Sensory Communication Group

Academic and Research Staff
Dr. S. James Biggs, Professor Louis D. Braida, Dr. Suvranu De, Lorraine A. Delhorne, Dr. Joseph G. Desloge, Nathaniel I. Durlach, Professor Dennis M. Freeman, Dr. Julie Greenberg, Dr. Andrew J. Oxenham, Dr. Jonathan D. Pfautz, Dr. Charlotte M. Reed, Dr. Wendelin L. Sachtler, Dr. David W. Schloerb, Dr. Mandayam A. Srinivasan, Dr. Thomas E.V. Wiegand

Visiting Scientists and Research Affiliates
Dr. Torsten Dau[1], Dr. Paul Duchnowski, Dr. Kenneth W. Grant, Dr. Dr. Karen L. Payton, Geoffrey L. Plant, Dr. Christine M. Rankovic, Dr. Suiren Wan, Dr. Lihua Zhou, Dr. Patrick M. Zurek, Dr. George Zweig

Graduate Students
Ivan Aguayo, Andrew G. Brooks, Louis H. Buell, Tim T. Diller, Peninah S. Fine, Joseph A. Frisbie, Michael Goertz, Daniel S. Jochelson, Kosuke Kawakyu, Hyun Kim , Jung Kim, Jean C. Krause, Chih-Hao Ho, Michael K. Qin, Balasundar I. Raju, Zachary Smith, Boon Tay, Steve Wang, Wan-Chen Wu, Han-Feng Yuan

Undergraduate Students
Lauren Bradford, Alberto J. Cividanes, Avin C. Gidwani[2], Vitaly Kulikov, Misty Pendexter, Tuyet-Trinh T. Phan, Ashok Sivakumar, Nattavude Thirathon

Technical & Support Staff
Merry Brantley, Andrew R. Brughera, Ann K. Dix, Rebecca L. Garnett, Seth M. Hall, Eleanora Luongo, Denise Rossetti, Phalguni P. Shah

Introduction

The Sensory Communication Group continues to be a highly interdisciplinary group (containing engineers, psychologists, and now a physicist) and to be concerned with basic research on human sensorimotor, perceptual, and cognitive processes, as well as with the use of technology to enhance human performance. In contrast to many other groups at MIT concerned with exploiting technology (including both the Media Laboratory and the AI Group), much of our work involves conducting experimental research on humans.

Research areas in the Sensory Communication Group can be organized roughly as follows:

Area 1: Auditory science and visual/auditory speech communication aids for the hearing impaired
Area 2: Tactual communication of speech and tactual aids for the deaf and deaf-blind
Area 3: Human and machine haptics (Haptics is the study of sensing and manipulation through touch and is the focus of the MIT Touch Lab within the Sensory Communication Group.)
Area 4: Virtual environments for training, education, and interactive information presentation
Area 5: Web-based testing of children
Area 6: Signal processing for modeling of biological processes and for use in human-augmentation systems

[1] Department of Medical Physics, Universität Oldenburg, 26111 Oldenburg, Germany.
[2] Boston University

1.1 Hearing Aid Research

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Project Staff
Professor Louis D. Braida, Dr. Paul Duchnowski, Dr. Julie Greenberg, Dr. Patrick M. Zurek, Dr. Kenneth W. Grant, Dr. Karen L. Payton, Dr. Christine M. Rankovic, Ann K. Dix, Merry Brantley, Phalguni P. Shah, Ivan Aguayo, Peninah S. Fine, Joseph A. Frisbie, Daniel S. Jochelson, Jean C. Krause, Michael K. Qin

Specific Aims

Our long-term goal is to develop improved hearing aids for people suffering from sensorineural hearing impairments. Our efforts are focused on problems resulting from inadequate knowledge of the effects of various transformations of speech signals on speech reception by impaired listeners, specifically on the fundamental limitations on the improvements in speech reception that can be achieved by processing speech. Our aims are

1. To evaluate the effects of style of speech articulation and variability in speech production on speech reception by hearing impaired listeners.

2. To develop and evaluate analytical models that can predict the effects of a variety of alterations of the speech signal on intelligibility.

3. To develop and evaluate signal processing techniques that hold promise for increasing the effectiveness of hearing aids.

4. To assess the relative contributions of various functional characteristics of hearing impairments to reduced speech-reception capacity.

Characteristics of the Speech Signal

Our previous work has shown that sentences spoken ``clearly'' are more intelligible (roughly 17 percentage points) than those spoken ``conversationally'' for hearing-impaired listeners in a quiet background (Picheny et al., 1985) as well as for both normal hearing and hearing-impaired listeners in noise (Uchanski et al., 1996) and reverberation backgrounds (Payton et al., 1994). While producing clear speech, however, talkers often significantly reduce their speaking rate. A more recent study (Krause and Braida, 1995) has shown that talkers can be trained to produce a form of clear speech at normal rates (clear/normal speech). This finding suggests that acoustical factors other than reduced speaking rate are responsible for the high intelligibility of clear speech. To gain insight into these factors, various signal processing transformations of conversational speech were analyzed in order to determine which acoustical properties of clear/normal speech contribute most to its high intelligibility.

The signal transformations that were evaluated were derived from the results of a comprehensive acoustical analysis of the conversational (conv/normal) and clear/normal speech of two talkers from Krause's study (Krause, 1995). Acoustical measurements, as in an earlier study of the acoustics of clear speech by Picheny (Picheny et al., 1986), were taken at three levels of detail: global, phonological, and phonetic. Differences in acoustic characteristics of clear/slow speech relative to conv/normal speech were consistent with previously reported results. Many of these differences, however, were not apparent when comparing clear/normal speech to conv/normal speech. Since talkers presumably do not have time to retain all of the characteristics of clear/slow speech when speaking at normal rates, they must pick a subset of characteristics to continue to emphasize in clear/normal speech. Moreover, some of the acoustic characteristics (e.g. segment duration, pitch, and voice-onset time) retained in clear/normal speech differed dramatically between talkers, suggesting that different talker strategies exist for producing clear speech at normal rates.

Based on the results of the acoustical analysis, signal transformations were developed to alter three properties of conv/normal speech that were found to be altered by one or more talkers in clear/normal speech. In processed (A) speech, vowel formant energy was increased by raising formant amplitudes and widening formant bandwidths; in processed (B) speech, low-frequency modulations (<3--4Hz) were enhanced; and in processed(C) speech, F0 (pitch) average and range was increased, since this acoustical property was exhibited by the talker whose clear/normal speech was most robust to other degradations. These intelligibility enhancement schemes were evaluated singly and in combination by both normal hearing and hearing-impaired listeners participated in intelligibility experiments to evaluate whether listeners could derive intelligibility benefits from artificial manipulation of these acoustic properties. Although the speech-based STI predicted that a majority of these processing combinations would improve intelligibility over conv/normal speech presented in wideband noise to normal hearing listeners, actual experiments with normal hearing listeners revealed an advantage only for clear/normal speech and processed (A) speech. Moreover, hearing-impaired listeners did not obtain similar intelligibility benefits from clear/normal or processed (A) speech as reliably as normal hearing listeners in noise, although these conditions did provide a statistically significant benefit for some individual hearing-impaired listeners and talkers.

A possible explanation of these results is that the benefits of clear/normal speech may be related to age, since the hearing-impaired participants in this study were older (40 to 65 years) than the normal hearing participants (19 to 43 years). Some studies report an age-related decline in speech reception for elderly listeners (Arlinger and Gustafsson, 1991), particularly those with hearing impairments (Hargus and Gordon-Salant, 1995). Another possibility is that the intelligibility benefits of these conditions do not extend to hearing-impaired listeners and that the additive noise model for simulating impairment in normal hearing listeners is inadequate. Although this simulation is appropriate for many mild to moderate impairments, it may not represent the effects of more severe impairments accurately. To investigate these two possibilities further, additional intelligibility tests will be conducted to evaluate the intelligibility of clear/normal, clear/slow, conv/normal, and conv/slow speech for young hearing-impaired, elderly hearing-impaired, and elderly normal-hearing listeners. These tests will differentiate the effect of age and impairment factors and clearly identify which groups can receive benefit from clear speech at normal speaking rates.

Because the intelligibility advantage provided by formant processing was not as large as the advantage provided by clear/normal speech, additional acoustic properties of clear/normal speech that contribute to its high intelligibility must exist. A factor that may have prevented identification of one or more of these properties is the complexity of the speech database used for acoustic analysis. While a sentence database was appropriate for the intelligibility experiments, the primary problem with using a sentence database for the purposes of acoustic analysis is the presence of acoustic variability due to word positioning within sentences or phonetic context within words. For some acoustic properties, this variability could be large enough to mask the variability between conv/normal and clear/normal tokens. Therefore, a new database of conv/normal and clear/normal speech should be created that consists of sentences with a fixed number of phonetic contexts. This type of database would best satisfy the conflicting demands of acoustic analyses and intelligibility experiments. To capture various talker strategies in the new database, a large number of talkers should be recorded. An acoustic analysis of a database of this type is likely not only to identify additional acoustic properties associated with clear/normal speech but also to provide a comprehensive description of a variety of talker strategies. This information will be essential to the development of processing schemes that can provide robust intelligibility improvement for a variety of talkers and environments.

Computational Model of Speech Intelligibility (Hearing Aid Research)

Much of the effort over the last year has gone into the development of Simulink-based hearing loss and hearing aid simulators. We have run preliminary experiments using these simulators and, based on our results, we have plans to run additional experiments. The signals generated by these simulators have also been used to generate speech-based STI predictions of subject performance (see Payton et al. 1999 for description of speech-based STI algorithm).

Hearing loss simulation: We developed a software, 14-band, hearing loss simulation that includes recruitment. It is based on the simulation of Duchnowski and Zurek (1995). The current simulation allows us great flexibility to modify parameters, should we choose to simulate different impairment characteristics. Our current experiments simulated a flat, 50 dB, hearing loss with recruitment. In each of 14 bands, 50 dB SL was attenuated to normal- hearing threshold. Expansion occurred independently in each band until the sound level in a band reached the threshold of recruitment, above which unity gain occurred.

Hearing aid simulation: The hearing aid simulation we developed allows up to 4 independent band compression with variable static compression ratios, attack times and release times. The hearing aid also includes NAL-R frequency gain characteristics. We can easily modify the characteristics of this simulation to predict the effects of different aids on various hearing losses.

New STI analyses: The Speech Transmission Index (STI), with modifications as described in Payton and Braida (1999), was applied to speech processed by the previously described hearing-loss simulation and either linear amplification (NAL prescription only) or one of two amplitude compression ratios (plus NAL prescription). The STI predictions were compared with listener intelligibility scores on nonsense sentences and with listener pleasantness ratings in quiet, in 0 dB SNR speech-shaped filtered Gaussian noise and in 0 dB SNR restaurant babble noise.

As reported in our poster at the IHCON 2000 conference last August (Payton et al., 2000), our preliminary experiments and analyses showed that the STI predicted speech in restaurant babble would be more intelligible than speech in noise for each compression condition. The data reflected this for the two nonlinear compression conditions. The STI predictions were also consistent with pleasantness ratings: Linear amplification was the most pleasant compression condition. The STI predictions did not agree with experimental results which showed higher intelligibility for compressed speech over linear amplification when speech was presented with babble. Based on feedback from other researchers who viewed our poster, we are reconsidering some of the parameters used in the preliminary experiments and we are also analyzing the envelope spectra data for the various conditions (envelope spectra are an intermediate step in STI computations).

In addition to the above efforts, work has been done to compare various STI computation techniques. In particular, we are trying to determine how the apparent SNR, based on the speech modulation transfer function, as computed in Payton and Braida (1999), differs from the apparent SNR proposed by Ludvigsen (1987) and that proposed by Drullman et al. (1994). Our first effort was to compare speech envelope extraction techniques. Houtgast and Steeneken, the first to apply the MTF to speech, computed speech envelopes by first passing speech through octave-band filters then squaring each filter output and lowpass filtering the results to generate envelope signals for each band (1985).Drullman et al., also computed envelope spectra by octave-band filtering then extracting the band envelopes. In contrast, Ludvigsen estimated his envelopes in the frequency domain. He computed the FFT magnitude of frames of windowed speech. The FFT magnitude values in a frame were summed into octave band magnitudes. By looking at successive frames, a time series was generated for each octave band. We found the two methods to generate roughly the same envelopes except in the lowest octave band. Further examination revealed that Ludvigsen's method had too little resolution for the lowest octave band (CF=125 Hz) to produce accurate results. When we doubled the FFT length in Ludvigsen's method, the differences between the two methods for the lowest band decreased.

