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Teletouch Display Development:
Phase 1 Report

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Human-tactual capabilities and previous efforts in tactile-display development are reviewed, and approaches are recommended for developing teletouch-display systems for telerobotic systems.

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INTRODUCTION

Teleoperated manipulators currently in use rely mainly upon visual feedback to accomplish simple manipulation tasks. In some cases, to enhance manipulative capabilities, force reflection and positional correspondence are provided between slave manipulator and master controller arms, along with simple end-effector proximity and slip sensors. However, as noted by Bejczy (1977), space-station assembly, satellite servicing in orbit, extraplanetary exploration, and undersea operations (which require only seemingly ordinary manipulative capabilities) can overwhelm present teleoperated capabilities. To extend telemanipulative capabilities and applications, proposals have been made (Bejczy, 1977; Coiffet, 1981; Overton & Williams, 1983; Overton, 1984; Cutkosky, 1985; Harmon, 1985) to improve the quality of current visual, proprioceptive, and kinesthetic feedback. Yet, without feeding back end-effector surface contact phenomena to the teleoperator, remote systems are difficult to field that possess a high degree of dextrous manipulative and haptic abilities. This report reviews human-tactual capabilities and previous efforts in tactile-display development, and recommends approaches for developing teletouch-display systems for telerobotic systems.

Advanced telemanipulation systems provide operators with visual, proprioceptive, and force feedback with varying degrees of fidelity. Teleoperators presently rely heavily upon visual displays of the end effector and task environment to accomplish operational tasks. However, operating environments often offer limited or confusing visual information (i.e., inadequate or nonuniform lighting, shadows or specularity, objects embedded in cluttered or complex visual backgrounds, image scaling, perspective distortion, limited acuity, and so on) or the end effector is obscured. Under such circumstances, many operational tasks are difficult or impossible to accomplish. Some examples of these tasks are

- perceiving the object to be grasped or explored.
- setting end-effector pose for grasping.
- evaluating the quality or stability of the grasp.
- efforts involving positioning and assembly.

Fusing visual, proprioceptive, and kinesthetic stimuli helps develop stronger percepts and relaxes the performance demands which would be placed upon any single sensor feedback system alone (Allen, 1983; Chandler, 1983). Conveying current levels of visual, proprioceptive, and kinesthetic information to teleoperators has provided insufficient feedback to accomplish all desired tasks. In addition to using tactical displays to verify or augment other sensory stimuli, they can singly provide feedback concerning the following:

1. the presence of forces or torques acting upon the surface of the end effector which are not large enough to be detected by proximally positioned force-torque sensors

2. distribution of forces acting upon the end-effector surface which cannot be accurately spatio-temporally resolved using proximately mounted force-torque detection systems (Fearing & Hollerbach, 1984)

3. intrinsic (e.g., texture, thermal properties, etc.) and extrinsic (e.g., object contact points and areas, contact location, contact edges, etc.) tactile primitives, or tactemes,* to teleoperators (Stansfield, 1986).

Providing some or all of this information to a teleoperator can facilitate timely construction of more complicated tactile features, or percepts, such as connected edges, corners, contours, holes, and so on, which are requisite for efficient and competent manipulation and object recognition.

*Larcombe (1981) refers to basic tactile-sensor primitives, which can be only combined to produce tactile features as tactemes.

TELETOUCH-DISPLAY DESIGN ISSUES

TACTILE-SENSING LIMITATIONS

Tactile-sensor performance initially determines the sensitivity, dynamic range, and spatio-temporal resolving capacity of teletouch displays. Scientists and engineers have designed and constructed a variety of simple and reliable contact-, force-, or slip-sensing devices to assist in robotic grasping, positioning, or edge-following. (See Appendix A for a review of current tactile-sensing capabilities.)

A consensus-based set of performance criteria for tactile sensors has been published by Harmon (1982). He queried a population of 55 scientists and engineers positioned in academia, industry, and government. The population responded to questions concerning tactile-sensing needs in robotic systems, and the responses were augmented with a summary of scientific and development progress to date. According to Harmon's findings, an ideal tactile sensor should have these capabilities:

1. forcel resolution of 2 mm in a 50- to 200-forcel array.
2. normal force-detection ranging between 0.4 to 10 N, with a dynamic range of 1:1000 with wide frequency response ranging between 0 and 1 kHz.
3. joint detection of displacement, force, and thermal stimuli.
4. ease of mating the sensor, or display, to small nonplanar surfaces, such as robotic-anthropomorphic fingers.
5. small power demands.
6. robustness in the face of potential overforce, thermal stress, humidity, radiation, corrosive environs, and resistance to abrasion.
7. economical to produce or to replace.

Though today's sensors are crude (in comparison to human-somatosensory capabilities), contemporary investigators are developing prototype sensors which are approaching many, and in some areas, exceeding, Harmon's benchmarks. Therefore, teletouch displays should always capitalize upon tactile-sensing capabilities.

LIMITATIONS IN CUTANEOUS SENSITIVITY

Our understanding of the sensor capacity of human skin and of local and central processing of suprathreshold stimuli is comparatively limited and remains under debate. Cutaneous receptors are embedded within a highly compliant and hysteretic medium that must balance requirements for protection, physiological control, regeneration, and other competing demands, against those of sensibility and perception. Performance tradeoffs have produced a highly nonlinear system whose response to force and thermal stimuli varies with the following: anatomical location, length of stimulus exposure, spatial and temporal coincidence with previous stimuli, activities of adjacent tissues, as well as the nature of the stimulus transmission. For detailed reviews of cutaneous-receptor anatomy, physiology, and psychophysical phenomena of human skin, see Mountcastle (1974), Verrillo (1975), and Cholewiak and Sherrick (1986). Such behavior defies presenting a brief and utilitarian set of guidelines for describing suprathreshold cutaneous stimuli. Fortunately, sufficient information exists to allow designers to specify useful and adequate stimulus parameters to ensure individual and task-dependent adjustment of cutaneous stimuli and stimulus detectability (Cholewiak & Sherrick, 1986).

STIMULUS MODE

The criteria for selecting the mode, or modes, for displaying contact-sensor information not only depend upon ideal absolute and difference threshold requirements, but also upon the following factors:

1. operational thresholds determined by the geometry and placement of the tactors.
2. resistance of the stimulus paradigm to stimulus masking and adaptation effects.
3. task-based spatial and temporal resolution requirements.
4. operator tolerance to prolonged or repeated stimulation.

Although skin can be stimulated mechanically, electrically, chemically, and thermally, only the mechanical and electrical cutaneous-stimulation modes will be discussed here (figure 1). This is because other stimulus modes for telemanipulation tasks have unacceptable dynamic range and limited bandwidths. (See Cholewiak & Sherrick, 1986.)

Cutaneous Thresholds for Mechanical Stimuli

Two forms of mechanical excitation of the skin have been studied: static displacement of skin, and oscillatory mechanical or vibratory stimuli. Weinstein (1968) found, using von Frey hairs and the Method of Limits, that mean values of absolute thresholds varied from 5 mg on the face of women (nose, cheek, and lip) to as much as 355 mg on the great toes of males. Gender interacted significantly among body loci, with the face and torso proving to be most sensitive to pressure, followed decreasingly by loci increasingly more distal from the head and trunk. Weinstein's findings disagreed with those of Wilska (1954) who had earlier studied cutaneous sensitivity to 200-Hz vibratory stimuli. Wilska showed a different sensitivity ranking, with finger tips proving to be quite sensitive. The discrepancy may be attributed to both differences in the receptors activated and in the mechanical impedance of the skin between slow onset displacements versus fast onset vibrations.

In search of vibrotactile absolute thresholds (ATs) and difference limens (DLs), investigators have used the following means to stimulate the skin: loudspeakers (e.g., Geldard, 1940); electrodynamic mechanical shakers (e.g., Sherrick, 1975); piezoceramic elements (e.g., Alonzo, 1964; Sherrick, 1975; Cholewiak & Sherrick, 1981); and air jets (e.g., Bellows, 1936; Kotovsky & Bliss, 1963). Many investigators have attempted to define the interrelationships between vibrotactile perception and displacement magnitude and vibration levels. Verrillo, Fraioli, and Smith (1969) published contours of equal

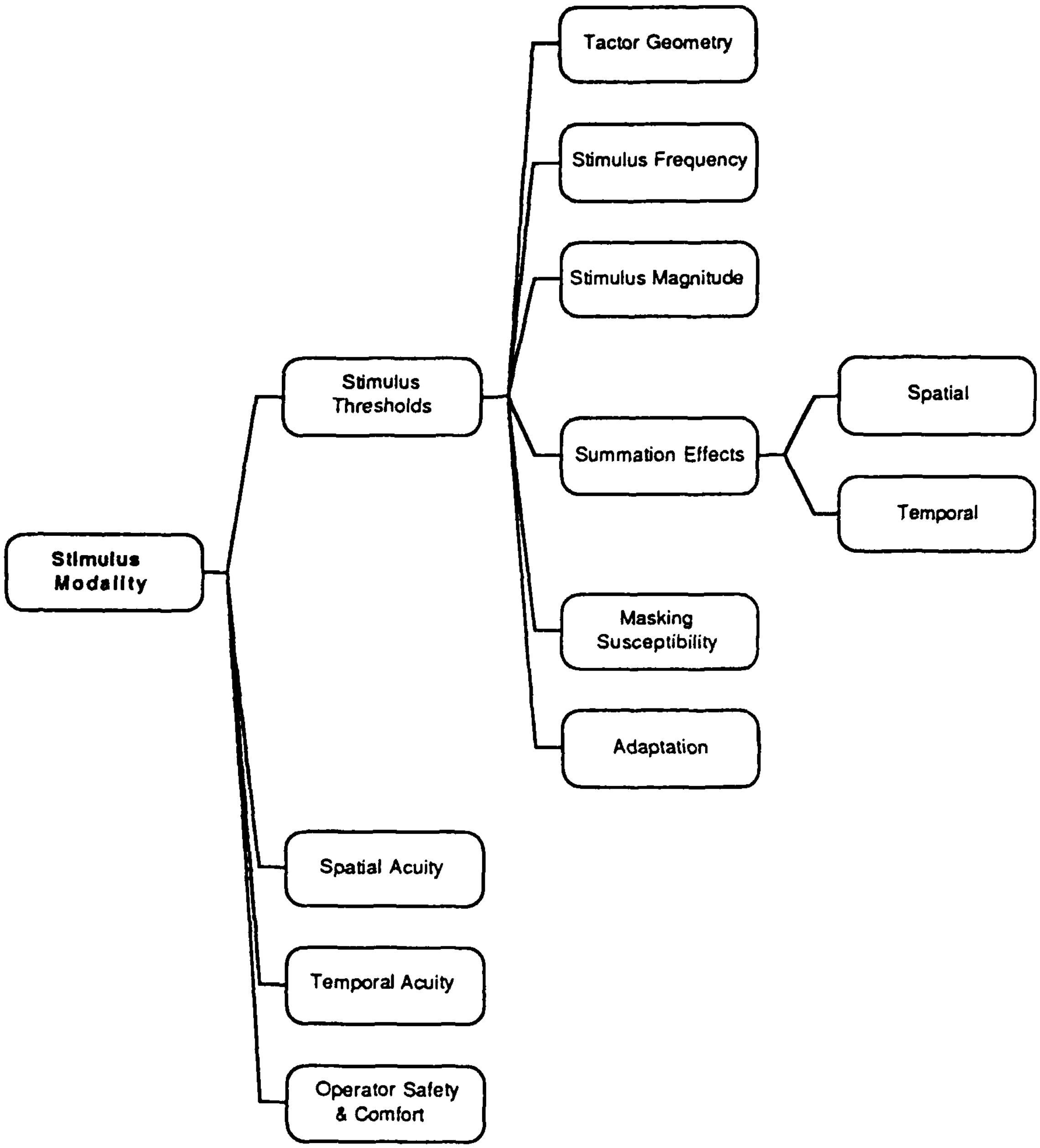

Figure 1. Factors to be considered when selecting a mode for cutaneous stimulation.

subjective magnitudes for a wide range of vibrotactile frequencies and intensities. Using direct scaling and intensity-matching techniques, subjective magnitudes (for frequencies up to 350 Hz) were best described by a power function with an exponent of about 0.89. Near threshold, the growth of the sensation was proportional to the displacement magnitude. Contours of equal subjective magnitude for vibration across 10 frequencies, and at 11 levels of intensity, showed a U-shaped displacement and stimulation frequency, with maximum sensitivity at about 250 Hz. At a given frequency, about a 20-dB increase in subjective intensity was found for every 10-fold increase in peak displacement. However, for vibrations at 250 Hz, Shannon (1976) found that the useful range of intensities, between AT and annoyance, was only slightly greater than 10 dB. Vibrotactile DLs ranged between 50 percent, with low sinusoidal frequencies (e.g., 10 Hz); and improved to 10 percent, at frequencies near minimum AT (e.g., 300 Hz). (See Rothenberg et al., 1977.) Displacement-temporal thresholds varied about the body and were generally most discriminating when pulsed displacements were employed rather than sinusoids.

