measurements in terms of skin displacement, reaction force, and resulting power, S.M. Thesis, Ecole D'Ingenieurs, June, 2003.

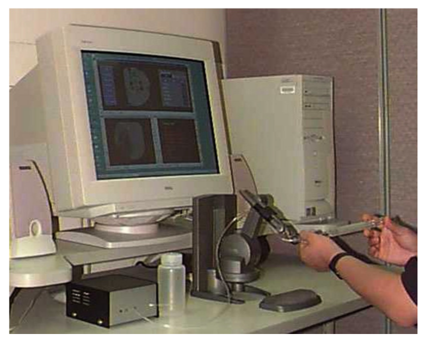
Our initial two-point tests are intended to measure spatial localization, the ability of a person to detect whether he or she is touched in the same or a different place on successive trials. The tests are performed using the Tactile Perception Test Apparatus developed in our lab {see Section 3}. In these ongoing tests, we plan to make measurements on the hands of several subjects.

3. 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.[4] 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.[5] 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.[6] [7] Work to "replace" humans (e.g., through the development of robotic hands) is part of our plans for the coming year.



Instrumented Screw Driver



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.

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[4] 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.

[5] 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.

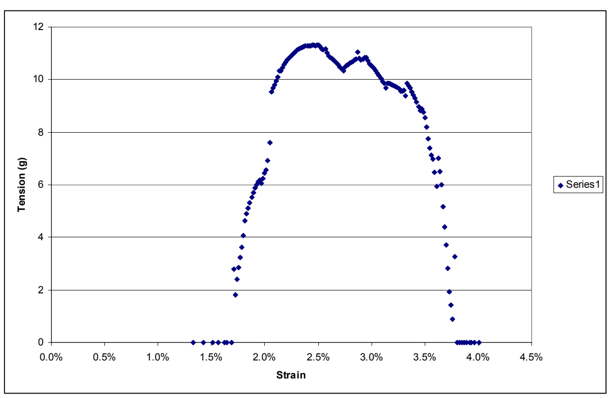
[6] Wessberg J, Stambaugh CR, Kralik JD, Beck P, Laubach M, Chapin JK, Kim J, Biggs SJ, Srinivasan MA and Nicolelis MAL, Adaptive, real-time control of robot arm movements by simultaneously recorded populations of premotor, motor and parietal cortical neurons in behaving primates, Nature, Vol. 408, No. 6810, pp. 361-365, 2000.

[7] Nicolelis MAL and Chapin JK, Controlling Robots with the Mind, Scientific American, 287 (4), pp 46-53, 2002.

Bistable Actuator for Tactile Displays

This past year we have been working on the design of a novel actuator for use in wearable tactile displays. This work began while it was still in the conceptual phase. The idea is to use the high power density of Nitinol, a shape memory alloy, to build an actuator that is smaller and lighter than the electromagnetic actuators that are currently used in tactile displays. To combat the fact that sustained contraction of Nitinol consumes large amounts of power, we are laminating the Nitinol to a bistable substrate so that power is only required to move the actuator between stable positions. The bistable substrate is simply a snap-through buckled beam which is easily manufactured and allows for very thin actuators. Therefore, the conceptual design consists of this bistable substrate onto which Nitinol is laminated to both sides. When a current is applied to the Nitinol on one side of the substrate, it heats up and undergoes a phase transformation. This phase transformation produces a contracting force that moves the bistable substrate to its other stable position.

In the beginning, a great deal of time was spent trying to resolve prototyping issues. We learned that by applying a thin layer of black paint to the surface of blue tempered spring steel (0.002" thick) we can use a 35W CO_2 laser to cut precise and intricate shapes in a matter of minutes. We then designed and built tooling to stamp kinks into the steel substrate. These kinks make the steel substrate bistable by supplying the compressive forces to buckle the snap-through buckled beam. With some of the prototyping issues resolved, we shifted our concentration to numerically simulating the behavior of the substrate as it is actuated by the Nitinol. Knowing that the Nitinol comes from the manufacturer with a strain of 3.5%, these simulations showed that for our design dimensions the mechanism should snap through when the Nitinol has recovered approximately 2.0% of its initial strain. This implies that our design should work since the Nitinol will try to recover all of its initial strain. We then designed and built the electrical circuits to both drive the Nitinol and measure the strain in the Nitinol fibers. With the drive circuit complete, we set up a fatigue experiment to measure the number of cycles until failure. The latest prototype mechanism has successfully completed over 10,000 cycles to date.