Computational Model of Speech Intelligibility (Cochlear-Implant Research)

A new component of our work in the area of models of speech intelligibility concerns predicting the intelligibility of cochlear-implant processed speech. The goal of this effort is to develop a subject-independent metric that can be used to predict the maximum possible intelligibility performance for a particular cochlear-implant speech processing strategy. (Subject-dependent factors may lead to lower performance for particular subjects.) Once such a metric is developed, it will be used to evaluate promising noise-reduction strategies for cochlear implant preprocessing. In this new effort, our previous experience with hearing-aid users in two main areas (models of speech intelligibility and signal processing algorithms for noise reduction) is being applied to benefit cochlear-implant users, a population for whom background noise affects speech intelligibility even more adversely than hearing-aid users.

The model of speech intelligibility under consideration is based on the speech transmission index (STI). STI was originally developed as a way of assessing room acoustics, and the original STI calculations are based on a system's response to specific test signals. Although these test signals are appropriate for assessing room acoustics, they are not suitable for many kinds of signal processing used in hearing aids and cochlear implants. As a result, several research groups, including our own, have attempted to develop methods for calculating STI based on the speech signal itself, rather than specific test signals.

We have completed an analysis of the various methods for speech-based STI calculation described in the literature, and we have established explicit relationships between the various speech-based STI calculations. This analysis revealed a number of issues that may hamper the performance of existing speech-based STI calculations for both noise reduction and cochlear-implant speech processing. We are currently developing an improved method for speech-based STI calculation that addresses these issues. This new method for speech-based STI calculation will be compared to previously proposed methods in a series of intelligibility experiments with both cochlear-implant users and normal-hearing subjects listening to a simulation of cochlear-implant speech processing.

Signal Processing for Hearing Aids

During the current grant year, work on noise reduction for hearing aids has progressed in two areas:

- Design, implementation and assessment of automatic gain control (AGC) algorithms for single-microphone noise reduction;
- Analysis of previously-obtained experimental results evaluating two-microphone adaptive-array hearing aids.

Automatic Gain Control Algorithms: Previous work has considered the use of automatic gain control algorithms specifically designed to reduce background noise, including modifications to the dual front-end AGC (Moore and Glasberg, Br. J. of Audiology 22, pp. 93-104, 1988). The main idea of the dual front-end AGC is to have two AGC components applied simultaneously; a slow-acting wideband automatic volume control, which determines the gain for most acoustic conditions, plus a fast-acting AGC with a higher threshold to provide transient suppression.

Recent work in this area suggests a number of modifications that affect the design, implementation and parameter choices of the dual front-end AGC algorithm (Stone et al., JASA 106, pp. 3603-3619, 1999). During the current grant period, we have implemented several algorithms based on this newer version of the dual front-end AGC, and we are currently evaluating the algorithm with hearing-impaired subjects.

The dual front-end AGC system that we are testing includes two optional features, a hold-timer, as proposed by Stone et al., and a signal-to-noise ratio (SNR) detector, as proposed in previous work performed under the current grant. The purpose of the hold timer is to reduce pumping without extremely long recovery times. It effectively prevents gain fluctuations during speech and during brief pauses in speech. The purpose of the SNR detector is to have modify the release time of the slow acting AGC component so that it releases more quickly when strong speech (from the hearing-aid wearer's voice) is followed by weaker speech (from another talker).

The current evaluation considers five algorithms, four dual front-end AGC algorithms (all combinations of with and without the hold timer and with and without SNR detection) plus a linear reference condition with compression limiting. A set of twenty acoustic test conditions representative of everyday listening situations have been selected. These conditions include speech in quiet at various levels, speech plus multitalker babble at various signal-to-noise ratios, speech plus continuous environmental noises (for example, vacuum cleaner, hair dryer, running water) and speech plus transient environmental noises (for example, glass breaking, hammering, door slamming). Multiple stimuli corresponding to these conditions have been processed by all five algorithms. Hearing-impaired subjects listen to the processed segments and rate each segment for subjective intelligibility and quality on 0-10 point scales.

These experiments are currently underway. Our pending analysis of the results will determine whether or not the dual front-end AGC provides practical benefits with respect to the reduction of environmental noises when compared to the linear reference condition. The results of these experiments will also provide information as to which components (hold timer and SNR detector) are beneficial with which types of interference.

Two-Microphone Adaptive-Array Hearing Aids: Traditional two-microphone array processors applied to hearing aids require binaural inputs and produce a monaural output with improved signal-to-noise ratio (SNR), but no binaural cues. Previous work with normal-hearing listeners has demonstrated the potential to obtain a tradeoff between localization and intelligibility with a lowpass/highpass system that splits the signal into two frequency bands, preserving binaural cues at low frequencies while improving SNR at high frequencies. Under another NIH-funded project, the lowpass/highpass system and a conventional broadband array processor were evaluated with eight hearing-impaired subjects. With the completion of that project, analysis and interpretation of experimental results are being performed under this grant.

Results show that the broadband array processor improved speech reception thresholds (SRTs) by an average of 10 dB relative to a binaural reference condition, while the lowpass/highpass method provided an average SRT improvement of 2 dB. This was unexpected in light of both physical measurements and the performance of normal-hearing listeners. These results suggest that hearing-impaired subjects rely on low frequency information more than normal-hearing listeners, and that effective array processing hearing aids must operate over the entire frequency range. Consequently, the lowpass/highpass approach is not advisable for hearing aids. Alternative methods for improving intelligibility of speech in noise while preserving a sense of auditory space should be pursued. A user-controlled switch to select between omnidirectional and directional listening modes is one possibility.

Characteristics of Sensorineural Hearing Impairment

Listeners with severe hearing losses when stimulated at high sound levels are the main focus of this work. Ching et al. (1998) have shown that many hearing impaired listeners with severe or worse high-frequency losses achieve little or no benefit from audible speech in the high-frequency region. Hogan and Turner (1998)report similar results and suggest that if the loss exceeds 55 dB at 3 kHz and above there may be little benefit (or even a detriment) associated with making high-frequency speech cues audible.

We are studying such listeners using approaches based on both functional and analytical modeling. Six subjects with hearing impairments and six controls with normal hearing have been tested Listeners will attempt to identify speech syllables presented in three conditions (e.g., 1) highpass filtered at 2100 Hz; lowpass filtered to 2100 Hz, and braodband-- the combination of the two previous bands). Ideal processor models will be used to predict the results observed in the combined-band condition from those observed in the sub-band conditions under the assumption of ideal cue integration (i.e. perfect integration with no interband interference). Comparisons of scores and error patterns can distinguish the effects of poor in-band representation of high-frequency speech cues from those of perceptual interference between bands.

1.2 Auditory Perception and Cognition

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Project Staff

Dr. Andrew J. Oxenham (P.I.), Dr. Torsten Dau[3], Kosuke Kawakyu, Zachary Smith

Introduction

Our aim is to further our basic understanding of normal and impaired hearing using behavioral, or psychophysical, techniques. This work is approached at two different levels. The first is concerned with finding behavioral measures of how the peripheral auditory system breaks down incoming sounds into their constituent frequency components. This work focuses on the perceptual effects of cochlear mechanics, in particular nonlinear filtering. The second level addresses how sounds, which are separated according to frequency content in the cochlea, are recombined at higher levels of auditory processing to form ‘auditory objects’ or ‘auditory streams’. The findings are used to place constraints on models of higher-level auditory processing and may act as guides to studies in search of the neurophysiological underpinnings of auditory perception.

Behavioral measures of phase response in the human auditory system

Detection thresholds for a sinusoid in a harmonic tone complex masker can vary by as much as 30 dB, based solely on the phase relationships between the individual masker components. It is thought that a highly modulated “internal” waveform produces lower thresholds than one with a relatively flat temporal envelope, but explanations of this phenomenon using so-called Schroeder-phase complexes have so far relied mainly on qualitative arguments. Whether a given acoustic waveform will produce a flat or modulated internal temporal envelope depends on the interaction between the component phases and the phase response of the auditory system itself. We have undertaken a quantitative investigation of these phenomena by comparing new data with model predictions in an effort to characterize the phase response of the auditory system. The results show that (1) none of the models of auditory filtering currently in use have both the correct phase

[3] Department of Medical Physics, Universität Oldenburg, 26111 Oldenburg, Germany.

and amplitude response; (2) the effective bandwidth of the auditory filters at medium sound levels is considerably broader than is suggested by the widely used ERB (Equivalent Rectangular Bandwidth) scale; and (3) peripheral compression is necessary to account for the large differences in threshold. The third conclusion is important as it provides quantitative support for earlier speculation that the large differences found between normal and hearing-impaired listeners in these tasks may be due to changes in peripheral compression (Summers, 1998).

The technique has now been extended to provide a behavioral measure of phase curvature in the human auditory system as a function of center frequency. Results have revealed that phase curvature does not scale with center frequency. Instead, at low frequencies there is a tendency for relative curvature to decrease with frequency but, unlike recent physiological data from cat (Carney, 1999), there is no evidence of a reversal in phase curvature at the lowest center frequencies. Our work shows that the phase response of the auditory filters can influence perception and that it is possible to provide behavioral estimates of this phase response. Decades of work have gone into defining the magnitude response of the auditory filters. The present studies represent the first systematic attempt to characterize their phase response. The results have implications for models of auditory processing and for the first time enable direct comparison between peripheral temporal processing in humans and in animal models.

Across-channel effects in the processing of amplitude modulation

Our ability to detect amplitude modulation is impaired in the presence of interfering amplitude modulation, even if the target and interfering carriers are remote in frequency. This effect, known as modulation detection interference (MDI), is an example of perceptual interference between components that do not interact in the auditory periphery. The question posed by this research is whether this effect is due to “hard-wired” convergence of peripheral auditory information at the level of modulation analysis, or whether it is due to more flexible assignments based, for instance, on auditory perceptual groups or streams. In other words, does the grouping of components into perceptual objects or streams occur before or after modulation analysis? Our results show that MDI can be understood in terms of perceptual grouping of the target and interfering carriers. This was achieved by showing that MDI could be eliminated situations promoting the segregation of the target and interferer. The results show that MDI is not a reflection of hard-wired neural convergence at higher levels of auditory processing and instead suggest that modulation analysis is only performed after some degree of perceptual grouping has occurred.

Comparisons between physiological and psychophysical measures of frequency selectivity in humans

Much effort has gone into characterizing the magnitude response of the so-called auditory filters using behavioral measures in humans and animals. The physiological basis of the auditory filters is thought to lie in the nonlinear mechanics of the inner ear and, based on animal studies, it is generally believed that there is a good correspondence between peripheral physiological and behavioral measures of frequency selectivity. In humans, there are little or no physiological data relating to frequency selectivity. A new technique, pioneered by Dr. Christopher Shera of Harvard Medical School, can be used to estimate peripheral frequency selectivity using otoacoustic emissions, or sounds emitted from the cochlea. The estimates from this technique are in conflict with most psychophysical measures in terms of how frequency selectivity varies as a function of center frequency: instead of bandwidths that remain roughly constant as a proportion of center frequency, the new estimates suggest that relative bandwidths decrease with increasing center frequency. The aim of our study, in collaboration with Dr. Shera, was to attempt to resolve the apparent discrepancy between physiological and psychophysical estimates of frequency selectivity in humans. Using non-simultaneous masking techniques, which avoid the possible confounding effects of suppression, our psychophysical results are in line with the physiological data. This suggests that currently accepted behavioral estimates of auditory filter bandwidth are inaccurate and that, specifically, they overestimate the bandwidths at high frequencies.