Unfortunately, the majority of mechanical stimulation techniques used in the past failed to independently vary mechanical displacement and vibration frequency (i.e., increasing vibration frequency reduced tactor displacement and vice versa). Moreover, vibration sensations were significantly influenced by:

- spatial and temporal summation.
- competing or masking stimuli.
- stimulus adaption.
- tactor-contact force or mechanical impedance of the contacting skin.
- area of skin surface stimulated by an individual tactor.
- other factors, such as stimulus onset transients that confound stimulus-response behavior.

These obstacles have prevented publishing or assembling a comprehensive description of vibration stimulus-response relationships.

Spatial and Temporal Summation of Vibrotactile Stimuli

Increasing the area or frequency of stimulation often lowers sensory thresholds (Mountcastle, 1974). Verillo (1968) found that, depending upon stimulus frequency, the size of the tactor employed affected sensory thresholds. Removing a collar surrounding the tactor reduced thresholds, if stimulus frequencies exceeded 40 Hz. Below 40 Hz, thresholds were independent of vibration frequency. Subsequent investigations have demonstrated the presence of spatial-summation effects upon absolute and DL thresholds (Craig, 1968; Boyer, Cross, Guyot, & Washington, 1970). However, from a pragmatic perspective, spatial-summation effects, where found, are small (~2 dB) and may not be meaningful, given Verillo's (1968) finding that small tactor diameters (~1 mm^2 or less) fail to produce significant spatial summation.

Masking of Vibrotactile Stimuli

Von Bekesy (1955, 1959) suggested that every stimulus produces an area of sensation surrounded by an area of inhibition and that, for skin, the size of inhibited areas changes significantly with the rate of skin displacement. Rapid displacement of the skin results in larger areas of inhibition, with sensation sharply localized within the center of the stimulated area. He referred to this phenomenon as "funneling." Some authors prefer to term this, and similar phenomena, as "masking effects." Introducing interfering stimuli prior to, following, or spatially adjacent to a stimulus of interest is respectively referred to as forward, backward, or lateral masking.

Vibrotactile masking effects increase with the intensity of the masking stimulus (Moore, 1968; Abramsky, Carmon, & Benton, 1971). They also increase when spatially remote stimuli are presented simultaneously and frequencies are within the response range of the Pacinian system (Verrillo, Gescheider, Calman, & Van Doren, 1983). Gilson (1969a,b) also found that the resultant shift in threshold produced by groups of masking stimuli was nearly additive.

From an operational perspective, masking hampers accurately recognizing (1) patterns of stimuli presented and (2) variations in perceived levels of vibrotactile intensity which might be experienced during manipulative activities. Craig (1984) suggested that masking stimulus patterns may influence the perception of a particular pattern of vibrotactile stimuli and their differences in intensity of presentation, both prior to and following the immediate stimulus. Masking has also been observed while initiating voluntary movements (Coquery & Amblard, 1973). Motor commands were attenuated, or obliterated cutaneous sensations stimuli were delivered, within tens of milliseconds before the appendage moved. It is not clear if this phenomenon is due to an inhibitory effect caused by motor commands, or to a decrease in perception caused by backward masking from cutaneous and proprioceptive afferents. The experimental paradigms used in these studies make it difficult to predict the impact of motor activity, or "extraneous" cutaneous stimulation, associated with master controller operation; particularly, if the display is directly integrated into the master controller.

Adaptation to Mechanical Stimuli

Upward shifts in ATs and DLs, or adaptation, with sustained displacement of vibrotactile stimulation, have been observed in many laboratories (Melzack & Schecter, 1965; Gesheider & Wright, 1968, Zubeck, Bross, & Gelfant, 1973, and others). Using a combination of intensity-matching and magnitude-estimation procedures, Gesheider and Wright (1968) found a reduction in both the describing power function's constant and an elevation in the exponent.

Onset of adaptation is slower, if vibrotactile stimuli are employed (Shannon, 1976), and if vibratory stimuli are composed of square-wave pulses, rather than sinusoids (Rothenberg et al., 1977). The time course of adaptation depends upon the stimulus characteristics; and, in Hahn (1966), adaptation persists for about 50 percent of the adapting stimulus' period (60 Hz, 6 mm diameter tactor with a displacement of 200 μm) of presentation. Following repeated mechanical insult, Hahn attributed adaptation to changes in the targeted skin's elasticity, viscosity, and resistance; however, mediation by the central nervous system was not ruled out as a factor. Sueda's (1972) finding that alterations in the stiffness of the skin, altered by changes in underlying muscle tension, supported Hahn's argument.

Clearly, adaptation to mechanical stimuli depends upon the stimulus locus, magnitude, duration, and frequency of stimulus application. Minimizing the amount of energy transmitted to the skin should reduce the magnitude and persistence of threshold shifts and other adaptation effects. Unfortunately, as with psychophysical-threshold determinations, no comprehensive investigation has been undertaken concerning the impact of the foregoing parameters upon adaptation. Until such a study is completed, adaptation impact of a particular display design can be evaluated only on a case-by-case basis.

Temporal and Spatial Acuity of Mechanical Stimuli

In comparison, the skin's temporal resolving capacity (~5 ms for pulses of 1-ms duration presented to the fingertip (Gescheider, 1974)) lies between that of the ear (~10 μs pulses) and the eye (~25 ms). Presenting vibrotactile stimuli at raster rates leads to a sensation of pressure underlying vibrations (von Bekesy, 1960a). If interstimulus intervals are increased to 20 ms, then stimulus order can be resolved in 75 percent of trials (Hirsch & Sherrick, 1961). Increasing the number of sites of stimulation also leads to longer decision times, regardless of spatial separation (Sherrick, 1982).

Interest in the skin's vibrotactile spatial acuity has focused upon the ability of subjects to discriminate between two adjacent punctate stimuli and upon errors in successive localization of points. Two-point limens and localization errors for various body loci are presented in Weinstein (1968). Finger tips proved to be most discriminating for both measures (~2.5 mm for two-point discrimination and ~1.5 mm for localization errors). Lateral inhibition, or funneling, may account for the poorer two-point spatial resolution capacity. Changes in stimulus intensity appear to have little consequence in spatial acuity (Johnson and Phillips, 1981). However, a combined spatio-temporal limen is smaller (i.e., rocking closely spaced points can reduce two-point discrimination distances).

Thresholds for Electrocutaneous Stimulation

Concentric surface electrodes (an active center electrode surrounded by an indifferent electrode, as small as 0.5 cm^2) have effectively produced pain-free stimulations with minimal current stray (Prior, 1972; Saunders, 1974). Both Gibson (1968) and Saunders (1974) have recommended using constant current and brief (5 to 20 μs) trains of 1 to 40 biphasic square pulses, presented in 250-Hz bursts, with 100-ms intervals, to avoid discomfort and untoward shifts in electrophysiological stasis of underlying skin. Typically, changes in current density are used to convey changes in perceived intensity. However, magnitude sensations can also be altered by varying the number of pulses transmitted to the skin (Stevens & Sheckman, 1959; Saunders, 1974). To avoid discomfort, current density is usually varied by adjusting pulse width rather than peak current. To reach thresholds, investigators have found that current intensities of 0.6 to more than 6 mA are required.

Gibson (1968) found that touch and pain thresholds are decreasing hyperbolic functions of the number of pulses presented in stimulus trains, and that touch and pain thresholds decreased at different rates. Pain thresholds decreased at a lesser rate than did ATs. The separation between thresholds, however, was comparatively small (pain and discomfort were experienced if intensities were raised more than ~1.5 times above the AT). Melen and Meindle (1971) found that for sufficiently small pulse durations (~0.5 ms), changes in rates of stimulation, up to 200 pps, had little effect upon ATs. Longer pulses, however, lead to sensations of burning. Reductions in stimulus rates also lead to reductions in perceived stimulus intensity, which, at very low frequencies, were sensed as prickling.

As with mechanical stimuli, electrocutaneous ATs and DLs depend upon tactor or electrode design and geometry, stimulus form (i.e., waveform and repetition rate), locus of stimulus, differences in skin impedance, and other individual factors. Cholewiak and Sherrick (1986) found similar subject-intensity functions among electrocutaneous and mechanical stimuli, when stimulus pulse durations were adjusted and repetition rates were held above 60 Hz (Hill, 1967; Rollman, 1973; Hahn, 1958; Buchthal & Rosenfalck, 1966; Girvin, Marks, Antienes, Quest, O'Keefe, Ning, & Dobelle, 1982). Thus, electrocutaneous displays must permit operators to adjust the intensity of the stimulus, based upon electrode coupling, task demands, and shifts in thresholds with repeated stimulation.

Spatio-Temporal Summation of Electrocutaneous Stimulation

From the aforementioned variations in electrocutaneous thresholds, spatial and temporal summation effects clearly play significant roles in determining the intensity of cutaneous perception. Temporal summation effects have received considerable attention in the past and are best understood at this point. Hill (1967) found that threshold currents decreased with increasing pulse duration, or current integration, as follows:

$$I_t = \frac{0.25}{1-e^{-2t}}$$

where

I_t = threshold current (mA)

t = pulse duration (ms)

Although not addressed by the preceding equation, temporal summation is further increased if multiple pulses are experienced (Gibson, 1968).

Masking Effects with Electrocutaneous Stimuli

Masking effects with electrocutaneous stimulation appear to be weaker than those reported with mechanical stimuli. Rollman (1973) found that use of an electrocutaneous masker produced a 13-dB elevation in a vibrotactile stimulus AT. However, when an electrocutaneous stimulus was masked with a vibrotactile display, AT dropped only 3 dB. Forward- and backward-masking effects reported by the relative magnitudes in AT elevation are often small and inconsistent among investigators (Schmid, 1961; Rosner, 1964). Unlike vibrotactile stimuli, masking electrical stimuli laterally appears to require much greater adjacency of masking and masked stimuli (Uttal, 1960).

Adaptation to Electrocutaneous Stimuli

Sustained or repetitious presentations of suprathreshold electrical stimuli result in elevated current thresholds. Use of pulsed, rather than sinusoidal stimulus waveforms, as with vibrotactile stimulation, reduces adaptation onset and magnitudes (Shannon, 1976). Reducing stimulus rates to below critical fusion pulse (cfp) rates and presenting stimuli in episodic trains, or bursts, reduces adaptation onset and magnitude.