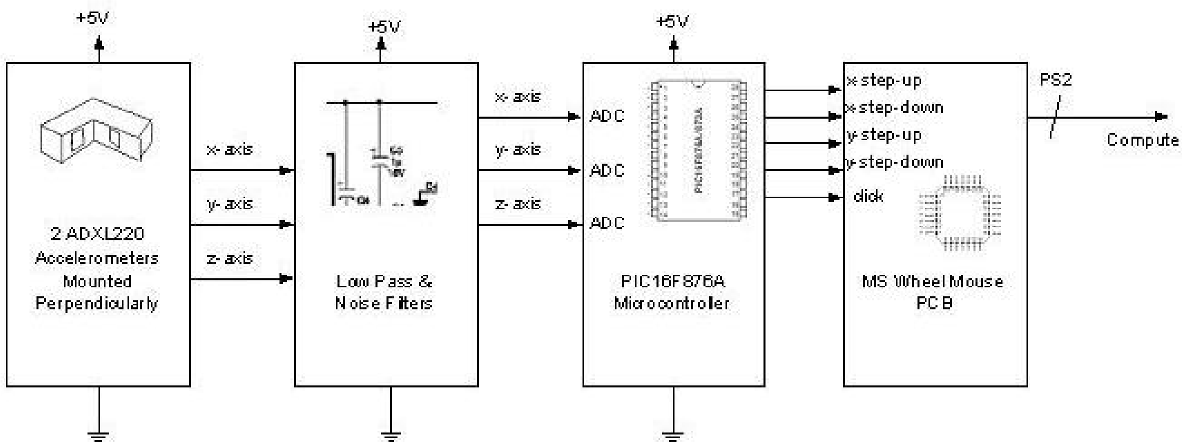
Results from numerical simulation show that mechanism snaps through at 1.7% strain.

Augmented Computer Mouse Development

Increasing emphasis on the human-computer interactions needs sophisticated and natural interface devices that do not need users adapting to the computer; rather these devices would allow the computers to adapt to each user. In our quest to such an interface device, we designed a mouse using low-cost MEMS based accelerometers.

The mouse uses two dual-axial MEMS based accelerometers from Analog Devices. The two accelerometers are mounted perpendicular to each other in order to mimic a triaxial accelerometer for x,y,z direction each. Using PIC microcontroller, the output from the accelerometers is low-pass filtered in order to avoid tremors. The output is then converted into suitable input to the standard PS/2 mouse protocol. We used a Microsoft mouse to interface with the computer.

Movement in the down direction (Z-axis) activates the mouse button (click button for selecting), while movement in the upward direction simulates release button. X tilts are integrated to move the mouse cursor either to left or right and Y tilts are integrated to move up or down. For selecting (or simulating a double click), a threshold acceleration in the Z-direction is used. With this mouse, the users need not restrict mouse movements to any surfaces. The same mouse gestures are used equally in both 2D and 3D applications.



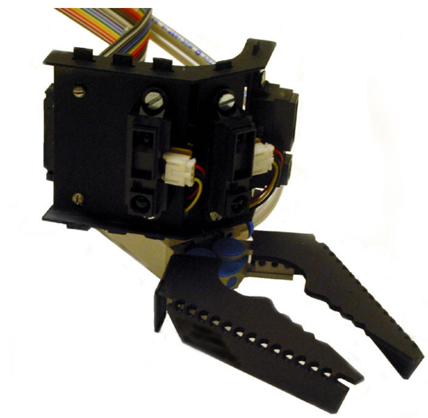
Augmented computer mouse design

Continuous Shared Control in Brain-Machine Interfaces (BMI)

Our research on Brain Machine Interfaces (BMIs) that enable direct real-time control of machines using signals acquired from populations of neurons in primate brains is partially directed toward enabling paralyzed individuals to manipulate their environment through slave robots. Using a slave robot to reach and grasp objects in an unstructured environment is known to be a difficult telemanipulation task for an able-bodied individual. Controlling the slave robot with brain signals instead of a force-feedback hand master adds further challenges, such as uncertainty about the intended trajectory coupled with a low update rate for the command signal. To address these difficulties, a new Continuous Shared Control (CSC) paradigm is introduced for BMI where sensors produce reflex-like reactions to augment the brain controlled trajectories. To test the merits of this approach, CSC was implemented on a 3-*dof* robot with a gripper bearing three co-located range sensors. The robot was commanded to follow eighty-three reach-and-grasp trajectories that had been previously estimated from the output of neurons recorded from the brain of a behaving primate. Five different levels of sensor-based reflex effort were tested. Weighting brain commands 70% and sensor commands 30% produced the best task performance, better than brain signals alone by more than seven-fold. Such a marked performance improvement in this test case suggests that low-level machine autonomy may be an important component of successful BMI systems in general.