2.1 Tactile Communication of Speech

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Project Staff
Andrew R. Brughera, Lorraine A. Delhorne, Nathaniel I. Durlach, Seth M. Hall, Eleanora Luongo, Geoffrey L. Plant, Charlotte M. Reed, Mandayam A. Srinivasan, Han-Feng Yuan

Goals and Significance

The long-term goal of this research is to develop tactual aids for persons who are profoundly deaf or deaf-blind to serve as a substitute for hearing in the reception of speech and environmental sounds. This research can contribute to improved speech reception and production, language competence, and environmental-sound recognition in such individuals. The research proposed here is designed to lead to improvements in tactual stimulation systems through two major areas of work: Work in *Area 1* (basic studies of human touch) is designed to increase our knowledge concerning the transmission of information through the sense of touch. One component of this work includes theoretical and experimental studies designed to increase our understanding of the capabilities of the tactual system for dynamic information transfer. The second component of work in this area includes studies designed to increase our understanding of the psychophysical properties of touch in the scientific design of tactual displays for a broad class of applications, including sensory aids for the deaf. Perceptual interactions will be examined using the following experimental paradigms: temporal-order resolution, masking, roving-level discrimination and identification, and training transfer. Work in *Area 2* (tactual displays of speech and environmental sounds) is concerned with the application of tactual displays to sensory aids for persons who are profoundly deaf or deaf-blind. Research related to speech includes studies related to the processing and display of envelope-based speech signals through a multi-finger tactual display, training and evaluation in the use of such signals as supplements to speechreading, and the development of a desktop multi-finger display. Research related to environmental sounds includes studies related to the development and evaluation of signal-processing and display schemes specific to such sounds, as well as a survey of the deaf community (including the signing as well as the oral community) to determine interest in simple tactual aids for environmental-sound detection and recognition.

Current Studies

Basic Studies of Human Touch
Experimental studies are being conducted to measure information-transfer (IT) rates for multi-dimensional tactual signals. While our previous results on IT and IT rates for artificial tactual signals presented through a multi-finger tactual display (see Tan et al., 1999) are encouraging in their implication that the rates observed for artificial tactual signals may approach those observed through natural methods of tactual communication, it is nonetheless important to demonstrate that these estimated IT rates can be maintained under conditions requiring identification of a stream of signals. Such a task depends on the ability to identify signals rapidly and to recall them in order; obviously, subjects must be well-trained in order to perform such an experimental task. In ongoing experiments, our goal is to demonstrate reasonably high IT rates (i.e., in the range of 10-15 bits/sec) for the sequential identification of stimuli. These experiments employ a set of 21 multidimensional signals of the type developed by Tan (1996) as stimuli for the studies. Subjects are first being trained to identify the 21 signals in an AXB paradigm, where A, X, and B are

chosen at random from the stimulus set and the subject's task is to identify X alone. Subjects then proceed to progressively more difficult tasks requiring the identification of more than one value of X, by extending the AXB paradigm to $AX_1...X_nB$, where n=2, 3, and 4. For each of the tasks, we are studying signal durations of 250 and 125 msec and values of inter-stimulus interval in the range of 0 to 640 msec. Through these studies we hope to determine the effect of the number of consecutive signals to be identified on the estimated IT rate; to the extent that well-practiced subjects are able to maintain the same IT rate as the number of signals in the sequence increases from 1 to 4, the current studies will lead to a more robust demonstration of the dynamic information-transfer capabilities of the tactual sense.

Tactual Displays of Speech and Environmental Sounds
Current work in the area of tactual displays of speech is concerned with the development of improved displays of consonantal voicing as a supplement to speechreading. This research includes work on signal-processing schemes to extract information about voicing from the acoustic speech signal, methods of displaying this information through a versatile tactual display, and perceptual evaluations of the reception of voicing using speech stimuli under conditions of tactual display alone, lipreading alone, and the combined condition. Preliminary studies have focused on the use of envelope cues for the reception of voicing and include a perceptual study of the effectiveness of these cues as supplements to speechreading as well as objective acoustic measurements of properties related to voicing that are available in the envelope signal.

The ability to discriminate voicing was studied for speechreading alone as well as for speechreading combined with three different envelope signals presented to the left index finger of the subject using the Tactuator device (Tan, 1996). The three envelope signals included: (1) An octave band-pass filter centered at 500 Hz, full-wave rectified, and smoothed at 50 Hz. The resulting signal was then multiplied by a 200 Hz sinusoidal carrier for presentation through the tactual display. This basic signal has been employed in previous studies of auditory and tactual supplements to speechreading (e.g., see Grant et al., 1991; Besing et al., 1995; Bratakos et al., 2001). The other two envelope signals were constructed from modifications to this basic signal. (2) The previously described envelope signal was modified to expand the fluctuations in amplitude envelope by a factor of 2. This modification was implemented on the basis of modulation-resolution studies that indicate that the tactual sense is less sensitive than the auditory sense (by roughly a factor of 2) to fluctuations in amplitude. (3) The third envelope signal was based on modification of the basic signal to yield a discrete on/off signal. A threshold value was established for presenting the output of the envelope signal, and at supra-threshold levels a 200-Hz tone was turned on at a constant level. Results for pair-wise discrimination of 8 pairs of consonantal voicing contrasts indicated speechreading-alone scores of 56% correct compared to scores ranging from 75% to 82% for speechreading combined with the three different tactual envelope signals. Envelope signals (1) and (3) yielded similar performance (75% and 77% correct, respectively), while performance was slightly higher (82% correct) for the signal that incorporated expansion of the amplitude envelope (signal 2). Performance with the best tactual envelope signal led to a 26-percentage-point improvement over speechreading alone.

A set of preliminary objective acoustic measurements on properties related to voicing were obtained from the basic envelope signal described above (derived from an octave band-pass filter centered at 500 Hz) as well as for envelope signals derived from a 300-Hz lowpass filtered band of speech and a 3500-Hz highpass filtered band of speech. Measurements were made for nonsense syllables as well as for words in sentences and included examples of stops, fricatives, and affricates in different vowel contexts and positions within the syllable or word. The 500-Hz octave band envelope signal was found to contain strong spectral and temporal distinctions between voiced and voiceless stops. Such distinctions were present consistently for certain pairs of fricative contrasts (/s z/ and /sh zh/) but not for other fricative contrasts (i.e., the "weaker" fricatives) or for the affricate contrast (/ch j/). However, measurements from the 300-Hz lowpass and 3500-Hz highpass envelope signals indicate consistent differences in these signals for distinguishing voicing contrasts among "weak" fricatives as well as for distinguishing voicing in the affricate contrast. Thus, cues combined across these three envelope signals appear to contain sufficient information for distinguishing the 8 consonantal voicing contrasts present in English.

Work in the area of tactual displays of environmental sounds is concerned with the development of a survey to assess the interest of members of the deaf community in such devices. Although previous efforts to develop tactual communication aids for the deaf have focused primarily on the reception of speech, field studies of the adult users of tactual aids have led to the observation that these aids are also highly useful in the reception of non-speech sounds in the environment. Thus, it may be possible that a broader class of deaf individuals, with little or no interest in speech reception, may nonetheless be interested in tactual displays for gaining information about acoustic events such as warning signals and sounds associated with nature. Work is underway to develop a preliminary survey for administration to members of the deaf community (both signing and oral) The main experimental variable of the survey is concerned with the informants' interest in the reception of various types of environmental sounds. These attitudes will then be related to factors such as linguistic background, history of hearing loss, and history of device use.

3.1 Role of Skin Biomechanics in Mechanoreceptor Response

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Project Staff

Mandayam A. Srinivasan (PI), S. James Biggs, Louis H. Buell, Balasundar I. Raju, Suvranu De, Avin C. Gidwani, Robert H. LaMotte[4], Lihua Zhou

Overview

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. In spite of the fundamental importance of the sense of touch in our lives, very little is known about the mechanics and the mechanisms of touch. Analysis of mechanistic models generates testable hypotheses about deformations of skin and subcutaneous tissues, and about the associated peripheral neural responses. Verification of the hypotheses can then be accomplished by comparing the calculated results with biomechanical data on the deformation of skin and subcutaneous tissues, and with neurophysiological data from recordings of the responses of single neural fibers.

The research under this grant is directed towards applying analytical and computational mechanics to analyze the biomechanical aspects of touch: the mechanics of contact, the transmission of the mechanical signals through the skin, and their transduction into neural impulses by the mechanoreceptors.

The research work consisted of four parts: (1) to develop 2 and 3 Dimensional (3D) mechanistic models of the primate fingertip, and gradually refine them so that their geometrical and material properties are increasingly realistic; (2) to expand the variety of stimuli that are pressed or stroked on the models in simulations of neurophysiological experiments; (3) to perform a series of biomechanical experiments under *in vivo* conditions using a variety of techniques including

[4] Yale University School of Medicine

videomicroscopy, Magnetic Resonance Imaging (MRI), high frequency ultrasound, and computer controlled stimulators; (4) to in obtain and analyze peripheral neural response data from monkey fingerpads for a variety of tactile stimuli (collaboration with Prof. LaMotte). During the past year, we have continued development of a novel device, the Ultrasound Backscatter Microscope (UBM), which is capable of imaging the papillary ridges as well as skin layers underneath at much higher resolution than MRI.

The following sections describe progress over the past few years and are organized according to the research area: (1) biomechanics, (2) neurophysiology and psychophysics, (3) computational Models, (4) theory, and (5) device design and construction.

Biomechanics

Determination of Compressibility and Mechanical Impedance of the Human Fingerpad In Vivo
For mechanistic modeling of the human fingerpad, the Poisson's ratio, a measure of compressibility, is required. Accordingly, the Poisson's ratio for the human fingerpad in vivo was investigated. In previous noninvasive experiments on human subjects, we have measured the change in volume of the fingerpad under static indentations with different indenters. Our results show that the compressibility of the fingertip increases with increases in both the depth of indentation and the contact area with the indentor. The highest change in fingertip volume was about 5%. For dynamic indentations, reductions in fingertip volume are in phase with stimuli, as the mean volume reduction slowly creeps upward over time. The volume changes during the ramp phase increase linearly with indentor displacement and are independent of velocity; during saw tooth stimulations, however, the nature of the hysteresis loops depend on velocity of indentation.

We have also measured the force response of the human fingerpad, *in vivo,* to indentation by stimuli of varying geometry. A computer-controlled tactile stimulator delivered a combination of static, ramp and sinusoidal indentations normal the skin surface, with the fingerpads of subjects held stationary and passive. Both input indentation depth and fingerpad force response were recorded as functions of time to capture transients and steady state features. Three rigid metal indenters, a point, a 6.35 mm diameter circular probe and a flat plate, were used for indentation to represent three general classes of loading profiles encountered in manual exploration and manipulation. With each stimulus, repeatability of the response was tested and the effects of varying amplitude, velocity, and frequency of indentation were investigated. The experiments revealed that the force response of the fingerpad is both nonlinear and viscoelastic with respect to indentation depth and velocity. A nonlinear Kelvin model was proposed and approximated as a piecewise linear set of springs in parallel with series spring-dashpots. Parameters were estimated for each subject and indenter. These “individual” models predicted data for that particular subject and indentor very well ($R^2 > 0.96$) but not as well for others. The means of the parameters across subjects were then used to construct more general, indentor specific versions of the model, which were able to predict better the force response of any subject’s fingerpad to a given indentation. These results were used in validating 2-dimensional and 3Dimensional (3D) mechanistic models of the primate fingertip.

Experimental Investigation of Frictional Properties of the Human Fingerpad
In manual exploration as well as manipulation, the frictional properties of the fingerpad play a dominant role in governing the forces applied, the amount of skin stretch, and the occurrence of slip. We used a tactile stimulator to indent and stroke the fingerpads of human subjects with different indentation depths, stroke velocities, and stroke directions. Three flat plates made of glass, polycarbonate, and acrylic were used as stimulus surfaces. During stroking, the normal and shear forces were recorded by a 2-axis force sensor. A videomicroscopy system captured images of the contact region between the fingerpad and the stimulus surface while stroking. The

stimulator and the videomicroscopy system were synchronized so as to match the images with the corresponding force data

The data show distinct frictional behaviors for different stimulus surfaces. For glass, the curves of normal as well as shear forces increased smoothly to steady state values. When the indentation depth was larger, the normal and shear forces were larger, but the friction coefficient was smaller. When the stroke velocity increased, the normal force was about the same for a given indentation depth, while the shear force and the friction coefficient increased. The stroke direction did not significantly influence the results. The images showed that relative motion between the fingerpad and the glass plate began at the periphery and propagated towards the center. Displacements of different finger ridges in the contact area also varied.

Polycarbonate and acrylic surfaces, although similar in smoothness and appearance to glass, caused a radically different frictional behavior: stick-slip phenomenon occurred consistently all through the stroke in every trial. An analysis of the stick-slip frequency and the stick-slip shear force was conducted with respect to various indentation depths and various stroke velocities. Based on adhesion theory a hypothesis about junction forming rate and junction breaking rate was proposed to explain the different results for glass and polycarbonate. The frictional data have been incorporated into our models of the primate fingertip to make the simulations of stroking of stimulus objects more realistic.