Spatial and Temporal Acuity of Electrocutaneous Stimuli

Spatial and temporal acuity of electrical stimuli is poorer than levels cited with mechanical stimulation. Two-point discrimination distances and temporal resolving periods were found to be two to three times greater in magnitude with electrocutaneous stimuli than values obtained with mechanical stimulation (see Jones, 1956; Saunders, 1973).

Haptic Perception

Haptic perception extends beyond detecting cutaneous stimulation and its qualities. As Gibson (1962, 1966) points out, passive stimulation of the skin of observers conveys sensations of tactile contact (e.g., pressure, temperature, etc.). However, tactile stimulation, when combined with active or exploratory movements, blends sensations into telling perceptions of objects positioned in space about the body. Unfortunately, study of the haptic system has been comparatively limited; and models have yet to be constructed that describe or predict haptic performance. Experiments conducted thus far can be characterized as efforts to (a) determine the importance of haptic capabilities in relation to other perceptual modalities; (b) determine limitations in haptic perception; and (c) evaluate the importance of interplay between cutaneous, proprioceptive, and kinesthetic feedback. (See Loomis and Lederman (1986) for a comprehensive and historical review.)

Teleoperators presently rely principally upon vision and blunt probing with an end effector to develop and test perceptions concerning the size, form, texture, and other properties of objects encountered or manipulated. Whether or not one can functionally identify object properties depends upon the quality of the visual surroundings, the quality of the kinematic correspondence and force control of the manipulator, and the period allowed for exploration. Past experiences have demonstrated that without some tactile feedback, haptic perceptual capabilities are substantially limited. Perceptual experiments have repeatedly demonstrated that development of haptic percepts requires corresponding sensations from cutaneous and either active or passive kinesthetic and proprioceptive receptors.

Determining the relative importance of each of these feedback systems, in terms of haptic sensitivities, has been difficult. Gibson (1962) and Caviness (1964) reported that when confronted with unseen three-dimensional objects, subjects would

a. curve their fingers around the objects and into concavities using all fingers.

b. move their fingers in a highly variable nonstereotypic manner.

c. pinch objects or oppose thumb and fingers when grasping.

d. rub and trace curvatures with one or more fingers.

The subjects clearly did not systematically investigate or scan the objects explored.

Our present understanding of the haptic system is based principally upon phenomenological evidence. A subset of this evidence, pertinent to teletouch displays, is summarized in the following section.

TACTILE-DISPLAY DEVELOPMENT EFFORTS AND FINDINGS

Efforts in tactual-display design have focused upon (1) the need to relieve the visual information burden of operators and (2) development of sensory-substitution displays for the visually or aurally impaired. Displays developed and tested may be classed as warning systems. Some examples of these are the Pilot "G-Limit" warning device (Thorburn, 1971); Silent Sentry Warning System (Hawkes, 1960); navigational aids (Driver Tracking Aids Fenton, 1966; Fenton & Montano, 1968; Schori, 1970; Hoffman & Heimstra, 1972; Ross, Sanneman, Levison, & Berliner, 1974); alternative modes for communication of nonsensory information (Hirsch, 1969; Kirman, 1973; Keidel, 1974; Mc Cray, 1970; Heller, 1985); and as prosthetics for the visually or hearing impaired (Kotovsky & Bliss, 1963; Ingham, 1969; Bliss, 1969; Nye & Bliss, 1970; Bliss, Katcher, Rogers, & Shepard, 1970; Melen and Meindl, 1971; Collins, 1970; Kaczmarek, Bach-y-Rita, Tompkins, & Webster, 1985; Cholewiak & Sherrick, 1986; and others). In comparison, however, tactile displays for enhancing telemanipulation and telepresence have received relatively limited attention (Bliss & Crane, 1965; Hill & Bliss, 1968; Hill & Bliss, 1971).

Bliss and Crane (1965) used an array of bimorph mechanical stimulators, approximately 1 mm in diameter, to stimulate the skin. Using a one-to-one correspondence between sensor and forcel, a subject was reportedly able to "feel" the shape and location of the object held in the remote jaws on his own thumb and index finger. Later, Hill and Bliss (1971) constructed a touch feedback system consisting of 21 forcels distributed on the outside surfaces of a robotic end effector. The sensors consisted of two [6,24] arrays of sensors distributed on the faces of the end-effector jaws. Each sensor directly controlled activation of airjet tactile stimulators mounted over corresponding areas of the operator's hand. These air jets produced an area (approximately 3/16 of an inch in diameter) of pulsating pressure on the skin. In an alternative display, forcels controlled piezoelectric bimorph stimulator arrays which were positioned on the distal pads of an operator's index finger and thumb. From these, and other studies, the following variety of phenomena pertinent to designing teletouch displays has been reported:

a. Variation in adjacent vibrotactile or electrotactile stimulation frequencies and phase relationships can produce anomalous or apparent sensations of position or movement. Apparent-motion effects can be obtained with just two stimulators. The effect is considerably improved when additional stimulators are energized in sequence (Kotovski & Bliss, 1963; Geldard & Sherrick, 1972). The "Cutaneous Rabbit," or phantom sensations of hopping between stimulator loci, lengthen hop distance, if stimulus frequency at each stimulus locus is reduced and vice versa, up to a limit. Hopping occurs when contactors are close (2 cm) or are far apart (35 cm) (Geldard & Sherrick, 1972).

b. Tactor resolution is an important factor in determining perception of edge intersection or corners. Corners are generally perceived as rounded (e.g., Bliss, 1967).

c. Pattern perception varies with repeated presentation of the stimulus set.

d. If the stimulus set is known prior to presentation, then the punctate patterns can be identified far more reliably.

e. Though tactile short-term memory has greater capacity than the span of immediate memory, it decays within 0.8 s. Information gathered by the hand appears to be less stable than for information gathered by the eye; it is more likely to show loss when the number of comparison objects is large. As memory demands increase, accuracy declines first on any matching that starts with inspection by hand (Goodnow, 1971).

f. Visual and tactile stimuli can give the same mean simple reaction times. However, when the number of response alternatives was increased, the mean visual-reaction times increased to a much smaller degree than did tactile-reaction times. When both visual and tactile stimuli are presented simultaneously, the mean-reaction time was significantly shorter than that found with either visual or tactile stimuli alone.

g. Tracking responses to step commands under various feedback conditions indicates that movements with visual displays tend to be faster than with the tactile display, but that stationary pauses were longer with the visual display (Schori, 1970; Siegel, Lanterman, & Macpherson, 1966). Hahn (1965) found, that for unidimensional compensatory tracking, error was 2.5 times greater with a vibrotactile display, which was estimated to have a gain 1/5 that of the visual display. With *continuous command* signals, describing functions were obtained which showed less gain and less bandwidth with an airjet tactile display than with a visual display. However, increased bandwidth was obtained with a contacting tactile display that produced tangential, as well as normal forces, on the skin.

h. Motion versus nonmotion of the tactile pattern results in a substantial increase in the number of correct form recognitions (e.g., Gibson, 1962; Bliss, 1967).

i. The number of stimulus positions perceived tactually increases approximately as the log of the stimulus duration, up to at least 500 ms (e.g., Hill and Bliss, 1968).

j. Changes in stimulator frequency from 1 to 100 Hz have little, if any, influence on performance. If there is any difference in spatial resolution, it is better at higher frequencies (e.g., Hill and Bliss, 1968).

k. Activating all the stimulators in an array immediately following a stimulus, tends to interfere with, or erase, information in the visual and tactile channels (e.g., Hill and Bliss, 1968).

l. The information from a brief tactile presentation appears to be transferred from the sensory register to higher centers in a parallel, rather than sequential, manner (e.g., Hill and Bliss, 1968).

m. Results from comparative visual and tactile stimulus presentations are consistent with a model in which the visual and tactile sensory registers are separate. Information processed per unit time is considerably less with tactile stimuli than with visual (e.g., Hill and Bliss, 1968).

n. Results from experiments with sequentially presented point stimuli suggest that temporal resolution may be better with small spatial-stimulus spacing (e.g., Hill and Bliss, 1968).

o. Processing of sequentially presented tactile or visual information is more consistent with a first-in, first-out model than with a push-down-store model (e.g., Hill and Bliss, 1968).

p. Linear point movement is perceived as a straight line across the volar surface of the forearm, if drawing rates are fast (e.g., 16 cm/s per Bliss, Crain, & Link (1966)). Slow linear stimulation produces sensations of curved and winding movements and of greater line length (Bliss, 1966; Langford, Hall, Monty, 1973).

q. Orientation of cutaneous stimulus patterns is determined by the location of the stimulation site in relation to a virtual tactual vantage point. Supination or pronation of the arm or placement of the hand behind the head can reverse stimulus orientation in most observers.

r. Roughness or texture perception is dominated by groove width and contact force, while intergroove spacing and rate of hand movement have little or no effect upon perception (Lederman, 1974; Taylor & Lederman, 1975).

s. Duration and mode of tactile-array activation affects perception of simple and complex two-dimensional forms presented. Sequential stimulus modes (e.g., tracing, sequential presentation of line segments defining the geometry of the form, scanning, and slit scan) are poorer than static or jitter modes, when the finger is the stimulus location. However, the opposite is true when the back or abdomen is selected for stimulation sites. Simple patterns presented in close succession interfere with each other, whether or not the stimuli are presented in a sequential or static mode. Patterned masking stimuli are more effective maskers than patternless uniform stimulations (Kirman, 1974; Shimizu, 1982; Shimizu, 1982).

PROPOSED APPROACH FOR DISPLAY EVALUATION

From a telemanipulation standpoint, tactile displays are helpful if they significantly improve our ability to locate, grasp, control, and identify objects of interest. Without a comprehensive characterization of human tactual psychophysics, nor a unifying model to account for and predict haptic perceptual capabilities, at this point, specifying *a priori* an optimal design for such devices is difficult.

We do, however, have enough information to construct devices that yield suprathreshold stimuli that can be adjusted, as needed, in response to threshold differences between individuals and within individuals with the onset of adaptation. Moreover, stimulus modalities can be selected to minimize masking interference, increase spatio-temporal resolution, discomfort, and so on.

Unfortunately, no stimulus modality can be considered ideal in any majority of such factors. For example, electrocutaneous display systems provide clearer, brighter, and greater masking resistance displays with lighter-weight and more energy-frugal hardware than can be obtained with mechanical systems. Electrocutaneous displays, however, offer (a) poorer temporal and spatial resolution; (b) the potential for inadvertently exciting adjacent musculature or shock, if improperly designed or placed upon the body; (c) an opportunity for presenting painful stimulations; and (d) longer time periods for display mounting and, perhaps, skin preparation than one would encounter with a vibrotactile display. Thus, some investigators have proposed using auditory or visual characterization of end-effector contact information.

Performance consequences of cross-modal display of tactile information are uncertain. Presenting such information, via the auditory or visual channels, does add additional perceptual and cognitive burdens to the operator; and processing requirements may be unacceptably long in certain tasks. Yet, a long line of research exists which demonstrates the capabilities of humans to map a sensory continuum for one mode onto that of another (see Stevens, 1966, for a review and bibliography). Bach-y-Rita, Collins, and their colleagues have demonstrated that the human perceptual system is rather plastic and have developed tactile-based vision-substitution display systems with excellent success (Bach-y-Rita, 1988;* Collins, 1987**). Cashdan and Zung (1970), and Butter and Bjorklund (1973), have also demonstrated that vision without tactile feedback permitted more rapid and accurate recognition of objects than did blind feel. However, providing tactile feedback to augment vision produced clearly superior object-recognition performance. Whether or not a visually based tactile-substitution system is a useful approach for telemanipulation activities has not received earnest investigation. Moreover, the operator may not require continuous and overburdening visual feedback of teletouch information to accomplish manipulation and object recognition tasks, if equipped with visual, proprioceptive, and kinesthetic feedback. Questions remain regarding what specific tactual information is augmentive, and when such information should be presented to the operator to meet operational objectives.