Pneumatic Gripper Design for Direct Brain Controlled Grasping

A light, back-drivable pneumatic gripper with integrated proximity sensors has been developed in order support experiments in shared control of Brain Machine Interfaces. The gripper system is remarkable for its low mass (<120 gram), making it suitable for mounting on the Phantom 3.0, a high performance, backdrivable 3-dof manipulator that is light enough to operate safely in a user's personal workspace .

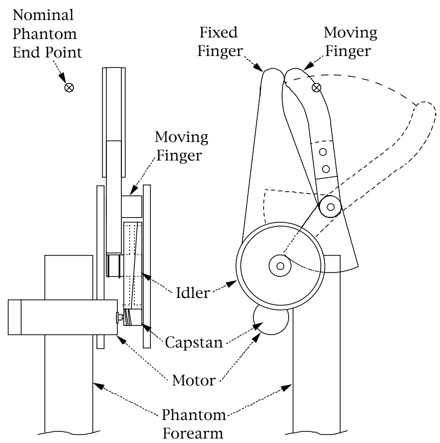


A light, backdrivable, sensorized gripper developed for the Duke-MIT Brain Machine Interface project.

The gripper has an integral six-axis force-torque sensor (ATI, Nano-17) that makes it possible to estimate where in the jaws an object is grasped. The three triangulating infrared proximity sensors (GDP 120, Sharp) mounted to the gripper base facilitate collision avoidance and reflexive grasping.

Back-Drivable Gripper Design for Direct Brain Controlled Grasping

This year we began 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.

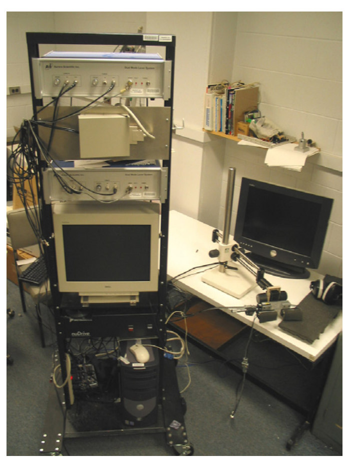


Preliminary gripper design.

The gripper will be about 14 cm long and will weigh about 100 to 200 g (the original design goal was 100 g, but current estimates are closer to the higher figure). It uses a cable drive similar to the design of the Phantom except with a two-stage speed reduction. The figure presents an illustration of the preliminary gripper design that identifies the principal mechanical components. The detailed design of the first prototype is almost complete and most of the mechanical parts are currently being fabricated in the MIT Central Machine Shop. The key electrical components, including the motor, encoder, motor amplifier, and computer interface card have been purchased and tested in breadboard form along with control software. We anticipate that the gripper will be operational by mid 2004.

Tactile Perception Test Apparatus

Development of the Tactile Perception Test Apparatus (TPTA, see Figure) continued in which we upgraded hardware and created new software tools for implementing experiments. On the hardware side, we purchased a computer and added a new A/D card that permits simultaneous sampling of position and force data. The new card is also equipped with onboard memory that makes it independent of the host computer allowing us to sample data at a faster rate.



Tactile Perception Test Apparatus set up for two-point localization tests.

On the software side, we invested significant time into the design and implementation of software for the TPTA. Our goal is to build a system that will make it easy for an undergraduate student that may be inexperienced in programming to quickly develop and conduct an experiment using the apparatus. To make this possible, we captured functionality common to many experiments in a software library that is easy to learn and use. The library is written in Matlab, a high-level language which many students are familiar with already and need to learn anyway to analyze experimental data. It includes functions for common tasks such as controlling the TPTA, saving data in a particular format, or generating certain types of signals. To illustrate use of the library, a sample experiment for measuring two-point spatial localization was implemented. This experiment also serves as a model which students may be able to modify to suit their needs. We expect the library will encourage students to reuse code rather than 'reinvent the wheel', saving significant development time and increasing productivity of the lab.