Investigation of the Internal Geometry and Mechanics of the Human Fingertip In Vivo *using Magnetic Resonance Imaging*

To gain insight into the mechanistic bases of the human tactile sensory system, we have developed a series of increasingly detailed biomechanical models of monkey and human fingertips. These models are necessary to generate testable hypotheses on tactile neural coding. Although 3D models of human and monkey fingertips with realistic external geometry and multi-layered interior have been completed, the geometry and material properties of the internal layers have been idealized. Empirical data on deformation of the internal layers is essential for validating these models.

We employed advanced techniques in Magnetic Resonance Imaging (MRI) to obtain realistic internal geometry and deformation of the tissue layers of the *in vivo* human fingerpad. The fingerpads of four subjects were statically loaded with various indenters to examine the effects of indentation depth and indentor shape on tissue deformation. Geometric surfaces, such as edges, rectangular bars, and cylinders were used to load the fingertip. Using a 4.7 Tesla magnet and a RARE sequence, we obtained images with in-plane resolutions much higher (125μm x 125μm) than typical clinical MRI data. Digital image processing was used to filter the images and to detect the boundaries of the tissues located in the fingertip. Edge detection algorithms based on conformable contours (“snakes”) allowed for separation of tissue layers. Published data on histology and anatomy were used to identify each tissue layer in the fingertip.

The geometric information extracted from each tissue layer was used to examine tissue deformation during loading, and is being used to improve the realism of the computational models. These data confirmed our earlier simulations that predicted soft tissues of the fingerpad act as low pass filters, attenuating the high spatial frequencies of edges and corners imposed on the skin surface before they reach the mechanoreceptors below. Additionally, MRI confirmed that the fingerpad is compressible under load.

Experimental Investigation of the Biomechanics of Papillary Ridges

We have begun using dynamic video microscopy (Figure 3.1-1) of cadaver finger pad cut in cross section to observe tissue biomechanics with spatial resolution (~2 μm/pixel) higher than *in vivo* methods (MRI and UBM) allow. Using MATLAB, we developed algorithms to track material particles and calculate strain fields as the skin is indented by points, lines, bars and cylinders. These measurements provide data to improve current models of touch biomechanics. The results are compared with finite element simulations and with previously obtained neurophysiological data from the corresponding experiments.

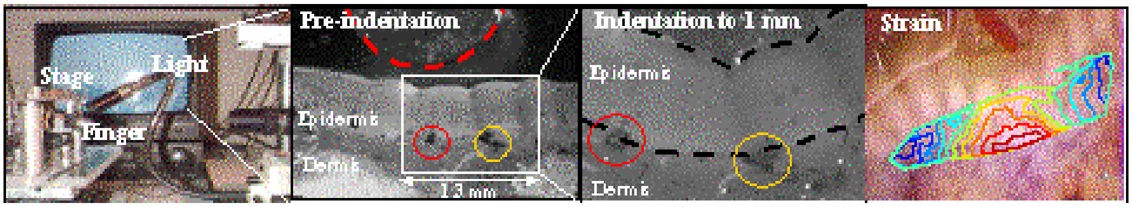

Figure 3.1-1. A video microscopy system (left image) provides high resolution images of skin. A cylindrical indentor loads a cadaver finger pad, while the tissue is viewed in cross section (middle 2 images). Strains around mechanoreceptors are estimated from displacements of markers on the tissue (right image).

Initial efforts assessed the usefulness of cadaver tissue for understanding biomechanics of living tissue. Measurements of mechanical impedance to sine and step inputs with a point indentor showed that fresh, unpreserved cadaver tissue exhibits stiffness and viscoelastic recovery that falls within the spread of values seen in living tissue, indicating that it is suitable for these experiments. Further work has improved the method. A color CCD is now used to differentiate epidermis from dermis. Material points in the tissue are now tracked with high contrast markers. A jig has been developed to ensure cross-sections are planar. To date, data have been collected from five human cadaver fingers and two primate fingers.

This technique facilitates study of some basic issues in touch transduction. Specifically, we hope to observe whether the papillary ridges concentrate strain in the tissue around mechanoreceptors. If so, we will have empirical evidence for a sensory function of fingerprints.

Neurophysiology and Psychophysics

Tactile Coding of Shape

A salient feature of tactile sensing is its ability to encode and decode the shape of objects. In collaboration with Prof. LaMotte of Yale University School of Medicine, we have recorded the responses of SAIs and RAs to a variety of 2-D and 3D shapes stroked across the monkey fingerpad. One set of experiments involved 2-D “wavy surfaces”, i.e., surfaces composed of smooth, alternating convexities and concavities of differing radii of curvature. The second set of experiments employed 3D toroidal objects mounted on a flat plate. With wavy surfaces, it was shown that only convexities were encoded in the neural responses; concavities evoked no responses. The primary findings from both sets of experiments were as follows: (a) discharge rates encode the magnitude and rate of change in the curvature of the skin produced by an object, (b) the orientation and shape of the two-dimensional outline of the object parallel to the skin are represented by the orientation and shape of the region of neural activity in both SA and RA populations, (c) object shape perpendicular to the skin is encoded in the shape of the object SA SPR (Spatial Population Response), (d) When object curvature is constant (e.g., circular cylinders), the slopes of the rising and falling phases of the SA response profile are constant, and (e) spatial measures of shape (width and average slope from base to peak) were generally found to be invariant with changes in the orientation of the object as well as the velocity and direction of stroking.

Using a novel paradigm we have also investigated how populations of RAs and SAIs encode shapes. Toroidal 3D objects were indented at a fixed location on the monkey finger pad, and an estimate of the responses from a spatially distributed population of mechanoreceptors was obtained by successively recording single fiber responses and plotting the collection of responses on a “virtual” monkey fingerpad. This was a shift from the usual experimental paradigm where “population response” is estimated by applying the stimulus to various locations in the receptive field of a single afferent fiber. A major conclusion from these studies was that the Spatial Population Response Profiles (SPR) of SAs coded stimulus shape and orientation unambiguously, while the RA SPR coded neither. This shape code is expected to be essentially invariant with changes in force or velocity of indentation, as demonstrated for raised toroidal objects on a planar surface described above.

Tactile Coding of Softness

Encoding of softness is perhaps even more important in tactile sensing than that of shape, because softness can only be sensed accurately by direct touch whereas shape can be inferred through vision as well. We have described, for the first time, how primates discriminate between objects of different compliances and described the biomechanical and neural basis of the perception of softness. We have shown that compliant springs with rigid surfaces (“spring-cells”) required both kinesthetic and tactile information for softness discrimination, whereas for soft rubber objects of different compliances, tactile information alone was sufficient. The reason is that for a given force applied by a compliant object to the skin, the spatial pressure distribution and skin deformation within the contact region depend on the specimen compliance if the object has a deformable surface (e.g., fruits), but is independent of the specimen compliance if its surface is rigid (e.g., piano key). Thus, tactile information alone is necessary and sufficient to encode the compliance of rubber-like objects.

We then focussed on finding a more quantitative neurophysiological and biomechanical basis for softness encoding. Using a computer-controlled tactile stimulator, we applied rubber specimens to the finger pads of anesthetized monkeys in a controlled manner and recorded the neural response from SAI and RA fibers. The discharge rates were observed to be lower in the SAI fiber's response to softer specimens compared to stiffer ones. In contrast, RA response was found to be practically indifferent to the relative variations in stiffness. Thus, it was concluded that tactile discrimination of softness was based more on the discharge rates from the SAIs than from the RAs. It was also found that when specimens were applied to the fingerpad at the same velocity, the softer the specimen, the lower the rate of change of net force and the higher the rate of change of overall contact area. Thus at a given instant during indentation, the difference in the average pressure between the two specimens was higher than the corresponding differences in either the forces or the contact areas. Just as the pressure increased more slowly for the softer specimen, the SA discharge rate also increased more slowly, resulting in a slower increase in cumulative impulses. However, the velocity of indentation affected the force, contact area, and discharge rate. For the same specimen, the lower indentation velocity resulted in lower force and area rates, giving rise to a lower discharge rate at a given instant during the ramp. Since the discharge rate of a single fiber is affected by both the compliance of the specimen and the indentation velocity, specimens of differing compliances could be made to give rise to the same single fiber response by appropriate adjustment of indentation velocity. Thus, discharge rate in a single SAI fiber cannot unequivocally encode the compliance of an object, but a population of spatially distributed SAIs can.

Psychophysics of Tangential Skin Displacements

Tangential displacement of the skin (as opposed to normal indentation) is an interesting tactile stimulus. To detect small (< 1 μm) features, humans must scan the fingertip over a surface, presumably to induce tangential displacements. We have measured subjects’ sensitivity to tangential displacements of skin on the finger pad and forearm. Subjects showed greater sensitivity to tangential displacements than normal displacements by a factor of about 3:2 at the finger pad and 3:1 at the forearm. These ratios were in rough agreement with a biomechanical analysis of how these tractions distribute energy to the mechanoreceptors embedded in the tissue. Subjects' high sensitivity to tangential tractions suggests that they are an efficient means of stimulating skin with tactile displays.

Computational Models

In order to better understand the mechanics of touch, it is necessary to establish a quantitative relationship between the stress/strain state at a mechanoreceptor location and the neural response of the receptor to a given mechanical stimulus. Due to the subsurface locations of the receptors and the opacity of the skin, the stress state and deformations in the close vicinity of a receptor cannot be observed experimentally in vivo. Moreover, no experimental techniques exist to record the responses from a population of mechanoreceptors. A mechanistic model of the skin and subcutaneous tissues that is validated through biomechanical and neurophysiological experiments is able to establish the stress/strain stimulus to a mechanoreceptor as well as predict the population response to a given stimulus. Therefore, we developed a series of increasingly realistic 2-D and 3D finite element models of the primate fingertip. We summarize below the development of the 3D model and the biomechanical and neurophysiological results obtained from it.

Development of 3D Layered Model of Human and Monkey Fingertips
The external geometry of human and monkey fingertips was obtained from precise epoxy casts made using dental cement molds. These casts were extremely accurate in reproducing the finger print ridges, details of the nail and wrinkles on the skin. A videomicroscopy setup consisting of a monochrome CCD camera with zoom lenses, a frame grabber, and a PC was used to acquire images of the casts in different orientations. A stepper motor was used to rotate the fingertip about an axis parallel to the bone axis in 1-degree steps, and an image was grabbed at each step. The boundary of the fingertip in an image frame essentially represented the orthographic projection of the fingertip for that particular orientation. These 2D sections were imported into a solid modeler (PATRAN) and a 3D model of the fingertip with realistic external geometry was generated. The relative thickness of the bone in the distal phalanx was determined from X-ray images and a concentric bone was generated inside the fingertip. To account for the several layers of skin and the adipose tissue underneath, the mesh was generated in layers such that each layer could be assigned a distinct material property and mechanistic constitutive behavior. The material of each layer was treated as linear isotropic and the innermost layer was made several orders of magnitude stiffer than all the other layers to simulate the rigid behavior of the bone**.** Two models with 8-noded isoparametric elements were generated and the number of nodes in the two models were 8500 and 30,000 respectively. The typical diameter of the monkey fingertips was approximately 9 mm and element size in the region of contact with indenters was approximately 500 microns and 160 microns for the two models respectively.

In subsequent work, the exterior of the 3D model has been fit with spline curves and meshed again in order to smooth surface irregularities and impose bilateral symmetry. Material properties of the soft tissues are now being calibrated so that predictions of the model match reaction forces measured in monkey finger pads indented with line loads.

Encoding and Decoding of Shape during Static Tactile Sensing
The model described above was used to simulate static indentation of the fingertip by rigid objects of different shapes such as cylinders rectangular bars, and sinusoidal step shapes. The large number of computations necessary to achieve a high spatial resolution and realism in the simulations required the use of a supercomputer (Cray C90). The results show that contact mechanics is important in governing the pressure distribution on the skin surface, which, in fact, is the stimulus unique to each shape. This surface pressure distribution within contact regions was found to be highly dependent on the curvature of the object that indented the finger. Further, we have shown that a simple equation is able to predict the surface pressure as a function of the indenting object's curvature and the local depth of indentation. To study the mechanism of

transduction by the mechanoreceptors (transformation of the mechanical stress state into neural signals), 21 mechanical measures were obtained from the calculated stress and strain tensor at mechanoreceptor locations, and were matched with experimentally recorded neural response data. Three quantities - maximum compressive strain, maximum tensile strain and strain energy density - were found to be related to the neural responses of SA-I nerve fibers through a simple scaling-threshold model and are thus possible *relevant stimuli* for SA-I afferents. Among these, strain energy density is more likely to be the relevant stimulus 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 the loads imposed on the skin.