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* Personal communication.

** Personal communication.

To evaluate various tactile-display design strategies, we have selected a set of perceptual-motor and cognitive performance-based criteria. Performance metrics have been selected that offer both operational validity, and construction of motor- and information-processing models that permit more appropriate findings for present and future design considerations.

In formulating the evaluation strategy, we first sought out metrics for psychomotor or manipulative performance. For the majority of activities, operators would rely upon tactile feedback to

a. indicate the presence or loss of contact between the end effector and object(s) or surface(s), even when the hand is subjected to a wide range of pressures resulting from manipulating the master controller(s).

b. position the end effector about an object to achieve and maintain a compliant and dextrous grasp.

c. enable efficient completion of object or tool transport, positioning, and assembly or applications.

Once such displays are found, or constructed, then the next objective of the effort is to evaluate the amount of haptically useful information that can be transmitted by such displays; that is, given (1) the differences in masking experienced; (2) the loss of visual image and contact expectancy; (3) the differences in tactor size, location, and resolution; and (4) the varied operator decision criteria (β's).

Selection of candidate displays was influenced by

a. the nature and potential interference with master controllers (e.g., the joystick and gestural glove controller).

b. the display's potential for transmitting spatio-temporal stimuli, dynamic range, and controllability.

c. the potential for resisting threshold shifting, masking, and adaptation.

d. previous and existing prototype display strategies.

An electrocutaneous 512 point array built by Sevrain-Tech, of Madison, Wisconsin, was selected because of the display's lightweight and flexible design. The display's electrodes were mounted upon a highly conformable plastic film. They can be individually controlled through a digital-to-analog driver that provides a full dynamic range between detection and pain thresholds. Array resolution is 5 mm between electrode centers, and this display provides a highly controllable grey-scale stimulation.

Another display system, constructed in-house from three Telesensory, Inc., Optacon modules, has also been selected for study. This display is more suitable for finger-tip stimulation. The modules can be linked, and the 6 by 24 tactor arrays can be individually controlled.

The following has been selected as a candidate display: a visual presentation of the magnitude and form of end-effector contact with stimuli at the site of the onscreen manipulator arm, along with auditory presentation of percussion and scraping sounds of an end effector encountering and exploring a stimulus.

Figure 2 outlines display design variables of principal interest in this study and also displays performance factors that will be used. The following experiment descriptions discuss these performance factors.

EXPERIMENT I

Contact Detection and Grasp-Force Tracking Capability

Teleoperators must be able to reliably detect contact of the end effector with objects, and control and maintain grasp forces acting upon objects or tools held within the end effector. A Signal Detection Theoretic (SDT) approach for describing improvements in teleoperator sensitivity (d') is provided by a candidate display across a range of operator decision criteria (β). High β's, or conservative response to stimuli, result in high-detection thresholds and few false alarms; while low β's or liberal response to stimuli, produce behaviors in which noise-only presentations receive positive responses, and false alarms are increased. Given the costs (e.g., localized muscle fatigue due to overly frequent gripping or misleading perceptions of object location and form) and benefits (e.g., reduced search or manipulation time), a teleoperator's β can be adjusted using (directly or indirectly) some form of payoff protocol to shift detection criteria. Detection performance for any given β will depend heavily upon the sensitivity (d') of the operator-display system to the stimulus of interest.

If one plots correct detections, or hits, against false alarm rates for a given β level, then a receiver-operating characteristic (ROC) curve is generated. Families of ROC curves may be constructed, as shown in figure 3, for candidate tactile-display designs and compared for sensitivity differences. (See Green & Swets [1969] for a detailed discussion of methodology.)

Once a subject has detected the stimulus which indicates contact has been made between the end effector and an object, then the subject will be instructed to maintain a grasp of constant force by manipulating the master controller. Indications of grip force will be fed back to the operator via the candidate tactile display. Essentially, this task becomes a compensatory tracking task in which the operator attempts to null out an error signal.

Independent Variables

- Priopriceptive and Kinesthetic Coupling
  - High - Gestural Glove Controller
  - Low - Joystick Controller
- Stimulus Modality
  - Electrocutaneous
  - Vibrotactile
  - Visual
  - Auditory
- Display Resolution
  - High
  - Low
- Spatial Correspondence
  - High - Mounted on Controlling Hand
  - Medium - Mounted on Forearm
  - Low - Mounted on Forehead

Performance Factors

- Experiment I
  - Grasp and Contact Detection (d')
  - Grasp Force Tracking Capability
- Experiment II
  - Movement and Positioning Performance
- Experiment III
  - Object Tacteme & Feature Information Transmission

Figure 2. Experimental variables and performance criteria to be used in evaluating candidate tactile displays.

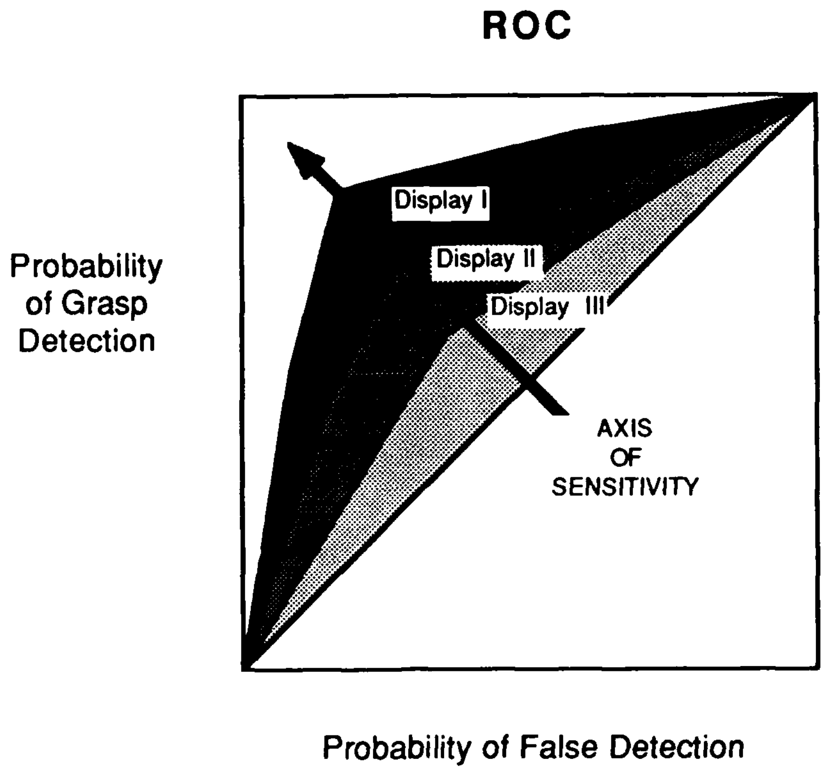


Figure 3. Example of a family of receiver-operating characteristic curves.

Teleoperators must frequently adjust grasp forces which act upon objects or tools held in the end effector. If the operator seeks to maintain a constant grasp force with a compliant parallel jaw end effector, then the behavior can be characterized by a single degree-of-freedom mass, spring, dashpot system where

$$m\frac{d^2x}{dt^2} + C\frac{dx}{dt} + kx = f(t)$$

with

$m\frac{d^2x}{dt^2}$	=	inertial force
$C\frac{dx}{dt}$	=	viscous damping force
kx	=	linear elastic force
$f(t)$	=	external forcing function

For this system, we can determine the damping ratios and undamped natural frequency of the operator-display system as follows:

$$\frac{C}{2\sqrt{km}} = \frac{\text{actual damping}}{\text{critical damping}} = \text{damping ratio}$$

$$\sqrt{\frac{k}{m}} = \text{undamped natural frequency}$$

Both the damping ratio and undamped natural frequency are the key factors in determining the characteristic equation and, thus, the response of the system to random shocks and disturbances. Therefore, if a tactile-display design effectively aids the teleoperator in grasping an object with a steady force, it will increase the magnitude of the restoring force and help the system behave as if it were critically damped.

The purpose of this analysis is to

a. rank the performance order of candidate displays by guiding operators in restoring desired grip forces.

b. characterize the nature of the operator's behavior using the display.

c. provide a means for "tuning" the display in terms of design characteristics for achieving improved performance.

d. provide performance specifications for decisions concerning the acceptability of the display to support particular grasping capabilities.

Methods and Materials

Candidate displays will be controlled by computer. Subjects, after receiving a series of calibrating stimulus sets, will await a stimulus to arrive that indicates contact has been made. If the subject perceives the stimulus, then a report will be completed indicating the degree of confidence in the stimulus' presence. The subject will then be provided a criterion stimulation and will be instructed to maintain the stimulus intensity via movements of the joystick or gestural controller. Step and pseudorandom changes in tactile-display intensity will be introduced by the computer which will also sample, at uniform periods, operator control behavior and store control errors for subsequent analysis.

After completing the trial, the controller behavior data will be analyzed using a nonlinear least-squares, autoregressive, moving-average modeling algorithm to determine the structure and estimate the coefficients of the characteristic or describing function of the system. Detection reports will be compiled and ROC curves constructed.

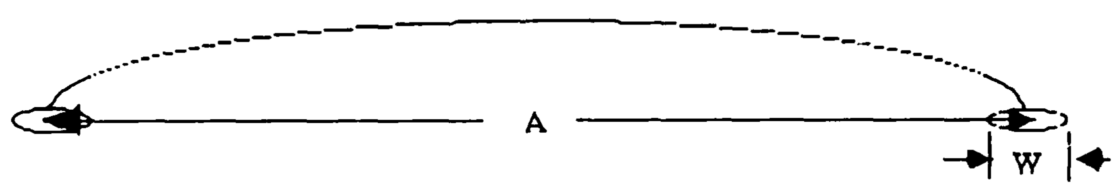
EXPERIMENT II

Impact of Tactile Displays Upon Telemanipulative Capability

Engineers and scientists have found that breaking down complex manual tasks into aggregations of simple motor elements is useful for describing tasks, analyzing methods, predicting performance, and inquiring into theory. Certain elements of manual performance are frequently encountered in assembly, disassembly, and other manipulative operations. Aberg (1963) surveyed several forms of industrial manual manipulation tasks and found that reach, move, and position therbligs were predominant (e.g., approximately 40 to 80 percent of cycle times).

Many experiments have shown that movement and positioning times are proportional to the movement's amplitude and end-point accuracy requirements. However, Fitts (1954) was the first to quantify movement capability under a variety of speed-accuracy conditions. He argued that the speed of accurate movements was bounded by the capacity of the neuromuscular system to control movements. If manual control was limited by the information-processing rate of the peripheral and central nervous systems, then movement times would increase according to their difficulty in terms of information-processing demands. Fitts described a movement's difficulty using an index which approximated the number of equally likely alternative movements that could be made, given amplitude and endpoint accuracy specifications.