4. 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.

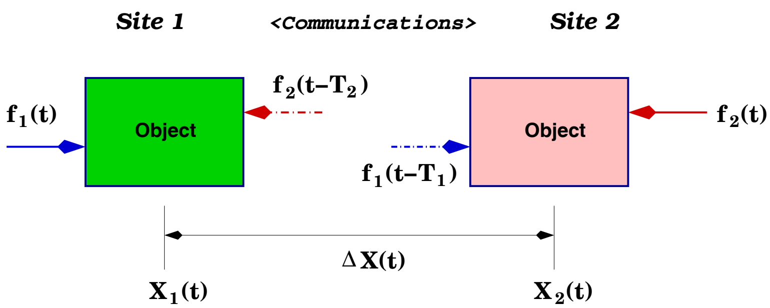
Collaborative Haptics

In this project, the use of haptics to improve human-computer interaction as well as human-human interactions mediated by computers is being explored. A multimodal shared virtual environment system has been developed and experiments have been performed with human subjects to study the role of haptic feedback in collaborative tasks and whether haptic communication through force feedback can facilitate a sense of being and collaborating with a remote partner. The results of the study in which the partners were in close proximity within the Touch Lab were reported in Basdogan et. al., 2000.[8] In 2002, in collaboration with Prof. Mel Slater's group in University College, London, we extended the previously developed techniques and demonstrated, for the first time, 2-way communication of touch signals across the Atlantic.[11]

The transatlantic touch experiment examined ways in which pairs of people interact directly via a haptic interface over a network path that has significant physical distance and number of network hops (Jordan et. al., 2002). The aim of the experiment was to evaluate the use of haptics in a collaborative situation mediated by a networked virtual environment. The task of the experimental subjects was to cooperate in lifting a box together under one of four conditions in a between-groups design. Questionnaires were used to report about the ease with which they could perform the task, and the subjective levels of presence and co-presence experienced.

[8] Basdogan C, Ho C, Srinivasan MA and Slater M, An Experimental Study on the Role of Touch in Shared Virtual Environments. ACM Transactions on Computer Human Interaction 7(4), 443-460, 2000.

Synchronization Control of Dynamic Objects in Shared Virtual Environments



Schematics of state separation in a shared virtual environment

Consistency and fast responsiveness are the two major requirements in a multi-user shared virtual environment (VE). The consistency means the status when there is no state difference between the each VE of every participants.[9,10] In large scale network communications, the consistency is preserved by the concurrent control which coordinates rules on how to schedule users' commands when plural number of users access and change the state of an identical object almost at the same moment. The responsiveness is the degree of how immediate a user gets the response to his/her own input. Thus, the responsiveness is directly related to the quality that users feel. Conventional multi-user VEs could not guarantee the two requirements because of the time delay in the networks. Therefore, often these two are compromised in the middle. In some of accurate dynamics based share VEs, however, there is a need for very high responsiveness as much as or more than a good level of consistency.

If the dynamic object follows a physically reasonable behavior (in the sense of Newton's laws), the user naturally expects immediate and continuous response to his/her input actions. One such example is the TransAtlantic touch communication[11], a haptic collaboration project, where two participants geometrically separated very far are manipulating together a dynamic object in a virtual Newonian world and feeling the reaction forces through the interface devices,. Each local user expects to see the motion of the object without delay when he/she pushed or pulled it, meanwhile hoping for the same kinematic state at both sites. Without serious consideration on the consistency, the latter condition is not satisfied. As a result, a new type of consistency coordination method must be developed, so as to deliver immediate responses and a very good level of consistency.

Figure above depicts the typical kinematic configuration of the project, where two users are pushing a block in the opposite direction with haptic interfaces. At current global time t, the motion of the block at site 1 is computed with input forces $f_1(t)$ and $f_2(t-T_2)$, while the motion of the block at site 2 is computed with input forces $f_1(t-T_1)$ and $f_2(t)$, where T_1 and T_2 are data communication delays from site 1 to site 2, and from site 2 to site 1, respectively. With these, the immediate response can be achieved, but because the input histories are different at both sites, the deviation of the motions, $\Delta X(t) = X_2(t) - X_1(t)$, develops and will accumulate as time goes on. Hence, the ``must-be'' consistent object in the shared VE is no longer consistent in terms of the kinematic state, even if the haptic communication can be maintained. Realizing that the