To identify the object contacting the skin, the CNS should be able to compute surface loads imposed on the skin from the peripheral neural response. To simulate this inverse problem of decoding, a nonlinear shift-invariant system, which treats the surface pressure as input and neural responses as output, was developed. Because of the nonlinearity (the relevant stimulus measures, such as the strain energy density, are nonlinear functions of the Cartesian stress-strain components), a simple inverse transformation cannot be applied. A signal estimation technique using the university method used in non-linear optimization techniques was employed to decode the surface pressure function from the neural response function. The decoding was demonstrated to be valid for both the ideal case where no sensor noise is present as well as the case where the sensor noise (assumed to be additive Gaussian) is present, as long as the signal-to-noise ratio is greater than 20 dB. This result shows a method by which the central nervous system could infer the shape of the object contacting the skin from SAI population response under static conditions.

Modeling the Dynamics of the Primate Fingerpad

The previous section describes our fingertip models that are able to explain and predict both biomechanical and neurophysiological phenomenon observed in experiments with static stimuli. Encouraged by this success, we have now begun to model the dynamic behavior of the fingerpad in order to realistically simulate the neurophysiological experiments involving dynamic stimuli, such as under stroking of shapes. We have now incorporated viscoelasticity into our computational models of the primate fingertip. To this end, the biomechanical data obtained from the indentation of the fingerpads of several human subjects using different indentor geometries was used. A consistent normalization scheme was developed which showed that most of the variation in the data obtained across subjects was scalable by a single parameter. This lead to the development of a second order Kelvin model which satisfactorily explains much of the observed force-displacement data for a truncated conical indentor. The Correspondence Principle was invoked to extend these results to obtain the material parameters of a generalized 3D linear viscoelastic continuum. These parameters were then incorporated into a 2D plane strain and a 3D layered finite element model. The results obtained from these computational models predict the observed force-displacement data very well for all the indenters (truncated conical, cylindrical and flat-plate indenters) used in the earlier biomechanical experiments. These models are now being used to simulate dynamic stimuli imposed on the fingerpad, such as stroking of shapes in order to understand the role of mechanoreceptors during haptic exploration. Neurophysiological recordings from slowly adapting (SA) and rapidly adapting (RA) mechanoreceptors have been made for a variety of shapes, both statically indented and dynamically stroked across the fingerpad. Previous biomechanics research has been to determine the mechanics underlying the role of SAs during static indentation. Mechanical cues have been determined which relate curvature to impulse response of the receptor. The purpose of the current investigation is to determine the mechanical response of both SAs and RAs during dynamic stroking, and to develop a unifying model of the role of each mechanoreceptor in touch sensation.

Skin Dynamics in the Tactile Encoding of Shape using a Realistic 2D Finite Element Model
Using previously obtained MRI images of the human finger, we created a multilayered finite element model that accurately represented the internal and external geometry of the human fingerpad. By matching model predictions with biomechanical experimental data, the viscoelastic parameters for each skin layer were estimated and the biomechanical behavior of the model was validated. Figure 2 compares the finite element analysis results of a 1/16 inch rectangular bar indenting the finger to the actual finger deformation obtained from MRI imaging. To simulate the mechanics of touch, surfaces of different curvatures were indented into the finger model, and the contact force was held constant until steady state conditions were reached. In addition, a surface of alternating convex and concave segments, each with a different curvature, was stroked across the finger at various velocities. The results from the simulation studies were compared with previously obtained neurophysiological data from the corresponding experiments.

The principal findings are as follows. (1) Under both indentation and stroking of shaped objects, the contact pressure across the fingerpad is the primary mechanical stimulus, and it is found to be directly proportional to the object curvature. (2) The use of a layered model, as opposed to a homogeneous model, has a profound effect on the shape of the contact pressure distribution across the skin surface. (3) The strain energy at depths below the skin surface can be predicted from a convolution sum of the contact pressure distribution. (4) A linear combination of the strain energy and the strain energy rate at typical mechanoreceptor locations can reasonably predict the SA-I neural response during both indentation and stroking experiments.

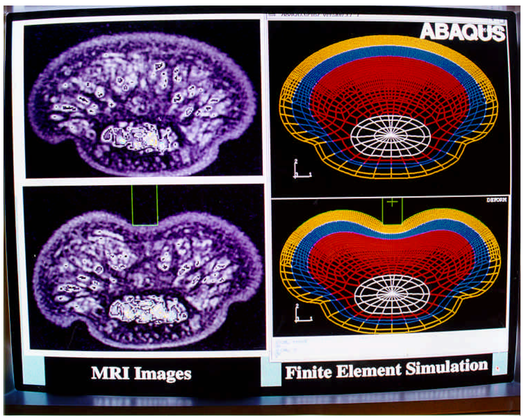

Figure 3.1-2. MRI data compared with finite element simulations. The images show the results for the undeformed human fingertip cross-section and its deformation under a 1/16 inch rectangular bar indenting the fingertip to a depth of 2 mm.

The method of finite spheres: a meshless computational technique for biomechanical simulations
We have used the finite element method extensively to model the fingerpad and analyze the stress/strain fields at the mechanoreceptor level. Both two-dimensional and three-dimensional models have been developed and analyzed using the finite element software package ABAQUS. Even though the finite element method is a robust numerical technique to solve elastostatic (e.g. indentation) and elastodynamic (e.g. stroking) problems, considerable amount of time and energy is devoted to the development of the finite element mesh. Moreover, once a particular model has been developed, it is extremely time consuming to modify it. To overcome these problems we have developed a novel computational technique, the method of finite spheres, which does not require a background mesh for discretization. This technique is very similar to the finite element method and is equally robust, but uses a set of nodes sprinkled on the computational domain to develop the discrete set of linear algebraic equations. We have successfully tested the method on several example problems.

Theory

Nonlinear Dynamics of Mechanoreceptor Response
One of the most interesting aspects of dynamic tactile sensing in humans is the nature of mechanoreceptor response to dynamic stimuli. In contrast to the response of the fingerpad tissue, the receptors seem to exhibit nonlinear behavior even for very small indentations of the fingerpad skin.

The most classic example of such nonlinear response is the so called "tuning curves" which are nothing but the variations of dead-zone and saturation thresholds as functions of frequency of input sinusoids. In order to model these nonlinearities, a generalized class of cascaded LNL-type filter banks were developed. Such models, in general, incorporate a linear describing function block followed by a static nonlinearity and another linear describing function block. It was observed that different receptor classes could be described by specializing this general model. For instance, the behavior of the SAI mechanoreceptors could be explained very well using a Hammerstein type of structure (a static nonlinearity followed by a linear dynamic block). These models provided good fits to the empirically recorded mechanoreceptor responses. The next step appears to be a successful link between the finite element model describing the geometric and material properties of the fingerpad and the neuro-dynamic transduction blocks, describing receptor behavior for each class of receptors. We are now in a position to predict the spatial response profiles observed during the stroking of complex shapes (toroids, wavy surfaces and sinusoidal step shapes) on primate fingerpads.

Identification and Control of Haptic Systems: A Computational Theory

This research provides a theoretical framework for haptics, the study of exploration and manipulation using hands. In both human and robotic research, an understanding of the nature of contact, grasp, exploration, and manipulation is of singular importance. In human haptics the objective is to understand the mechanics of hand actions, sensory information processing, and motor control. While robots have lagged behind their human counterparts in dexterity, recent technological developments have made it possible to build tactile sensor arrays that mimic human performance. We believe that a computational theory of haptics that investigates what kind of sensory information is necessary and how it has to be processed is beneficial to both human and robotic research.

Human and robot tactile sensing can be accomplished by arrays of mechanosensors embedded in a deformable medium. When an object comes in contact with the surface of the medium information about the shape of the surface of the medium and the force distribution on the surface is encoded in the sensor signals. The problem for the central processor is to reliably and efficiently infer the object properties and the contact state from these signals. We first investigated the surface signal identification problem: the processing of sensor signals resulting in algorithms and guidelines for sensor design that give optimal estimates of the loading and displacement distributions on the surface of the fingerpad. We have shown that three quantities, mean normal stress and the two shear strains at mechanosensor locations, are not only necessary and sufficient to infer the surface signals, but also maximize the spatial bandwidth of signal reconstruction. We then focused on how the information obtained from such optimal sensing can be used for exploration of objects. We have shown that an accurate reconstruction of object properties can occur using two basic building blocks of Exploration Strategy and Finger Control. Exploration Strategy pertains to the problem of inferring object properties such as shape, texture and compliance, and interference properties such as state of contact, from the estimated surface signals. This involves determining, in each case, what kind of sensor information and what kind of action is needed. Finger Control refers to the transformation of the action needed into a command trajectory for the fingerpad, which defines the desired direction of movement for manipulation. We have defined and analyzed the components of both these blocks, provided explicit mathematical formulation, and have solved numerical examples where appropriate. Our formulation of this computational theory of haptics is independent of implementation so that it is applicable to both robots and humans.

Device Design and Construction

Ultrasound Backscatter Microscope for In Vivo Imaging of Human Fingertip
One of the conclusions of our earlier MRI studies was that if a noninvasive imaging system with higher resolutions than MRI could be designed, it would be a powerful tool to observe deformations of the skin tissue around mechanoreceptors and would help validate our computational models. We have now developed an Ultrasound Backscatter Microscope (UBM), which is able to display the geometry and deformation of skin layers *in vivo*. UBM is similar to B-mode diagnostic ultrasound imaging, but uses higher frequency acoustic waves (about 50 MHz) to achieve resolutions of the order of tens of microns. In UBM, contrast depends on the mechanical properties of tissues, a feature that complements techniques such as optical microscopy, CT and MRI that rely on other tissue properties. This feature also makes UBM ideal for studying the mechanistic basis of tactile sensing. In addition, UBM is less expensive than most imaging techniques, and is also noninvasive. However, because of increased attenuation of the acoustic waves at higher frequencies, the tissues being imaged must be located within a few millimeters of the surface. A UBM system was designed and built using a high frequency PVDF transducer (nominal frequency of 75 MHz), a pulser, a digitizing oscilloscope, a scanning system and the IEEE488 interface.

The device was used to image the internal structure of the human fingertip skin *in vivo* (Figure 3). At each skin location, the transducer was energized and echoes from tissues at different depths were recorded. By mechanically scanning the transducer across the fingerpad surface and keeping track of signals from successive lateral locations, data on mechanical contrast in skin cross sections were assembled. Signal processing was done on the echoes to obtain 2-D images. Images of fingerpad skin of six human subjects showed three distinct layers up to a depth of about 1.2mm. Comparison images of fingertip skin on the dorsal side also showed a layered structure, with lesser thickness for the first two layers. The data obtained are consistent with known anatomical information that the three layers imaged are the stratum corneum, the rest of the epidermis, and the top region of the dermis.

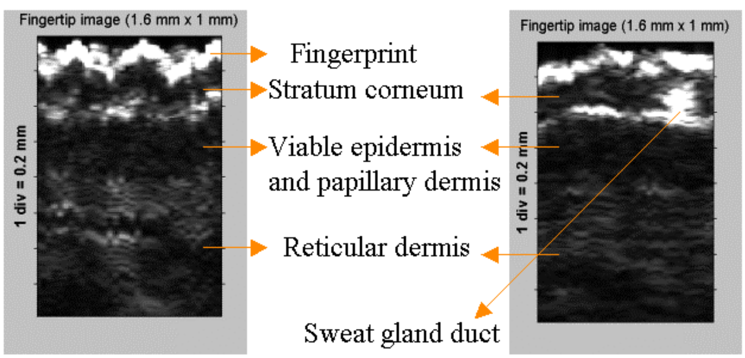

Figure 3.1-3. Two images from the ultrasound backscatter microscope. In the left image the scan direction was across the finger ridges and it is possible to identify the ridges on the surface and layers within the skin. In the right image, the scan is along the ridges and it is possible to identify even features such as a sweat gland duct within the stratum corneum.