Assuming that the "motor capacity" for a particular limb system was fixed, Fitts predicted and found that average movement time (MT) in a speed-accuracy task was linearly related to the task's Index of Difficulty (ID). Moreover, if amplitude tolerance ratios were maintained, then movement times would be equal, within measurement error, regardless of the magnitude of the movement's amplitude, or endpoint accuracy requirements. Regression of average MTs against IDs produced MT/ID slopes of approximately 100 ms/bit for continuous reciprocal movements and 74 ms/bit for discrete movements (Fitts & Petersen, 1964). Fitts' equation is presented below:



$$MT = a + b\,(ID)$$

where

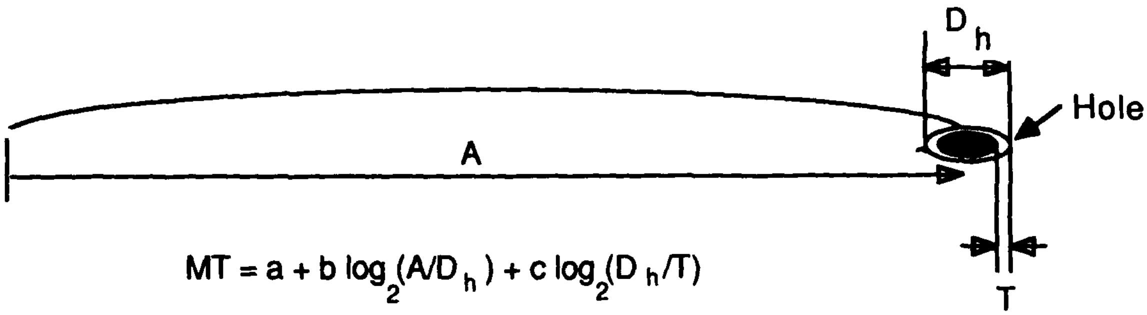
MT	=	Average Movement Time
ID	=	$\log_2(\frac{2A}{W})$ the Index of Difficulty
A	=	Movement Amplitude
W	=	Positioning Tolerance or Width
a	=	Slope Intercept
b	=	Increment or Slope of MT per unit ID

The movement time prediction in the preceding description, often referred to as "Fitts' Law," is extremely robust and typically accounts for well over 90 percent of the variance in MT, under a wide variety of experimental paradigms (see Welford, 1968; Keele, 1981; Schmidt, 1982; and Smyth & Wing, 1985 for extensive reviews). The prediction agrees well with Predetermined Time Systems (PDTS) used to predict manual-assembly performance in industry (Knight & Dagnall, 1967; Langolf, 1973) and serves as the basis for a microscopic movement PDTS (MTM-M, Langolf, 1973).

Fitts' research, and that of the following investigators, has proved that human movement behavior is orderly and predictable for a range of movement amplitude and accuracy requirements. Fitts argued that movement behavior would remain orderly, although MT/ID slopes might change, given different limb systems or task properties (e.g., wearing exoskeletal master controllers used for teleoperation).

The chief limitation of Fitts' Law is that one may not *a priori* predict the effects of new variables upon movement time capability; empirical analyses must be performed to obtain slope values. Once determined, however, changes in MT/ID slopes are very useful, from an engineering design and evaluation perspective. For example, MT/ID slope changes have been used to evaluate differences in movement capabilities of different limb systems. Langolf, Chaffin, and Foulke (1976) found that Fitts' Law held for finger, wrist, and arm movements; and that MT/ID slopes differed markedly between finger (26 ms/bit), wrist (43 ms/bit), and arm (105.8 ms/bit) movements. The technique has also proven to be useful in analyzing control design (Knight & Dagnall, 1967; Drury, 1975); manipulator performance characteristics (McGovern, 1975); and arm and shoulder posture upon movement and positioning capabilities (Wiker, 1986).

An alternative extension of Fitts' Law was proposed in which ballistic and other submovement components could be described by a set of Fitts' IDs. For example, one can adequately model a pin-to-hole task using two IDs; one for the ballistic component, the other for the positioning element (Welford, 1968; Hoffman, 1981; Chung, 1983; Wiker, 1986). The multistage model proposed is described as follows, and figure 4 gives an example output of the findings.

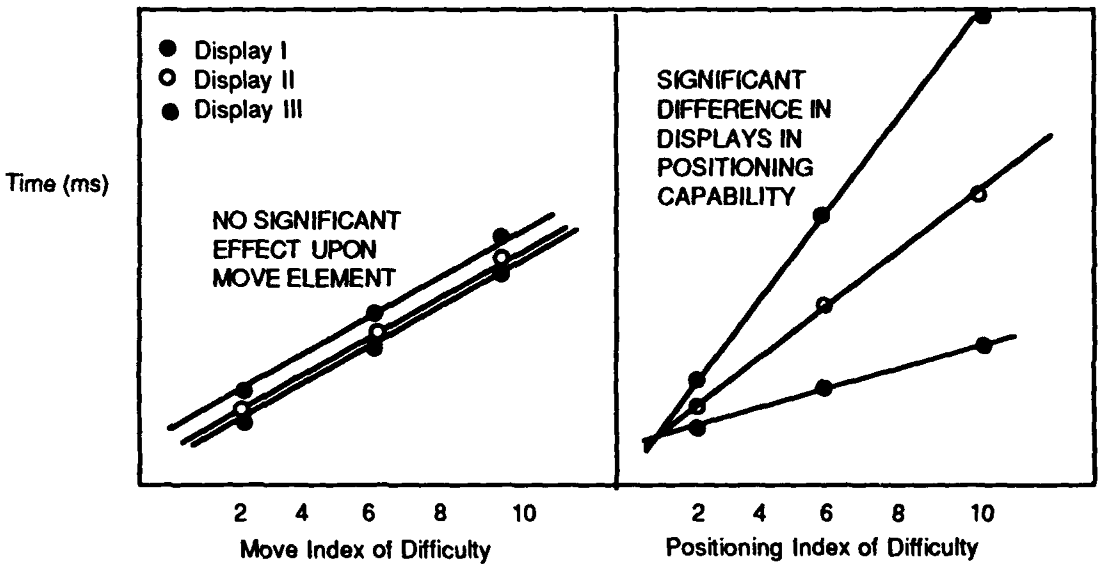


$$MT = a + b \log_2(A/D_h) + c \log_2(D_h/T)$$

Ballistic Phase   Positioning Phase

where:

A = Movement Amplitude
D = Target Diameter
T = Target Diameter-Pin Tolerance
b, c = Regression Coefs or Slopes



Example of Findings

Figure 4. Example output from a multistage Fitts' model of movement performance.

Table 1 lists several data sets of movement time that have been fit with the model and MT/ID slope coefficients for each submovement.

Table 1. Summary of MT/ID regression coefficients obtained from fitting pin-to-hole transfer time data using Hoffman's (1981) model.

Data Source	Slope Coefficients (ms/bit)		
	b_1	b_2	R^2
Schouten (Westhoff, 1964)	140	54	.973
Work Factor PDTS (Quick et al., 1962)	117	58	.953
DMT (Geppinger, 1955)	121	39	.944
Annett, Golby, and Kay (1958)	120	64	.999
Chung (1983)	106-131	17-40	.972-.996
Wiker* (1986)	74-93	25-37	.980-.995

*For arm postures comparable to those used in studies noted above.

A significant advantage of this approach is that one can (a) characterize and quantify performance advantages offered by a particular display design and (b) predict where the modeled display would prove effective in manipulative tasks characterized by a set of Indexes of Difficulty.

Methods and Materials

The task proposed, and associated apparatus have been designed, to simulate several teleoperator assembly activities (e.g., application of powered nut-drivers, welding guns, powered screw drivers, drills, and insertion operations), while producing basic movements amenable to more general analysis. The insertion task, like those in industry and the field, requires that movements be completed, and completed within specified spatial accuracy. Movement performance will be evaluated by recording average move and positioning time intervals for discrete movements of a virtual end effector grasping virtual solids and performing an insertion task. The principal advantages of this apparatus are as follows:

a. The geometry of the manipulator and end effector may be changed quickly and economically.

b. No significant maintenance costs nor concerns exist over the mechanical reliability of the manipulator system, other than those of the computer system, itself.

c. Experimental findings are not bounded nor perturbed by the physical limitations of a specific manipulator (e.g., inertia, friction, stiction, backlash, etc.).

d. Virtual tactile sensors, with spatial resolutions and frequency response that far exceed those of current and near future systems, may be placed anywhere upon the virtual end effector.

e. Integration of visual and tactile presentation of contact stimuli is much more straightforward.

Figure 5 shows the schema, along with the status of apparatus construction.

During experiments, subjects will make discrete movements of the virtual manipulator and transport an object from a standard point to a hole, where the object is inserted. This behavior is repeated under a range of Indexes of Difficulty (i.e., different movement amplitudes and positioning tolerance ratios) until a statistically reliable set of slopes is obtained (about 12 IDs with 10 to 20 replications each per subject) for each candidate display system. Multiple least-squares regression models will be constructed within and across subjects for comparing display benefits in terms of move and positioning capability.

EXPERIMENT III

Impact of Tactile Displays Upon Information Transmission

Tactile displays offer the potential to convey tacteme information to the operator for constructing more complex tactual features. If so, this increases the overall information (and possibly the rate of information) transmitted to the operator about the object grasped or explored. Operators will then be able to make better decisions about selecting and using motor programs, and will face less difficulty in identifying or recognizing objects. One tool that has reliably served as an information metric is the Shannon-Wiener formula for information transmission (see Attneave, 1959).

The goal of this approach is to determine how much information is transmitted to the operator (referred to as T(,x;y)) and how much is lost. To compute T(,x;y), we (a) estimate the amount of information provided in the joint occurrence of a particular stimulus-response combination [H(x;y)], (b) estimate the conditional probability of a response given a particular stimulus [Hy(x)], and (c) estimate the conditional probability of a stimulus given a response [Hx(y)]. See figure 6 for the calculation method, described by Attneave (1959), in which information transmission was imperfect. Perfect transmission is characterized by responses falling only in the superdiagonal; every stimulus was properly identified.

With the first set of trials, subjects will receive complex, but controlled, point, edge, and area stimulations, corresponding to a set of geometric entities equivalent to Stansfield's (1986) list of tactemes. Confusion matrices will be constructed for each subject after completing sets of trials with each of the candidate displays. Subjects will