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[10] Barrus J.W., Waters R.C. and Anderson D.B. "Locales: Supporting Large Multiuser Virtual Environments," IEEE Computer Graphics and Applications, vol.16, no.6, pp.50-57, 1996.
[11] Kim J, Jordan J, Srinivasan MA, et al., "Transatlantic Touch: A Study of Haptic Collaboration Over Long Distance," Presence (in press).

inconsistency measure Δ X(t) should remain as small as possible, we tackle this as one of the feedback control problems and propose a synchronization control method in order to compensate for Δ X(t), making the state sufficiently consistent. We allow some amount of transient deviation while the updated data is being transmitted, but guarantee sufficient consistency in slow or static conditions. If there is not any local excitation at a site, the object of the site will simply follow that of the other site. If there are simultaneous excitations at both sites, there will be a little more transient deviation, but soon the deviation will be compensated as the external excitations die out. The speed of recovery strongly depends on how large the time delay is. Also, the stable bound of control parameters highly depends on the amount of time delay.

5. Medical Applications

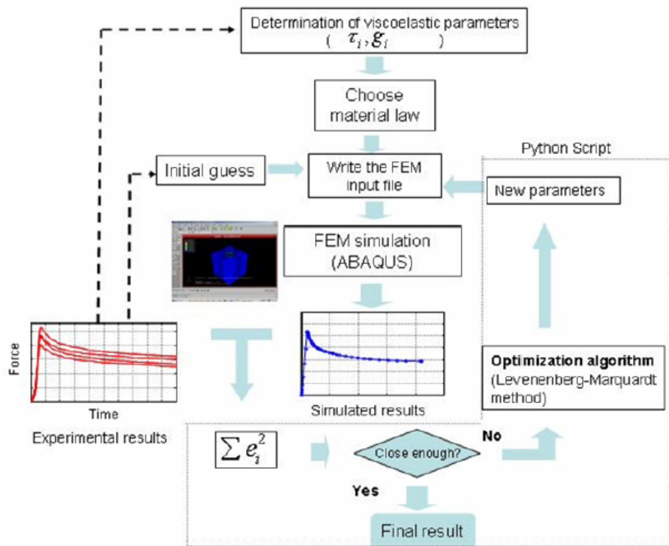
Touch Lab research has a wide range of medical applications. On a fundamental level, our investigations of human haptics offer insights into the functioning of the human body that should ultimately lead to improved medical care. Many of the experimental techniques and apparatus developed in these studies also have specific clinical uses that are explored in collaboration with various medical researchers. For example, the ultrasound backscatter microscope developed to study the biomechanics of touch is being investigated for possible use in screening for skin cancer in collaboration with the Wellman Laboratories of Photomedicine at the Massachusetts General Hospital. 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). The organ models used by the laparoscopic simulator are currently being improved by measuring the *in vivo* mechanical properties of real organs in collaboration with laparoscopic surgeons at the Massachusetts General Hospital and the Harvard Center for Minimally Invasive Surgery. Work on improved graphics, meshless simulation methods for tool-tissue interactions such as cutting and ablation, multimodal rendering, and training effectiveness are also ongoing in our lab. Following is a summary of the work done over the past year in connection with this project.

Characterization of In Vivo Tissue Properties

We have conducted a series of animal experiments measuring *in vivo* mechanical properties of soft tissues in collaboration with the surgeons in the Massachusetts General Hospital. As a next step, we have developed the tissue characterization algorithms from these sets of data in order to use them in real time tissue models for surgical simulation. The goal of tissue characterization is to find the parameters by correlating of the mathematical model with the experimental data. These parameters then can be used in an off-line simulation using finite element analysis packages for further analysis or in real time tissue models.

From the tissue responses from the animal experiments, two dominant characteristics are observed: nonlinear elastic and viscoelastic responses. These phenomena cannot be modeled by a simple linear elastic model so that more advanced models are necessary to represent this behavior. Assuming an isotropic, homogeneous and incompressible material, we have developed a few tissue models that capture the behavior of soft tissues to a high degree. We determined the parameters of three biomechanical models in which vary in how accurately they describe a soft tissue behavior. First, we determined the parameters of a linear elastic model assuming a semi-infinite medium assumption. Second, sets of parameters of more accurate biomechanical models were determined by using a curve-fitting technique. Finally, we have developed an algorithm to find the parameters of a continuum mechanics model, which is capable of describing the tissue behavior in a more comprehensive way (see figure below).



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