We had previously developed an ultrasound backscatter microscope system that employed high frequency ultrasonic waves (50 MHz) for obtaining high-resolution images of the human fingertip. We are currently extending the research to clinical applications such as skin cancer detection and staging. The main focus of this work is the development of physically based algorithms for characterizing normal tissues and skin lesions. Unlike conventional image processing algorithms that act only on the final images produced by the ultrasound device, these algorithms will exploit the physics of interaction of acoustic waves with skin tissues. As a first step, over the past year,

we obtained in vivo attenuation and backscatter coefficients of normal human forearm dermis and subcutaneous fat from about 40 volunteers. Data were collected using three different transducers to ensure that results were independent of the measurement system. Attenuation coefficient was obtained by computing spectral slopes vs. depth, with the transducers axially translated to minimize diffraction effects. Backscatter coefficient was obtained by compensating recorded backscatter spectra for system dependent effects, and additionally for one transducer, using the reference phantom technique. Good agreement was seen between the computed attenuation and backscatter results from the different transducers/methods. The attenuation coefficient of the forearm dermis was well described by a linear dependence with a slope that ranged between 0.08 to 0.39 (median=0.21) dB/mm/MHz. The backscatter coefficient of the dermis was generally in the range 10^{-3} to 10^{-1} Sr^{-1} mm^{-1} and showed an increasing trend with frequency. No significant differences in attenuation coefficient slope between the forearm dermis and fat were noted. Within the range 14-34 MHz, the ratio of integrated (average) backscatter of dermis to that of fat ranged from 1.03 to 87.1 (median=6.45), indicating significantly higher backscatter for dermis than for fat. Data were also recorded at the fingertip where the attenuation coefficient slope of the dermis was seen to be higher than that at the forearm.
Current work in this area is in three directions: (1) Further analysis of backscattered signals from skin tissues in terms of additional parameters such as echo statistics (2) Upgrading the ultrasound system to a fast-scan system that reduces acquisition time by an order of magnitude and (3) Collection of data from patients with suspected skin lesions and comparison with normal skin tissue parameters. [Work also partly supported by a Grant-in-Aid of research from the national Academy of Sciences through Sigma Xi].

3.2 Tactile Displays Realized Using MEMS Actuator Arrays

Sponsor
Defense Advanced Research Projects Agency - Grant N00019-98-K-0187

Project Staff
Mandayam A. Srinivasan (PI), S. James Biggs, Andrew R. Brughera, Lorraine A. Delhorne, Tim T. Diller, Nathaniel I. Durlach, Dennis M. Freeman, Kaigham J. Gabriel[5], Tuyet-Trinh T. Phan, Charlotte M. Reed, David W. Schloerb

Introduction

The purpose of this project is to develop new tactile interfaces that capitalize on advances in MicroElectroMechanical Systems (MEMS) technology to create high-bandwidth displays for stimulating the user's tactile sense. Such devices may also receive manual or other types of pressure/contact input. We envision two major classes of applications: (1) Tactile interfaces mounted on machines could indicate the state of the machine--such as the remaining charge in a battery--or it might respond to the operator's touch in subtle ways not possible with conventional controls, (2) Tactile interfaces attached to the human body--for example, through a glove or wrist band--could be used with wearable computers or communication devices for both input and output.

The project is a collaboration between the MIT Touch Lab at RLE and Prof. Kaigham J. Gabriel at the MEMS Laboratory at Carnegie Mellon University (CMU). To date, the work at MIT has consisted of experimental studies of biomechanics and tactile perception. This work is intended to guide the design of tactile interfaces and it will also advance the science of human haptics. The

[5] Department of Electrical & Computer Engineering, Robotics Institute, Carnegie Mellon University.

group at CMU is developing the MEMS stimulators and sensors that will be incorporated in future prototype interfaces. Following are summaries of the work accomplished in each task area.

Characterization of Human Skin and Tissue Impedance

The goal of this part of the project is to measure and characterize the mechanical impedance of human skin at various body sites. This involves *in vivo* measurements of the force response to mechanical displacement of the skin. The measurements are made using the Skin Dynamics Test Apparatus (SDTA) that we have developed. The SDTA uses an Aurora Scientific Inc. Dual-Mode Lever Arm System that is controlled by a PC via an A/D card. The apparatus continuously samples both the position and the resulting force on a flat-ended 0.5 mm diameter probe as it is first pressed against the skin and then displaced sinusoidally about the mean pre-indentation depth. The resulting biomechanical data will be useful in the development of tactile displays.

To date, sinusoidal vibration stimuli have been applied with the probe either glued or not glued to the skin. Both normal and tangential stimlui were applied to the skin surface in the glued case and only normal stimuli were applied in the non-glued case. The stimuli were applied to live human subjects at four body sites: the finger pad, wrist, forearm, and forehead. The force-displacement response was measured and used to calculate mechanical impedance, power absorption and duty factor (an estimate of the fraction of time that the stimulator is in contact with the skin).

Results showed the mechanical impedance generally increasing in magnitude with frequency and higher in magnitude for tangential stimulation than for normal stimulation. Power absorption linearly increased with frequency, and duty factor decreased with increasing frequency and amplitude. The measured properties varied widely between body sites and subjects.

A mathematical model previously developed to calculate bulk and shear moduli from normal and tangential impedance data was tested against data at the four body sites. However, because the model assumed isotropy and semi-infinite thickness of the stimulated tissue, data taken did not fit the model well, especially at the finger tip.

Tactile Perception

Perceptual Resolution Measurements
The goal of this part of the project is to determine the limits of perceptual resolution for various kinds of vibratory tactile stimulation at various body sites. The measurements are made using apparatus that is similar to that used for the skin biomechanics experiments (i.e., the SDTA). The Tactile Perception Test Apparatus (TPTA) will ultimately include two Aurora-Scientific-based tactile stimulators and it will incorporate a 5-axis micro-positioning assembly (x, y, z, theta, and stimulator separation). Under computer control, the motorized micro-positioning assembly will be able to continuously adjust the position of the two stimulators over the course of hundreds of successive experimental trials.

The TPTA is still under construction, but as an interim measure we have used the SDTA to make some one-point threshold measurements. To date, detection threshold measurements have been made at three body sites (finger, wrist, and forearm) on three adult subjects (a fourth subject took part in the finger tests) for sinusoidal stimulation at eight frequencies in the range of 2 to 256 Hz. Thresholds were estimated using a two-interval forced-choice adaptive-level procedure with trial-by-trial correct-answer feedback. Each run began with the stimulus level set well above threshold. Presentation level was changed following two correct responses (resulting in a decrease in stimulus level) or one incorrect response (resulting in an increase in stimulus level). The step size was set initially to 4 dB but was changed to 2 dB after the first reversal. A run was terminated after 8 reversals in level and the threshold for that run was calculated by averaging across the levels of the final 6 reversals. The two observation intervals were 500 msec in duration and were separated by 200 msec. Visual cueing of the observation intervals was provided on a computer terminal. The tactual stimulus was presented in one of the two observation intervals, selected at random on each trial. Data were collected in 8-run blocks with random ordering of the 8 frequencies within each block. Five blocks of data were collected on each of the subjects, leading to five threshold estimates at each of the 8 frequencies (2, 4, 8, 16, 32, 64, 128, and 256 Hz).

Reliable threshold estimates were obtained that appear to be consistent with other measurements reported in the literature. Unfortunately, some measurements at the higher frequencies were limited by the resolution of the apparatus. The principal innovation of this work is that we were able to measure the reaction force of the skin and calculate the mechanical power transmitted into the tissue at threshold. We plan to publish this data in the near future.

Surface treatments to increase the perceived vibration of a piezoelectric foil
Piezoelectric polyvinylidene fluoride (PVDF) film is a semi crystalline homopolymer. When the foil is stretched the dipoles and their attached crystalline structure move -- changing the polarization of charge at the foil surfaces, thus changing the voltage across the metallized electrodes. Conversely when a voltage is applied across the electrodes the foil changes dimensions. This investigation sought surface modifications that increased subject˙s perceptions of vibration when they touched the foil with the right fingertip. Eight modifications, and the foil alone, were tested on five human subjects. The subjects were asked to adjust the vibration amplitude of a small speaker to match the perceived vibration amplitude of each PVDF sample as it was driven with a sinusoidal voltage (250 Hz, 240 Vpp). The adjusted RMS voltage of the speaker was taken to be a gage of the intensity of subject˙s perception. Six of the surface modifications worked better than the unmodified foil with statistical significance ($p<0.05$, one tailed t-test, df=8), with the three most successful increasing perceived intensity by 10-12 dB. All the successful surface treatments incorporated a stiff mylar lamination that converted the tangential stretch of the PVDF into normal vibration that tapped (rather than stroked) the finger.

This study showed that surface treatments can increase perceived vibration, and warrant further work. In particular, laminated PVDF foil with surface modification showed promise. In future work, we propose to imbed many small beams into the mylar lamination. The beams will be fixed at one end to the PVDF foil, leaving the other end free to vibrate at a resonant frequency of 250Hz.

Development of MEMS Tactile Stimulators and Sensors

The goal of this part of the project is to develop the MEMS stimulators and sensors that may be incorporated into tactile interfaces. Initial work has focused on the development of a single stimulator or actuator that consists of two gas- or fluid-filled chambers as shown in Figure 3.2-1. The chambers are covered and sealed by a common membrane such that when the membrane covering the outer chamber is displaced by electrostatic force, the membrane covering the inner chamber is also displaced (a greater distance) by the movement of the fluid.

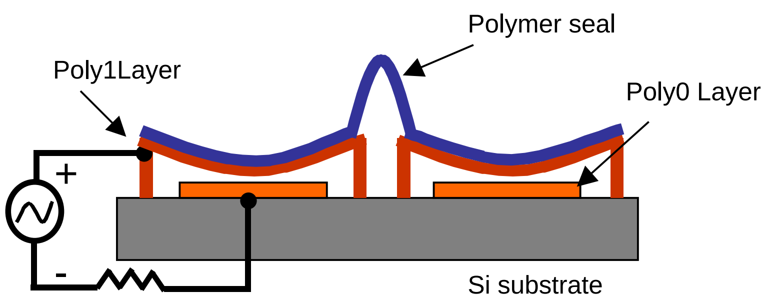

Figure 3.2-1. Surface Micro-machined Actuator with Polysilicon Membrane.

During the last year, fabrication was completed on the 1 cm x 1 cm "test taxel chip" which contains 25 taxels on its surface. Characterization of the electrical and mechanical properties of the chip was initiated. See the discussion of "Tactile Displays Using MEMS Actuator Arrays" on the web site of the CMU Microelectromechanical Systems Laboratory for further details (http://www.ece.cmu.edu/~mems/projects/index.shtml).

3.3 Cortical Control of Robot Manipulators

Project Staff
Mandayam A. Srinivasan, S. James Biggs, Jung Kim, Miguel A. L. Nicolelis[6]

The MIT Touch Lab has begun collaboration with the Laboratory for Neural Ensemble Physiology at Duke University directed by Prof. Nicolelis. The Nicolelis lab has developed a system that continuously estimates hand position based on signals recorded from neurons in motor areas of the cortex of behaving primates. The Touch Lab has developed software that uses these signals to control a robot manipulator (Phantom, Sensable Technologies) in real time. Accurate, real-time predictions of one and three dimensional arm movement trajectories have been demonstrated in two monkeys at Duke. In addition, cortically derived signals were successfully used for real-time control a robot manipulator locally at Duke and remotely at MIT via the Internet (Wessberg et al. 2000.).

3.4 Role of Haptics in Human-Computer Interactions

Sponsor
Defense Advanced Research Projects Agency - Grant DAAD17-99-C-0060

Project Staff
Mandayam A. Srinivasan (PI), W. L. Sachtler, Jung Kim, Misty Pendexter, Ashok Sivakumar, Nattavude Thirathon

We have used the upgraded Virtual Workbench for a number of investigations of human sensorimotor processing, with focus on Human-Computer Interaction. One set of experiments was devoted to characterizing the role of contact forces during manual interaction with a surface through a tool. We found that forces tangential to a surface, applied to the tip of the tool on contact, systematically bias the perception of the orientation of the surface in space. Previous work had shown that changes in the normal force can be used to simulate smooth bumps and indentations in a flat surface. The mapping of tangential force to change in perceived surface orientation may have applications for algorithms to simulate three-dimensional haptic features with two-dimensional force-feedback devices.