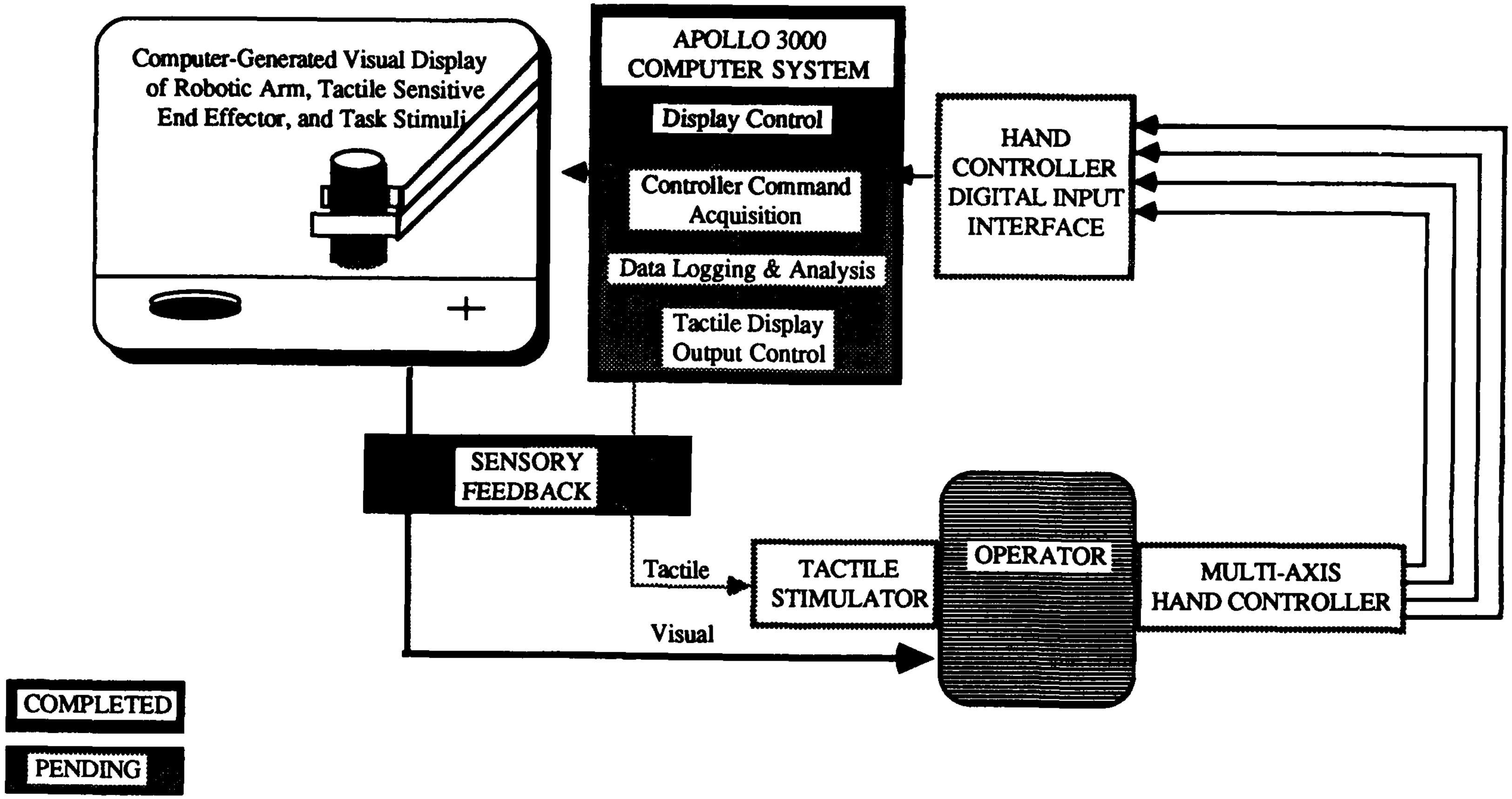


Figure 5. Tactile-display development of an experimental apparatus.

Imperfect Transmission

	Response 1	Response 2	Response 3	Response 4	Row Σ	Pj	Pj•log2(1/Pj)	
Stimulus 1	20	5	0	0	25	0.25	0.5	
Stimulus 2	5	15	5	0	25	0.25	0.5	
Stimulus 3	0	5	15	5	25	0.25	0.5	
Stimulus 4	0	0	10	15	25	0.25	0.5	
Column Σ	25	25	30	20	100		2	= H(s)
Pi =	0.25	0.25	0.30	0.20				
log2(1/Pi) =	2.00	2.00	1.74	2.32				
Pi•log2(1/Pi) =	0.50	0.50	0.52	0.46				

H(r) = ΣPi•log2(1/Pi) =	1.99	bits
H(s,r) = ΣΣPij•log2(1/Pij) =	3.11	bits
H(t) = H(s) + H(r) - H(s,r) =	0.88	bits

Figure 6. Imperfect transmission of information.

then use the display to actively explore and identify tactually discriminable shapes used for lever-handle coding per AFSC DH 1-3, 1977. If subjects assemble tactemes into more complex features, then displays which convey the most information about these primitives should also prove superior, when confronted with very complex, but haptically discriminable objects.

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APPENDIX A

TACTILE-SENSING TECHNIQUES FOR TELEROBOTS

Within the last decade, substantial progress has been made in tactile-sensor technology. Commercial manufacturers now offer sensors that can provide information well beyond that of simple contact-switch, force-probe, or strain-gauge devices. A variety of devices differing in transduction methods and signal analysis requirements can be found in industry and experimental laboratories. This summary focuses upon strategies used for transducing contact stimuli and extracting information peculiar to prehensile object recognition.

TRANSDUCTION METHODS

Several methods have been proposed or developed for transducing micromechanical and other contact stimuli encountered during physical interplay between objects or surfaces and robotic end effectors. Transducers developed thus far may be classified as switch, piezo, capacitive, magnetic, or photomodulation-based devices. In the following paragraphs, each mode of transduction is described briefly, and representative examples are presented. Figure A-1 summarizes the range of techniques used to transduce contact stimuli and provides graphics of representative sensor devices. Table A-1 summarizes the sensing capabilities reported for the principal modes of transduction.

Contact Switch Devices

Switch devices are typically used in manipulator applications where knowledge of a suprathreshold contact force is of principal interest. A pin or forcel, coupled to a spring, cantilever beam, or other elastic element, is physically displaced; and if forces applied are sufficient, continuity is established between a set of electrical contacts. There are a number of examples of this sensing approach. In some cases, small microswitches have been used to line the surface of the robotic end effector (Inoue, 1971). In others, arrays of pins have been built, which, when displaced by collision with objects or surfaces, result in contact between a conductive elastomer membrane and an underlying metal electrode (Goldgewicht, 1974).

The advantages of using traditional forms of contact switches are that they are simple in design and implementation, and are capable of functioning reliably in harsh environs. In addition, they offer linear behavior, with almost no hysteresis, and require minimal signal analysis. On the other hand, contact switches provide limited force information; one has or has not exceeded a suprathreshold force at the switch. In addition, object or surface compliance cannot be gaged; and because of limitations in miniaturizing mechanical switch arrays, shape and texture detection is also limited. Finally, employing switch-like sensors requires the use of control models that can tolerate open-loop performance, except for momentary corrections of cumulative error, when switch closing or opening occurs.

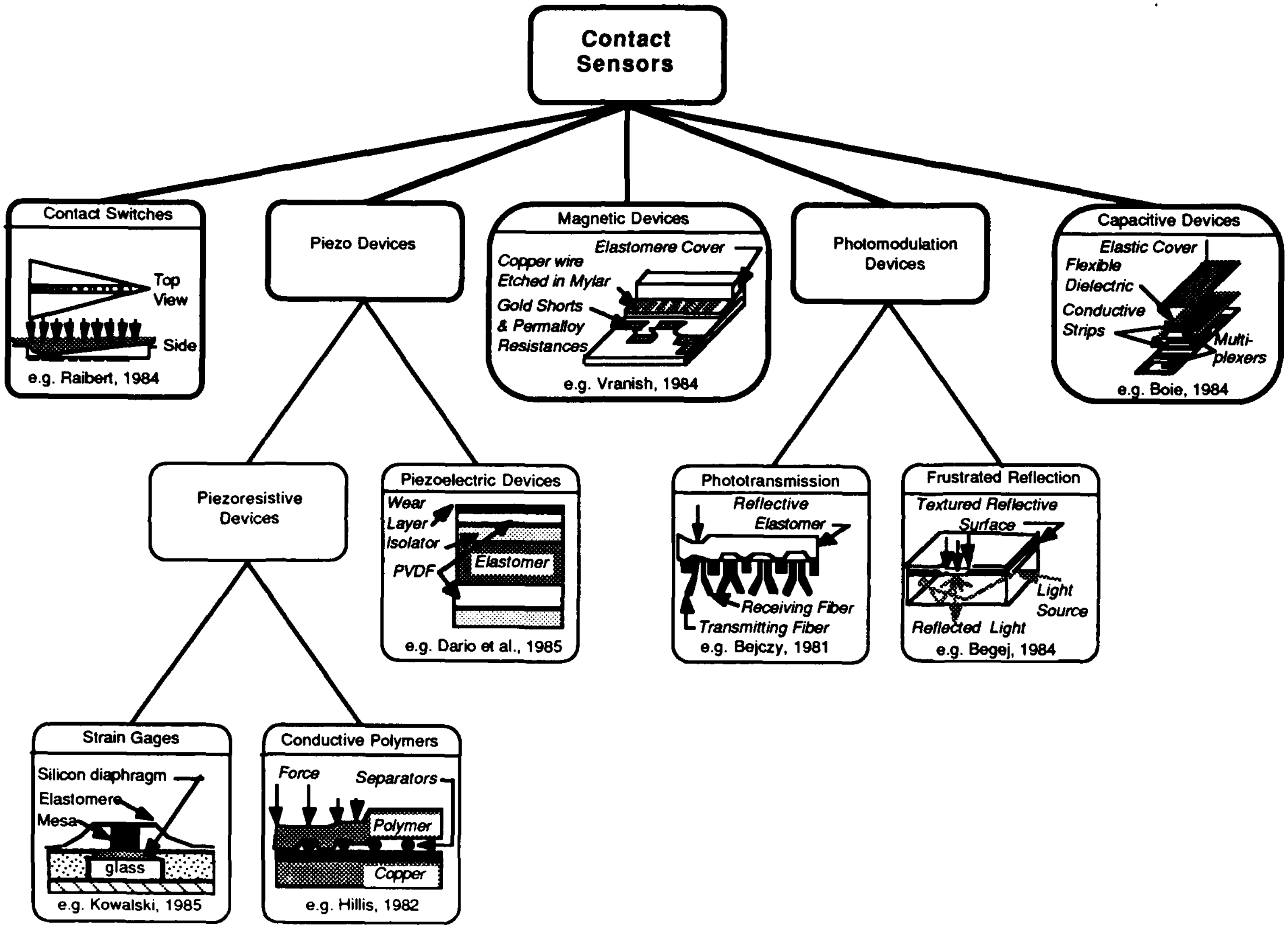

Figure A-1. Technological taxonomy of contact sensors.

Table A-1. Summary of capabilities of array-based tactile sensors.

BASIS OF TRANSDUCTION	DEVELOPERS	SPATIAL RESOLUTION (mm)	FREQUENCY RESPONSE (Hz)	FORCE SENSITIVITY (N)	RESPONSE RANGE (N)
IDEAL	**Harmon, Case Western**	**1.0**	**1000**	**0.01**	**0.01-9.81**
PHOTOMODULATION	Lord Corporation Schneiter and Sheridan, MIT Tactile Robotic Systems	0.6-2.5	12-333	0.0004-0.03	0.1-6.68
PIEZOELECTRIC	Dario et al., University of Pisa University of Florida	0.3-3	100	0.20	0.20-784.80
PIEZORESISTANCE	Hillis, MIT Purbrick, MIT Transensory Devices Inc. Barry Wright Corp.	0.6-2.0	30-40	0.05-2.26	0.5-490.0
CAPACITIVE	Siegal et al., MIT	1.9	-	0.02	2.00

Adapted and modified from Pennywitt, 1986.

A nontraditional and ingenious development in contact switch technology was achieved by investigators at Carnegie-Mellon University and Cal Tech (Raibert & Tanner, 1982 a,b; Raibert, 1984). The latest sensor described by Raibert (1984) consists of a conductive elastic layer overlying a VLSI chip in which an array of tapered notches is carved into the silicon-dioxide overglass. Pressure applied to the wear-surface causes the conductive elastomer to protrude into the cavity and contact one or more of the metallic electrodes arranged in a linear grid at the bottom of the notch. As force levels are increased, the elastomer protrudes up through the narrowing notch and incrementally and sequentially contacts the metal electrodes aligned in a linear grid upon the base of the notch. Thus, the grid of electrodes performs a mechanical analog-to-digital conversion of force inputs. Along with economizing upon digitization circuitry, the investigators have exploited VLSI techniques to permit local and parallel processing of digital representations of forces. Force-response characteristics can also be modified by selecting an elastomer with the desired modulus of elasticity, or varying the geometry or size of either the notch in the overglass or electrode grid. Overall, the design is quite attractive to applications where

a. central-processing capabilities and power requirements must be minimized.

b. a composite of incremental forcel sensitivities must be intermingled within a sensor surface.

c. surfaces for sensor mounting are fairly planar.

d. the risks of significant over-force or high electrical fields are low.

e. low cost is not mandatory.