In another set of experiments we are exploring the role of force feedback in input control in virtual environments in a manual optimization task. Subjects use sets of sliders to control a set of bar graphs, with the aim of setting them to equal heights. Graphs are driven by a set of linked linear equations controlled by multiple sliders. We are comparing performance with different sets of sliders: simple one-dimensional sliders; sliders that can move in a plane and control two parameters simultaneously, and sliders that can move in three dimensions.

In a third project, we are testing the performance in a 3D Fitts' task using targets of various consistencies: simulating solid objects in a VE requires costly equipment, and soft or visco-

[6] Duke University Department of Neurobiology

elastic objects could be rendered on devices of lower cost, which may serve to improve interaction in 3D simulated environments.

3.5 Laparoscopic surgical simulation using visual and haptic feedback

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Massachusetts General Hospital

Project Staff
Mandayam A. Srinivasan (PI), Suvranu De, Jung Kim, Hyun Kim and Boon Tay

With increase in computational power and the availability of interface devices, there has been considerable excitement about the possibility of developing a surgical simulator to train physicians much like the use of flight simulators to train pilots. In order for such a simulator to be realistic, it should provide multisensory interaction capabilities and real time. We have started work on developing a simulator for laparoscopic surgical procedures where the user can interact with three-dimensional models of internal organs using visual as well as tactile sensory modalities. For real time visual display an update rate of 30Hz is sufficient. For haptic display, we use the Phantom haptic interface device. For stable simulation, the haptic loop requires an update rate of about 1 kHz. This imposes severe restrictions on the complexity of the models that can be rendered haptically.

We have developed rapid collision detection algorithms based on hierarchical bounding boxes. For physically based real time response prediction of soft tissues, we have developed a specialized version of the method of finite spheres (a meshless numerical technique developed in our lab). In this technique nodal points are sprinkled around the surgical tool tip (not the entire domain) and the interpolation is performed using compactly supported functions on spheres surrounding the nodes. A point collocation technique is used to generate the discrete set of equations that are solved in real time. The localization provided by the finite influence zones of the nodes and the elimination of numerical integration results in a highly accelerated numerical procedure. The flexibility in the placement of the nodes allows complex operations like surgical cutting to be performed easily.

4.1 Virtual Environment Technology for Training

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Project Staff
Mandayam A. Srinivasan (PI), S. James Biggs, Alberto J. Cividanes, Lorraine A. Delhorne, Nathaniel I. Durlach, Chih-Hao Ho, Misty Pendexter, Wendelin L. Sachtler, Steve Wang, Thomas E.V. Wiegand, Wan-Chen Wu, Han-Feng Yuan

Introduction

This work is being conducted within Virtual Environment Technology for Training (VETT), a large inter-disciplinary, inter-institutional program which is studying the use of virtual environment (VE) technology to improve Navy training. At RLE, two mutually supporting components of this program are being pursued: (1) Enabling Research on the Human Operator (ERHO) and (2) Development of haptic interfaces and multimodal virtual environments. The ERHO component is concerned with how human perception and performance in virtual environments (VEs) depend upon (1) the physical characteristics of the VE system, (2) the task being performed, and (3) the user's experience with the system and the task. To the extent that the ERHO research is successful, the results will not only provide important information for the design and evaluation of VE training systems, but also for VE systems in general. The second component is focussed on the development of haptic interfaces that enable the user to touch, feel and manipulate objects in VEs. Software is being developed to generate haptic stimuli and to integrate visual, auditory, and haptic displays. Experiments on multimodal illusions due to interactions between haptic and visual or auditory displays have also been conducted.

Over the past year, we have upgraded the hardware for several of our VE systems, developed new software for graphical and haptic rendering, and conducted several suites of experiments for gaining insight on human operator's perception and performance in VEs. Our progress is described in the following subsections.

Visual Perception in VEs

Background in this area is available in RLE Annual Report 141, pp 337-338 (also see V. Wiegand et al, 1999). During the past year, attention in this area has been focused on further data analysis and the preparation of results for publication. A paper was published on our Motion Parallax research in the journal Presence during this reporting period (Yuan et al, 2000). This work is concerned with the degradations that occur on lead-motion-parallax depth perception when there are time delays between head movements and image displays. The paper completely describes the experiment, data analysis, and results of the past year. A second paper was submitted to the journal Perception and Psychophysics in January of 2001 (Schloerb and Durlach) related to our work on enhanced stereoscopic depth perception in VEs. This work studied the effects of expanded (supernormal) interocular distances.

Part-Tasks Trainer for Position-Velocity Transformations

Experiments in the area of Naval Part Task Trainers have been completed. The PC-based part-task trainer for training individuals to rapidly and accurately estimate relative motion from information on absolute motion (and vice versa) was used to collect data on 22 subjects. Learning curves were measured for a variety of tasks and instructional formats. Both response time and accuracy of response were measured for all tests. We are in the process of analyzing the data and writing a report.

Conveying the Touch and Feel of Virtual Objects

Haptic displays are emerging as effective interaction aids for improving the realism of virtual worlds. Being able to touch, feel, and manipulate objects in virtual environments have a large number of exciting applications. The underlying technology, both in terms of electromechanical hardware and computer software, is becoming mature and has opened up novel and interesting research areas. The following sections summarize the progress over the past few years in our "Touch Lab" at RLE. A major advance has been the birth of a new discipline, Computer Haptics (analogous to computer graphics), that is concerned with the techniques and processes associated with generating and displaying haptic stimuli to the human user.

Over the past few years, we have developed device hardware, interaction software and psychophysical experiments pertaining to haptic interactions with virtual environments (recent reviews on haptic interfaces can be found in Srinivasan, 1995 and Srinivasan and Basdogan, 1997). Two major devices for performing psychophysical experiments, the linear and planar graspers, have been developed. The linear grasper is capable of simulating fundamental mechanical properties of objects such as compliance, viscosity and mass during haptic interactions along a linear track. Virtual walls and corners were simulated using the planar grasper, in addition to the simulation of two springs within its workspace. The Phantom, another haptic display device developed previously by Dr. Salisbury's group at the MIT Artificial Intelligence Laboratory (now available commercially from SensAble Technologies, Inc.), has been used to prototype a wide range of force-based haptic display primitives. A variety of haptic rendering algorithms for displaying the shape, compliance, texture, and friction of solid surfaces have been implemented on the Phantom. All the three devices have been used to perform psychophysical experiments aimed at characterizing the sensorimotor abilities of the human user and the effectiveness of computationally efficient rendering algorithms in conveying the desired object properties to the human user. See last year's report for further discussion of our prior work in this area (RLE Progress Report 142, Chapter 23, VETT, Sections 5-9).

Haptic Rendering and Constructing Multimodal VEs

Haptic rendering, a relatively new area of research, is concerned with real-time display of the touch and feel of virtual objects to a human operator through a force reflecting device. It can be considered as a sub-discipline of Computer Haptics. We have developed both point and ray-based techinques for detecting collisions with virtual objects (Ho et al. 1999; Ho et al. 2000). We have also experimented with multi-threading (on a Windows NT platform) and multi-processing (on a UNIX platform) techniques and have successfully separated the visual and haptic servo loops in order to develop effective software architectures for multimodal VEs. Our experience is that both techniques enable the system to update graphics process at almost constant rates, while running the haptic process in the background. We are able to achieve good visual rendering rates (30 to 60 Hz), high haptic rendering rates (more than 1 kHz), and stable haptic interactions. All of the this work is described in a doctoral dissertation completed during the last year (Ho 2000)

Mass-Damping-Compliance Experiments

Using a one dimensional force-feedback interface (the "Linear Grasper") we are conducting a series of experiments designed to examine a subject's ability to discriminate between viscous, inertial, and spring forces. In these experiments we plan to evaluate a model which addresses the perception of these three physical qualities in terms of work (i.e., force times distance) performed. Refurbishment of the Linear Grasper haptic interface has been completed. Software to simulate a physical mass-spring-damper system, control the progress of two-alternative forced-choice experiments, and record the time-course of force inputs and end-effector position has been completed. We are currently running subjects and have begun to analyze the resulting data.

Force-Torque Experiments

An experimental study was performed to determine the role of torque feedback in haptic perception of object location within virtual environments (Wang 2001). The experimental setup consisted of two Phantom haptic interfaces connected by a common stylus and a ray-based rendering technique for modeling the interactions between the user-controlled stylus and the virtual environment. Subjects were asked to identify 7 locations of a virtual object under various force display conditions, which ranged from force feedback only at the stylus tip to accurate force and torque feedback. Subjects' ability to determine the location of a real object was also examined in order to establish the effectiveness of the hardware and software utilized in the study. In order to obtain their best performance, subjects were trained in each case with correct-answer feedback.

Results indicate that the most significant improvement in perception occurred during the first training session. The accuracy of subjects' haptic perception of virtual object location was the same as the perception of real object position when full force and torque feedback were provided, thus validating the realism of the simulated haptic environment. Estimated percentage JND for these conditions, ranged from approximately 20% for the nearest objects to 12% for the farthest objects. The information transmitted (IT) for these conditions were also the same, at approximately 1 bit (out of a maximum of 2.81 bits). When subjects probed the virtual object by rocking against it, thus freely changing the orientation of the rod, even with forces reflected only at the front tip of the stylus, performance was the same as when true force and torque feedback were provided. However, when subjects were permitted only to tap the probe against the object, thereby limiting the motions and orientations of the rod, providing force feedback only at the tip of the stylus resulted in poor identification of object location. In this case, percentage JND ranged from 37% to 27%, while IT was .17 bits. Torque feedback and object contact with multiple probe orientations, then, provide equivalent haptic information in terms of determining object position. Denying both results in inaccurate haptic perception of object distance.

Visual-Haptic Experiments
Psychophysical experiments were conducted in order to determine the impact of manipulated visual information and 3-D perspective on the haptic perception of stiffness in virtual environments (Cividanes 2000; also see Wu et. al. 1999). The Phantom force-reflecting haptic interface and a computer monitor were utilized to run experiments on the human discrimination of stiffness of two virtual springs. Ten subjects were asked to use the Phantom to compress two virtual springs sequentally and feel the corresponding displacement and forces through their hand, while they observed the visual deformation of the springs on a computer monitor. The subjects were asked to judge which spring was softer. Without the knowledge of the subjects, the visually presented deformation of each spring was manipulated systematically across experimental trials so that its relationship to the haptic stiffness of the spring was varied. Experiments were run on two different placement configurations of the springs. When the springs were placed side by side, only the effect of this manipulated visual information was studied. In a second configuration where the springs were placed one in front of the]other, the effect of 3-D perspective was added as another factor. Results show that for both configurations, the percentage of correct responses decreased dramatically as the visual]scaling parameter increased, demonstrating a visual-haptic illusion in stiffness perception. This suggests that visual information has a clear dominance over the kinesthetic hand position information in the discrimination of stiffness in this type of virtual environments. Thus, a proper combination of manipulated visual information and 3-D perspective can be used to enhance the range of haptic experience in multimodal virtual environments. Both the deliberately incorporated visual illusions and the ones created by 3-D perspective can be exploited in order to compensate for the limitations that current haptic interfaces have.

Virtual Workbench

The Virtual Workbench has been fitted with faster processors and a commercial haptics-rendering software package to facilitate development of new experiments. This streamlined system is being used to study: a) the importance of physical object manipulation for learning spatial relations among parts (as during assembly of complex mechanical devices); b) the ways in which haptic and visual representations of objects in space interact to form a more stable percept of the external world or to deal with discordant information; c) the processes by which spatio-temporal sampling and integration of haptic scans lead to elemental perception of surfaces.

Shared Multimodal VEs

Investigating virtual environments has become an increasingly interesting research topic for engineers, computer and cognitive scientists, and psychologists. Although there have been several recent studies focused on the development of multimodal virtual environments (VEs) to study human-machine interactions, less attention has been paid to human-human and human-machine interactions in shared virtual environments (SVEs), and to our knowledge, no attention paid at all to what extent the addition of haptic communication between people would contribute to the shared experience. We have developed a multimodal shared virtual environment and performed a set of experiments 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 (Basdogan et al. 2000). The study concerns a scenario where two participants at remote sites must co-operate to perform a joint task in a SVE. The goals of the study are (1) to assess the impact of force feedback on the task performance, (2) to better understand the role of haptic communication in human-human interactions, (3) to study the impact of touch on the subjective sense of collaborating with a human as reported by the participants based on what they could see and feel, and (4) to investigate if gender, personality, or emotional experiences of users can affect the haptic communication in SVEs. The outcomes of this research can have a powerful impact on the development of next generation human-computer interfaces and network protocols that integrate touch and force feedback technology into the Internet, development of protocols and techniques for collaborative teleoperation such as hazardous material removal, space station repair, and remote surgery, and enhancement of virtual environments for performing collaborative tasks in shared virtual worlds on a daily basis such as co-operative teaching, training, planning and design, cybergames, and social gatherings. Our results suggest that haptic feedback significantly improves the task performance and contributes to the feeling of 'sense of togetherness' in SVEs. In addition, the results show that the experience of vision first, and then subsequently vision plus haptic feedback generates a higher performance than presentation of visual plus haptic feedback first followed by visual feedback only.

4.2 Realism in Virtual Environments

Sponsor
Office of Naval Research- Grant N00014-01-1-0197

Project Staff
Nathaniel I. Durlach (PI), Dr. S. James Biggs, Andrew G. Brooks, Dr. Jonathan D. Pfautz, Dr. Mandayam A. Srinivasan, Dr. Thomas E.V. Wiegand

In this project our goal is to determine experimentally how sense of realism, objective task performance, and training transfer, are influenced by the physical characteristics of Virtual Environment training systems, with emphasis on the effects of interaction fidelity. This effort also includes the development of technologies to facilitate these studies, including bodyworn haptic stimulators, physiological-state monitoring equipment, high-accuracy aim tracking, and various audio presentation and interface devices.

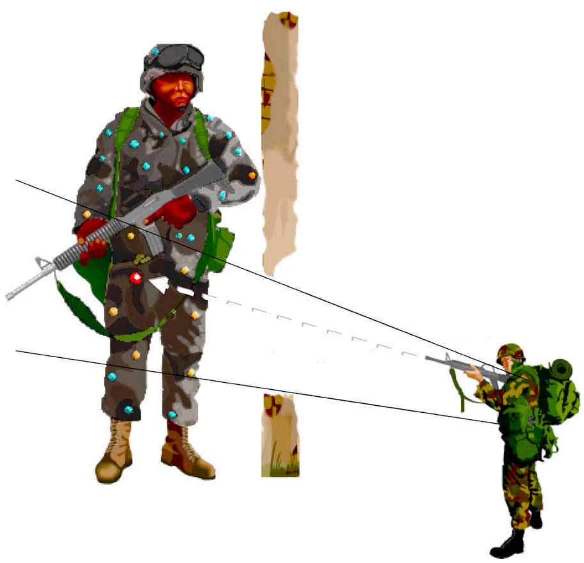

Figure 4.2-1. Depicts envisioned usage of bodyworn haptic stimulatiors in combat simulation. Self-contained pods distributed about the surface of the user signal exposure, contact, and impact, based on their position relative to objects in the virtual world. Signals can be mechanical (e.g., vibration) or electrical (e.g., electrocutaneous stimulation).

Figure 4.2-2. Depicts usage of bodyworn haptic stimulators in context of immersive virtual environment presentation. Weapon is instrumented with infrared laser tracking and wireless communication of trigger state.

4.3 Training Spatial Knowledge Acquisition using Virtual Environments

Sponsor
Office of Naval Research - Grants N00014-96-1-0379 and N00014-01-1-0062

Project Staff
Nathaniel I. Durlach PI, Dr. Thomas E.V. Wiegand, Lorraine A. Delhorne, Andrew G. Brooks, Lauren Bradford, Vitaly Kulikov

Much of our effort during this period has been directed towards further refinement and development of the generic spatial-training simulation incorporating a "World In Miniature" (WIM) navagational aid, and the construction of a photorealistic model of a building at MIT for use in experiments involving this simulation. As part of this development, the entire simulation was rewritten in order to achieve compatibility with simulations in development at other ONR-funded institutions. Several improvements were made to deal with fidelity and operator interface considerations.

Figure 4.3-1. World In Miniature simulation in use with head-mounted display and handheld operator interfaces to control and interact with the display.

The second major focus of our attention has been a program of basic research into cognitive factors that may affect the acquisition of spatial knowledge. Experiments were performed investigating the relationship between imagined translations and imagined rotations, following results reported elsewhere in the literature. These results have implications for the structure of coordinate space in egocentric mental representations.

A white paper, "Virtual Environments and the Enhancement of Spatial Behavior" (Durlach *et al.*, 2000) was published in the journal Presence during this reporting period. This paper outlines a general research and development program in the area of VE-assisted spatial training in collaboration with other researchers outside MIT. A paper detailing the Automated VE Generation System (TOADS) created in previous years of this grant was accepted for publication in Presence and is currently in press.

In addition, with the assistance of undergraduate research assistants, in the last year we began investigating three-dimensional textural enhancements for the Automated VE Generation System, as well as model optimizations for enhanced computational performance on automatically generated virtual models.

5.1 Visual Psychophysics Via Uncontrolled Channels

Sponsor
Children’s Progress Incorporated, NYC

Project Staff
Dr. Thomas E.V. Wiegand PI, Dr. Wendelin L. Sachtler, Dr. Jonathan D. Pfautz

Work to date has focused on the development of techniques for administering tests of visual performance over uncontrolled/uncalibrated channels such as typical computer video monitors. Although a few attempts to perform sensory psychophysics on a broad scale using the world-wide-web have appeared in the literature, these studies have been bound to particular I/O devices or have neglected the effects of the uncontrollable delivery channel. Initial work has been directed towards the development of a color-blindness test, which is programmed to function as a Macromedia Shockwave script and serve as a component of an “automated clinical interview” that will be used in conjunction with a web-based educational evaluation suite.

Many tests of color vision require that colors lie along particular confusion lines in color space. Testing over the internet provides only limited control of monitor calibration, so colors displayed at a remote location may not render as specified. Color deficient observers could pass the test if colors do not fall on a confusion line, so tests need to be particularly robust for Web-based assessment. In addition, both vision and display deficiencies should be detected from the observer's response, though it may not be possible to discriminate between the two.

In the test we have developed, a set of distractor colors is distributed across a region of color space such that the confusion line through a single target color intersects the middle of the set. The distractor set spans a region extending in both chromaticity and luminance, and extends above and below the luminance plane containing the target color. This provides some leeway for display errors since the confusion line will intersect the set even if colors do not render exactly as specified. In this case, color deficient observers would still not be able to identify the target.

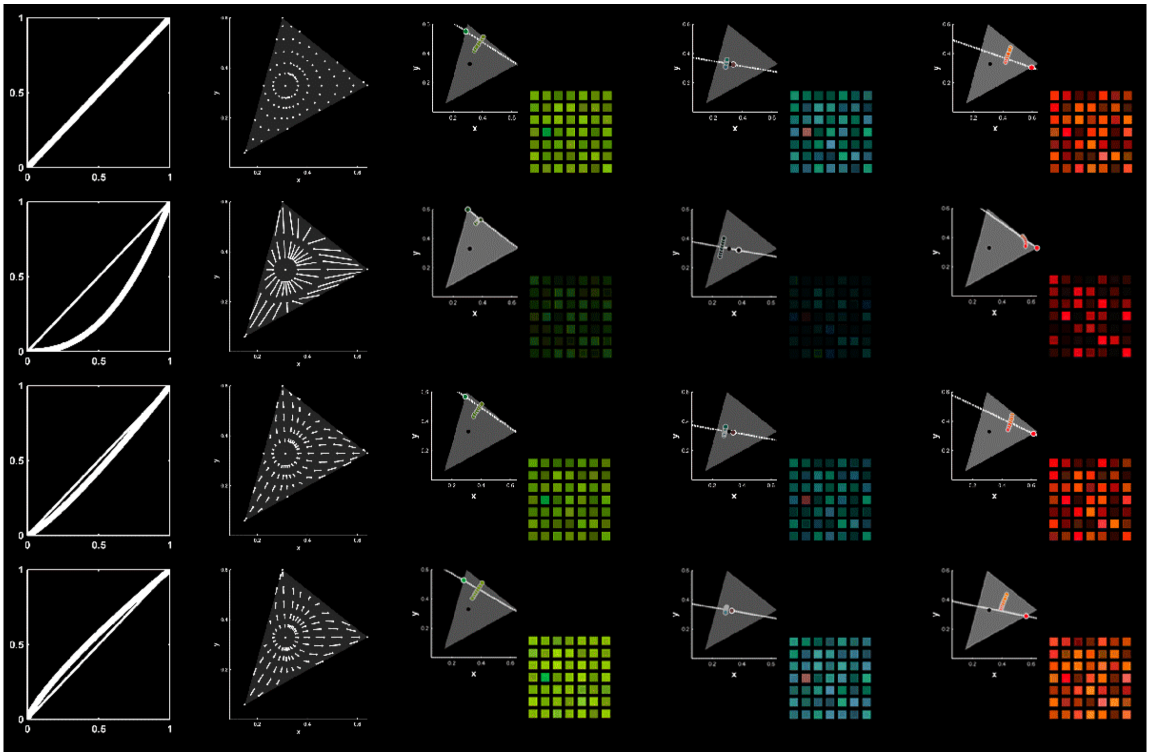

Figure 5.1-1. Effect of CRT display calibration errors on test functionality. Each column shows a different test for protan deficiencies: for any of the color distortions shown on the diagram, the target and distractor set of one of the tests will lie closer together, making identification of the target more difficult. This reduces the likelihood that a color deficient observer would identify the target. Similar principles can be applied to protan and tritan deficiency tests. Rows: (1) gamma = 1.0; (2) gamma = 2.4 (uncorrected); (3) gamma = 1.2 (undercorrected); (4) gamma = 0.8 (overcorrected). Columns, from left to right: (1) CRT gamma curves; (2) color shifts due to gamma distortion (Triangle shows color gamut of CRT monitors); (3) Test 1 for protan deficiencies, placed in green domain of color gamut.; (4) test 2 for protan deficiencies, placed around white point.; (5) test 3 for protan deficiencies, placed in red domain of color gamut.

6.1 Supernormal Listening System

Sponsor

Defense Advanced Research Projects Agency - Grant N00019-98-K-0188

Project Staff

Nathaniel I. Durlach PI, Dr. Thomas E.V. Wiegand, Dr. Joseph G. Desloge, Michael Goertz

This work has been oriented towards the development of a system to enable military personnel to hear what they want to hear in backgrounds of intense, multisource, acoustical interference. The system currently under development makes use of an array of microphones, spatial processing (parallel spatial filtering), automatic signal-classification, and various types of displays. The Supernormal Listening Systems work during the past includes (1) development of a number of spatially diversified microphone arrays, (2) design and DSP implementation of algorithms to separate out and make simultaneously available the signals being generated in various spatial cells of the environment, (3) development of ear adapters for presenting processed signals to the listener and attenuating direct unprocessed signals, (4) development of a wristwatch-like device for displaying various characteristics of the acoustic environment visually and for controlling various features of the acoustic presentation, and (5) development and evaluation of methods for selecting and presenting to the ears both foreground signals (to which primary auditory attention should be directed) and background signals (to which secondary auditory attention should be directed for purposes of monitoring and situation awareness). In addition to these laboratory studies, we have conducted a number of field recordings of battlefield sounds and bullet fly-by sounds. Finally, a new line of research is being formulated to incorporate independent component analysis into a system for supernormal listening as well as application to models of human auditory scene analysis. Further information can be found at the web site http://pellicle.mit.edu/Audio/sls.html.

Figure 6.1-1. Polar plot depicting sensitivity of microphone array at one moment in time during complex battle audio scene. The system in this case is attempting to preserve the upper left sectors while attenuating the remaining sectors.

6.2 Oxygen Intelligent Room

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Project Staff
Nathaniel I. Durlach PI, Dr. Thomas E. V. Wiegand, Dr. Joseph G. Desloge

Work on this project is an outgrowth and synthesis of our Supernormal Listening System work and our collaboration with the Artificial Intelligence Lab of LCS. The goal is to determine the best approaches (algorithms, hardware, etc.) to dealing with multiple speech sources in a typical office environment containing incidental noise sources. During the past year we have consulted with the AI Lab on both hardware and algorithms, and have begun to measure and model room acoustics for eventual application to creating demonstration smart rooms.

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