Piezo-Based Devices

A large number of contact sensors have been based upon the changes that occur in the electrical properties of certain materials when subjected to mechanical or thermal stress. In some materials, stress produces changes in electrical resistivity; while in others, stress generates small transient electrical currents.

Piezoresistive Devices

Metals, silicon, and several conductive materials have demonstrated piezoresistive effects; that is, changes in electrical resistance when subjected to mechanical stress. This class of contact sensor, often referred to as strain gages, generally exhibits good sensitivity, response linearity, limited hysteresis, good signal-to-noise ratios, response stability, and adequate frequency response. However, piezoresistive devices typically offer limited spatial resolution of forces and are relatively expensive. Exceptions to this characterization are found with piezoresistive polymers, which offer pliable conformable arrays at the expense of signal hysteresis and poor durability.

Metal Strain Gages. These gages consist of metallic conductors (e.g., wire or metal foil) bonded to beams or other objects of interest. They have been employed for several years to measure strain produced in response to force, torque, pressure, displacement, or acceleration stimuli. Deformation of the structure and the gage provokes a positive or negative shift in gage resistance. Metal strain gages are reliable, fairly linear in behavior, exhibit limited hysteresis, and can resolve a force-torque system in three space, if rosettes of gages are properly positioned about the structure (Critchlow, 1985).

Metal strain gages are also susceptible to noise or drift, when exposed to other physical stimuli (e.g., temperature shifts, corrosion, and so on). Some extraneous stimuli, such as thermal drift, can be counteracted by adding a compensating gage into the bridge circuit. This additional gage is exposed to all but the mechanical stimuli.

Silicon Strain Gages. These gages are based upon the same principle as metal gages, but offer some advantages. Higher gage factors found with silicon devices permit increased force sensitivity. Silicon enables forcels to be highly miniaturized and densely packaged, without encountering significant electromechanical connector burdens. In addition, it permits the processing circuitry to be placed on the same chip as the piezoelement.

However, silicon does have drawbacks. It can be stiff, fragile, and difficult to mount on nonplanar surfaces. Forcels can be micromachined to obtain flexibility, but at the expense of sensitivity (Kowalski, 1985). To ensure adequate end-effector friction, sensors also have to be covered with a compliant elastomer wear surface, which can introduce hysteretic behavior.

An example of a strain gage application can be found with Peruchon's dynamic touch probe which is sensitive to both static (position detection) and dynamic (force detection) stimuli (Peruchon, 1979; cited in Coiffet, 1981). A rod-like probe (3 mm in diameter by 12 cm long) contacts the object and transmits forces to the central part of a flexible, cross-shaped blade; the blade is equipped with three gage bridges that detect the normal force component of the pressure and the moments about the x and y axes. The probe is moved about the object of interest under computer or manual control, continuously recording forces and moments in Cartesian space to produce scan contours of the object or surface explored. An ingenious extension of this design can be found in the bonding of eight pairs of gages upon a Maltese Cross structure mounted within the most distal digit of a robotic hand (Brock and Chiv, 1985).

To overcome some of the fabrication limitations encountered with metal and silicon gages, and to provide improved spatial resolution of contact pressures, some investigators have experimented with *piezoresistive polymers and carbon fiber felts* (Larcombe, 1981). Though they are limited in number, the materials that exhibit piezoresistive properties are inexpensive, tolerate wide ranges in temperatures, and permit construction of conformable arrays of forcels. The chief disadvantages encountered are that piezoresistive polymer materials are often noisy, frequently exhibit nonlinear and hysteretic responses, are highly susceptible to drift, and often fatigue at unacceptable rates with repeated use.

Purbrick (1981) developed a conductive silicon rubber array in which both row and column electrodes are made of conductive silicon rubber. Row and column elements are lengths or rubber, formed convexedly to minimize the area of contact between electrodes, as well as to reduce resistance to current flow between electrodes in the unstressed state. When force is applied, the array rubber electrodes are deformed; and the area of contact increases, resulting in a logarithmic decline in electrical resistance. The design has several advantages. It offers good force sensitivity and pressure resolution, uses sequential scanning techniques, is inexpensive, and can withstand large force overloads. Aside from the operational limitations of using a conductive elastomer, Purbrick reported non-trivial drift in the baseline signal after 5 minutes of use.

Hillis (1982) built a 1 cm^2 16 by 16 array using an anisotropic conductive elastomer laid upon an intervening separator and, subsequently, a circuit board etched orthogonally to the elastomer's direction of conduction. The separator served to isolate the conductive polymer from the PC board, when contact forces were removed. As contact force was applied to the wear surface, the conductive elastomer protruded through the separator material and contacted the printed circuit (PC) board. Force magnitudes were correlated with the contact area, and ultimately, current flow between the elastomer and underlying electrode surface(s). Both force sensitivity and response range were found to depend highly upon the properties of the separator material. For example, large force ranges were obtained with a sheet of nylon stocking serving as the separator. On the other hand, limited response range, but high sensitivity, was obtained when the separator consisted of nonconductive paint particles sprayed between the elastomer and PC board. These devices are reported to be rugged and to tolerate overforces; however, force response curves obtained showed nonlinear behavior.

Overton and Williams (1983) developed a sensor using an 8 by 16 array of hairpin loops of conductive silicone rubber embedded within a thin (25 by 25 by 8 mm) silicon rubber cube. Each forcel was capable of reliably responding to a 10 percent of full-scale (0 to 8.8N) loop deformation force. The entire array could be sequentially scanned at a rate of 44 Hz.

Development efforts with conductive elastomers have progressed to the point that a commercial sensor has been developed. The Barry Wright Corporation markets a proprietary conductive-polymer 16 by 16 array, which is claimed to possess limited hysteresis. Sequentially scanning the 4 cm^2 matrix at 30 Hz provides a 1:256 dynamic range with spatial resolution up to 1.3 mm.

In search of a more robust conductive piezoresistive material, Larcombe (1981) has used a filamental form of carbon woven into a felt. The carbon-fiber felt is quite robust and possesses a large dynamic range. Yet, like conductive polymers, the material can be easily formed about a variety of end-effector geometries. Larcombe has constructed a matrix of felt strips placed across one another to produce multistrip junctions and, thereby, spatial resolution of force application. Compression of the fibers reduced resistances of felt strips, which were sequentially scanned to determine force distribution.

Piezoelectric Devices

In certain materials, mechanical deformation or thermal absorption produces electrical polarization and generation of transient electric fields. Electrical charges produced are short-lived and decay with a time constant determined by the material's dielectric constant, internal resistance, and the input impedance of the electronic interface to the material. Recent advancements in materials have produced pliable piezoelectric films, such as polyvinylidene flouride (PVDF), which is rugged enough to withstand 120 °C, thousands of volts, and millions of Gs, before its piezoeffects are destroyed (Chatigny, 1984). These properties have interested investigators searching for "artificial skins" to use in prosthetic and robotic tactile-sensing applications.

Sensors based upon the ferroelectric* properties of PVDF are best exemplified by the work of Dario and his colleagues at the University of Pisa (Dario, P., DeRossi, D., Domenici, C., & Francesconi, R., 1984; Dario, P. & De Rossi, D., 1985). Studies of the basic properties of PVDF, and use of human skin as a development model, have led Dario and coworkers to develop a composite ferroelectric and conductive polymer tactile sensor capable of transducing both mechanical and thermal stimuli. The sensor consists of a formed printed-circuit board containing an 8 by 16 array of metal electrodes on 3 mm centers. It is produced as follows. A thick sheet of PVDF film is bonded to the PC board to allow capacitive transfer of its electrical activity to the electrode array. A sheet of pressure-sensitive conductive silicone rubber is then laid upon the PVDF film, referred to as the "dermal" layer, to enable measurement of static force. Finally, a thin layer of metal-coated PVDF film is used to cover and shield the conductive rubber layer. The outer layer of PVDF film is referred to as the "epidermal" layer and is used to detect very small pressure variations or vibrations, as required for texture analysis.

To evaluate thermal characteristics of objects, a thin layer of flexible resistive metallic paint was applied to the back of the "epidermal" layer of PVDF, with its temperature regulated at 37 °C by a dc power supply. Heat flow occurring between the PVDF film and the object contacted is determined by the thermal properties of the object. This was to be estimated by comparing differences in electrical activity between the outer and inner PVDF layers, which are partially thermally isolated by the intervening layer of silicone rubber.

Dario et al. (1985) argued that the sensor would provide the capability to sense and detect

a. fine contact, as well as vibrations experienced while exploring textured surfaces or when objects slip along the sensor's outer layer of PVDF.

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* Ferroelectric materials generate electric charges in response to either mechanical or thermal stress.

b. solid geometric and mechanical properties of objects by conveying differential pressures to densely packed electrode arrays beneath the inner PVDF sheet.

c. differences in the thermal properties of objects contacted by differential pyroelectric response between outer and inner layers of PVDF.

d. static force by changes in the resistance in the compressed conductive elastomer.

An alternative to using conductive elastomers for monitoring static force, or pressure, was to rely upon ultrasonic time of flight measurements (Dario et al., 1985). An inner layer of PVDF would be excited, transmitting ultrasonic pulses to the outer PVDF layer. Time of flight through the elastomer would be related directly to the extent of elastomer deformation.

Battelle Labs has also developed such a sensor using arrays of shaped conductors upon an excited layer of PVDF film segregated into forcels. Sequentially energizing the forcels in the transmitter array and recording time of flight in the receiving PVDF film (lying between an elastic separator and an elastic wear surface) provided excellent force-resolution capabilities for selected driving frequencies, and spatial resolution of force stimuli.

Capacitive Devices

Capacitance-based contact sensors rely upon changes in the impedance to ac-current flow through an elastic dielectric material sandwiched between parallel conductors. Impedance is reduced when contact forces reduce the separation between plates. Several tactile sensors have been developed using this strategy (Boie, 1984; Chun & Wise, 1985; Siegal, Garabieta, & Hollerbach, 1986).

One example of a capacitive sensor is provided by Boie (1984), who described an array of capacitors composed from a flexible three-layer sandwich. Flexible PC boards with electrode strips running orthogonally to one another comprised the top and bottom layers with an intervening elastic dielectric layer placed between the boards. Capacitor elements were formed at those locations where strips overlapped. An 8 by 8 forcel array, with an active area measuring 2.5 cm^2, allowed sampling rates of 390 Hz. The disadvantages of this sensor design were (a) only normal forces were detectable, (b) the top electrode strips were susceptible to puncture, (c) susceptibility to electrical interference was high, and (d) problems with mechanical and electrical cross talk had not been eliminated.

Later, Siegal, Garabieta, and Hollerbach (1986) built a more flexible 8 by 8 capacitive tactile array with 1.9 mm taxel spacing. Force-response characteristics of the sensor revealed large linear regions existed in spite of hysteresis. The array was augmented with a 4 by 4 thermal-sensing thermistor array and heating layer to provide thermal-sensing to aid in object recognition tasks. By monitoring the thermal-decay profile upon contact with the object, objects could be differentiated that possessed different thermal coefficients.

Capacitive-based sensors offer good sensitivity and spatial resolution of force, high-frequency response, the potential for forming about complex geometries (such as a finger-like end effector), and good signal-to-noise ratios in certain environments. The chief disadvantage of these devices is that they are susceptible to drift and exhibit poor signal-to-noise ratios when exposed to significant electrical fields commonly found in manufacturing areas (Critchlow, 1985).

Magnetic Devices

Given the variety of magnetic ranging or proximity sensors available in the commercial market, it is not surprising to find recommendations for developing magnetic-based contact-sensing systems. Recent design proposals have relied upon magnetoresistance, magnetoinductance, and the Hall effect to sense normal, and in some cases, shear forces. When subjected to changes in magnetic-field strength, magnetoresistance devices produce changes in electrical conductivity, magnetoinductive devices produce electrical fields, and Hall effect devices produce differences in charges between opposite sides of a semiconductor supplied with current.

Hackwood, Geni, and Nelson (1983) described a magnetoresistive sensor comprised of an array of magnetic dipoles embedded within an elastomer. Deformation of the elastomer resulted in displacement, changing the relative position of the magnetic dipoles with regard to permalloy magnetoresistor pickups. The electrical output from the magnetoresistor elements varies with alterations in magnetic-field strength resulting from dipole repositioning. Assuming the magnetic dipole behaves like a zero-radius rod, appropriately placed magnetoresistors could detect 5 degrees-of-freedom, translation, shear, and normal torque.

Vranish (1984) proposed a magnetoinductive approach for detecting normal forces applied to a thin elastomer. Within the elastomer was a dense matrix of wires carrying an ac current. Displacements of the "metallic glass" overlying small transformers were proposed to sense induced magnetic fields. Vranish felt that such a device could be used as an imaging skin, with forcel separations of 0.5 mm, and forcel sensitivities as low as 0.1 N, with a 9-bit dynamic range.

The Hall effect offers another method for measuring contact forces. Sensors may be designed so that contact forces displace Hall cell(s) toward a magnetic field. Force, or displacement, is calibrated against the change in potential produced when the current-carrying semiconductor is immersed farther into the magnetic field (Kinoshita, Ohishi, & Yoshida, 1983; Critchlow, 1985).

Magnetic-based contact sensors have only recently been considered as candidate contact sensors, thus requiring further refinement. However, present significant design and development problems must be faced. For example, the gage factor for normal forces is far less than that for shear or torque stimuli in Hackwood et al.'s (1983) magnetoresistive device. Shear-force information is important, but not at the expense of normal-force sensitivity. Magnetic-based devices are also very susceptible to noise from magnetic or electric fields, which are frequently encountered in robotic applications outside the laboratory. Finally, fabrication into flexible nonplanar surfaces can be difficult and costly.

Photomodulation Devices

Photomodulation techniques offer response sensitivity and spatial resolution of force patterns which are difficult to match by other transduction methods. The transduction scheme is essentially unaffected by the presence of significant electromagnetic fields, and offers the potential for detecting and measuring shear forces. For these reasons, photomodulation transduction methods are being developed at industrial and basic research institutions (Betts, Duckworth, & Austin, 1980; Bejczy, 1981; Rebman & Trull, 1983; Schneiter & Sheridan, 1984; Tanie, Komomya, Kaneko, Tachi, & Fugikawa, 1984; Mott, Lee, & Nicholls, 1984; Begej, 1984, 1985; White & King, 1985; Schoenwald, 1987*). Development activities have focused upon either modulation of phototransmission or frustration of internal reflection.

At present, two photomodulation techniques are used. The first method uses disruption of light transmission at photo-optical junctions. Devices currently marketed by the Lord Corporation rely upon displacing a pin attached to an elastic element, which shades, and can ultimately occlude light transmission between pairs of phototransmitters and receivers. Another commercially available sensor, produced by Tactile Robotic Systems, measures the degree of disruption of phototransmission across a fiber-optic junction which is misaligned when the forcel is displaced. Disruption of phototransmission is proportional to the force experienced (Hill & Sword, 1973; Rebman & Trull, 1983).

An alternative photomodulation technique is currently under development at Rockwell International (Schoenwald, Thiele, & Gjellum, in preparation). The sensor consists of eight optical fibers arranged in an equispaced linear-array matrix of sensor sites, created by a row and column arrangement of fibers. The rows are separated from the columns by either a transparent or opaque elastomer with light-transmission channels drilled at row column junctions to permit direct optical coupling. Forces applied to a wear surface compress the elastomer and increase phototransmission by decreasing the transmission distance at junctions. Optical-fiber surfaces were abraded at intersecting points to enhance coupling of light radiation from one fiber to the other. Normally, no light would radiate from the fibers for the kind of lateral deformation experienced in this design. Fibers in one array are sequentially excited by light-emitting diodes. Fibers in the receiving array are completely scanned during the time interval that a single transmitter fiber is excited, and receiver fibers are connected to photodiodes which are sequentially scanned to detect differences in phototransmission.

*Personal communication.

To achieve greater spatial resolution of contact forces, some investigators have developed methods to characterize the degree and pattern of elastic-membrane displacement. Bejczy (1981) attached 16 pairs of fiber-optic cables (one fiber serving as the phototransmitter, the other as a receiver) to a transparent elastic membrane which possessed a reflective wear layer. Forces applied to the membrane distorted the reflective surface, reflecting light away from the receiving fiber. Receiving optical fibers captured the reflected light and transmitted it to a photodiode matrix for recording and analysis. Later, Schneiter and Sheridan (1984) economized the design by treating each optical fiber as a phototransceiver and then densely packing the membrane with additional fibers. Spatial resolution was increased significantly to 0.6 mm between fiber-optic array elements which were scanned using a television camera.

In another strategy, light is transmitted into the side of a transparent plate. A textured reflective elastic membrane is placed upon one side of the plate, and a photoreceiving device is attached to the opposite side. The remaining surfaces are reflective. Forces applied to the membrane result in sections of the membrane contacting the surface of the plate and then reflecting light directly across to the photoreceiver. The principal differences between devices among investigators was the method used to record reflected light. Tanie, Komomya, Kaneko, Tachi, and Fugikawa (1984) used a photodiode array to record light patterns and intensities; while Mott, Lee, and Nicholls (1984) used a solid-state camera. Begej (1984, 1985) relayed visual patterns, via fiber-optic cables, to a remote camera to aid in miniaturizing end effectors. In general, these sensors performed superbly and in a similar manner. Any variations in performance were due to the nature of the elastomer's texture, its modulus of elasticity, and the resolution and sensitivity of the photoreceiver.

In summary, both techniques of photomodulation and frustration of internal reflection offer good response sensitivity, excellent spatial resolution of forces, tolerance of electromagnetic fields, and the potential for detecting and measuring shear forces (White & King, 1985). The present drawbacks with photomodulation devices are that densely packed fiber-optic arrays often do not adequately tolerate prolonged usage or abrasion; and the large number of optical fibers, along with the photodetection devices, is difficult to accommodate when mounting the devices upon small nonplanar structures.

INFORMATION EXTRACTION

Until recent years, tactile sensors were crude; and force stimuli were recorded as either binary suprathreshold inputs for confirming contact, or as calibrated analog or digital signals used to measure and regulate (via servo-control) gripper forces. Though rudimentary estimates of object boundaries could be derived from end-effector postures recorded during successive controlled-grasping movements, these data offered little difficulty from the standpoint of signal recording, processing, or interpretation. For this reason, little technique development could be found for analyzing tactile information, until the arrival of array-based sensors, which provided information beyond that of normal force (e.g., shear, torque, thermal, texture, etc.).

In some respects, tactile images pose fewer difficulties in extracting information from sensor records. The tactile image is local and, thus, is not cluttered with extraneous background stimuli. The image obtained can be relatively noise-free; and many existing visual-image processing and interpretation techniques (e.g., thresholding, filtering, mask or template analysis and matching) can be used to evaluate the tactile image. Finally, many of the tactile primitives described by Stansfield (1986) can be easily and quickly extracted without significant computational demand, and can be used directly for pruning search space and for probabilistic evaluation of remaining candidate objects.

However, difficulties are encountered when analyzing tactile images. The mechanical contact required for the object of interest can distort its form and present deceptive images. Cases also exist where visual-image processing algorithms fail when applied to tactile-imaging problems. For example, Ellis (1986) describes analytical failures with tactile imprints of textured surfaces when visual imaging techniques were employed for characterizing texture. Failures were attributed to (1) limitations in the density of step discontinuities and (2) poorer step localization typically encountered with tactile images. Finally, a most difficult problem lies in scheduling and controlling contacts or movements the tactile sensor makes (Schneiter, 1986) about the object. As previously noted, the tactile sensor is often smaller than the object of interest and provides only a limited sensory experience in any given grasp. Repeated contact is required for object recognition. Although the goal is clear (i.e., to obtain only as much information as is needed to identify the object in as few movements as possible), a generalizable strategem has yet to be devised.

We should consider developments in tactile-image analysis strategies as being in their initial stages. Candidates are being proposed (Stansfield, 1986) for tactile primitives and hierarchies to be used for deriving more complex haptic features. Psychological studies have also begun for finding procedures humans use for haptically exploring and discriminating the object's "form, substance, and function" (Lederman, 1982; Klatzky, Lederman, & Metzger, 1985) and for establishing corollaries useful in the robotic domain (Bajcsy, Lederman, & Klatzky, in press).

CONCLUDING REMARKS

Impressive developments in contact-force transduction have occurred over the past decade. A few experimental devices have demonstrated sensing capabilities exceeding several criteria that Harmon (1985) viewed as ideal not more than a few years ago. However, significant development hurdles still remain to be cleared in transducing and extracting information from tactile-sensor inputs.

For transduction, further efforts must be made to (a) detect and measure shear and torque forces at the surface of the sensor, (b) find or develop flexible materials with low hysteresis and limited fatigability for use in constructing and protecting sensors, and (c) improving packaging systems for sensors mated to dextrous anthropomorphic end effectors operating in space, the deep sea, and in other harsh environs. The few sensors that now provide some form of shear or torque information do so at the expense of device compactness and normal force sensitivity, or require relatively clean operating environs to prevent the mechanical slip-sensing elements (Harmon, 1985) from clogging.

New materials must be found or developed to improve linearity and the range of sensor response and flexibility, while concurrently increasing material robustness and tolerance of the inevitable abrasion encountered with robotic manipulation. Such limitations face all high-performance transducers developed thus far.

At this point, greater thought must also be given to sensor packaging. Prototype transducers which offer excellent force sensitivity and spatial resolution also present difficulties when integrating them (1) into relatively small dextrous anthropomorphic end effectors or (2) aboard autonomous mobile robots that must economize on both size and energy demands. Furthermore, packaging schemes must anticipate the need for frequent replacement; particularly, when robots are placed in operating environs where access is difficult due to distance or because of biohazards. Damage will inevitably occur to tactile-sensing elements placed upon robotic end effectors; and robust processing algorithms, or human operators, will probably not function well when large numbers of forcels are damaged and are not replaced nor repaired.

The most significant difficulty facing development and application of future tactile sensors is the lack of a grammar for haptic sensing. Present sensor capabilities allow detection and recording of many primitives believed to underlie the haptic sense. These primitives must be assembled and combined with other sensor data (e.g., posture, kinesthesia, vision, etc.) to permit discriminating touch and to sufficiently characterize, in realtime, the essential micromechanics of manipulation. Present algorithms are efficient only for simple manipulation tasks or when using a highly constrained search space for object identification. Increasing the difficulty of object identification, or relying upon multiple tactual cues to complete complex manipulations, demands human intervention to fuse, selectively filter sensor information, construct and test percepts, and to plan and execute control over manipulators. Until a valid haptic model and hierarchical control schema are developed, the following processing criteria will be difficult to implement:

a. ensuring that transducers are properly designed for acquiring requisite touch features.

b. guiding decisions about end-effector geometry and the spatial organization of sensors.

c. optimizing data-acquisition procedures; i.e., both information extraction and timely execution of probing and grasping movements.

d. optimizing construction and transversal of object search space.