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TACTILE FEEDBACK FOR TELEOPERATOR SYSTEMS
PREPARED BY M VERCRUYSSEN, SEACO, INC.

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Tactile Feedback for Teleoperator Systems

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Visual and auditory feedback systems in teleoperators have been used in a variety of ways. Although, tactile feedback to remote operators is one of the most important types of sensory feedback in teleoperator systems, such displays have not been implemented because development has been slow. This paper is intended to assist researchers in initiating research efforts involving tactile feedback in teleoperators. Included are brief descriptions of teleoperator systems, the concept of telepresence, the psychophysics of tactile sensing, the research literature available, and a follow-up experiment.

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ABSTRACT

Visual and auditory feedback systems in teleoperators have been used in a variety of ways. Although, tactile feedback to remote operators is one of the most important types of sensory feedback in teleoperator systems, such displays have not be implemented because development has been slow. This paper is intended to assist researchers in initiating research efforts involving tactile feedback in teleoperators. Included are brief descriptions of teleoperator systems, the concept of telepresence, the psychophysics of tactile sensing, the research literature available, and a follow-on experiment.

CONTENTS

INTRODUCTION

Teleoperators or telerobots are semi-intelligent remote controlled operators that perform a variety of tasks and provide feedback in the form of audio, visual, and tactile information to the human operator with a complete array of displays and controls in a remote locale. These teleoperators exist in a crude form today as industry's robots. If the computer was the single most significant invention of the twentiety century, the area of technology to benefit most from the advent of microcomputer chips is teleoperators. A glimpse further into the future reveals a time when human will be sheltered from adverse environments by telerobots/teleoperators. Teleoperators will be used in environments too hostile or too remote for humans. These include environments such as the depth of space, remote ocean areas, and for dangerous jobs such as cleaning radioactive spills or other toxic wastes. In addition, the quality of life for handicapped people can be improved through research and development of teleoperators in the form of artificial limbs. The purpose of this paper is to introduce the reader to teleoperators, telepresence, developments in the areas of kinesthetic and tactile feedback and the necessity for more research in the area of tactile feedback in teleoperators.

TELEPRESENCE IN TELEOPERATORS

Teleoperators

Teleoperators are composed of four distinct although integrated systems: (1) operator display and control, (2) software functional subsystems, (3) a knowledge database, and (4) manipulator systems with associated sensors, as illustrated in Figure 1. The operator display and control system provides information regarding systems operation (visual, aural, and tactile) and includes any means of operator communication with the system.

[Insert Figure 1 about here]

The software functional subsystem contains five components (Larsen, 1985). One, the planner takes the job order in a high level description and converts it into a plan of action. Two, the executor is the program that accepts the plan for action and translates the plan into commands to initiate action much like an interpretive language for computers. Three, the monitor evaluates continually progress of the plan for task accomplishment on a real time basis. Four, the diagnoser receives reports from monitor, assesses progress and informs the planner of the present state of affairs and probability of successful completion after conferring with the knowledge database. Finally, the simulator receives inputs from all other subsystems and drives the operator displays.

The knowledge database in its most ideal sistuation is heuristic and contains all knowledge available to the teleoperator. Advances in research areas of artificial intelligence (AI) will much enhance the capability of the knowledge database and thus the teleoperator.

Larsen (1985) delineates the manipulator systems with associated sensors into two related systems: (1) the **perceptor**, which contains all of the sensing devices (cameras, force/torque sensors, strain guages, etc.) and (2) the **effector**, which contains all devices used in manipulation to accomplish the system objective.

As illustrated in Figure 2, there are three control loops involved in teleoperator system architecture: (1) the supervisory loop which is the operator interface for the system, (2) the autonomy loop which provides for operation of the system with very little operator intervention, and (3) the manipulator loop which is for low-level control of the teleoperator as in industrial robotic systems and relaying sensory infomation. Figure 3 shows various interactions of these three loops in different operating modes of the teleoperator. According to Larsen (1985), these are: (1) the **Factory Robot** which is simply a closed manipulator loop, (2) **Teleoperation** where the operator displays and controls are connected to the manipulator loop, (3) an **Intelligent Robot** with a highly sophisticated autonomy loop, and (4) **Supervisory Control**, an area that utilizes all three loops equally but also necessitates the most research. This latter made is the type of teleoperator used in satellite serviceing or in other remote locations.

[Insert Figure 2 about here]

[Insert Figure 3 about here]

Telepresence

Telepresence is the ability to project the human sense of presence to a remote site via a teleoperator system. Visual and auditory systems for teleoperator systems are well within the realm of todays technology. At the present time, however, we are still in the expreimental stages with tactile sensing capabilities. It is likely that with continuous advances in microprocessor development, we are arriving at the threshold of great advances in teleoperation. Robots are in utilized in an increasing number of industrial working systems such as assembly lines. Such systems will veventually replace heavy, dull, repetitive, and dangerous tasks in the work enveironment, thus making it safer for humans. Numerous applications are taking shape in todays military defense forces. Increasing technical advances in the field of teleoperation will probably bring teleoperators into our daily routines even more in the near future. The next few paragraphs describe the sensory projections of telepresence by individual senses.

Visual Displays

In a true teleoperator display, one of the most important projections of telepresence is probably the use of visual sense. This remote presence would not be as realistic, without the ability to see the environment and its interactions with the tasks teleoperators perform. Thus, it is not surprising that vision is the most developed of the sensory display systems in belepresence. Mono and stereo television systems in use with teleoperators today are high in resolution and vivid. Research involving hyperstereoscopic displays has shown great promise (SEACO, date unknown).

Research on psychophysical aspects of visual telepresence are ongoing in several center, including Naval Ocean Systems (NOSC), Hawaii. Pepper, Spain, and Cole (1984) have done encouraging work with retinal disparity and parallax cues using the NOSC helmet mounted stereo display (HMSD) and a isomorphic head-motion tracking system. The system consists of a flight helmet with two black and white, square one inch monitors, giving the operator three dimensional perception of the remote area. A system of color stereoscopic cameras with microcomputer controlled zoom, focus, light, and camera movement is currently being developed (Pepper, Spain, & Cole, 1984).

Auditory Displays

The NOSC dune buggy is an example of a teleoperator equipped with binaural hearing and the ability to transmit voice. This is accomplished via a fiber optic communication link that also sustains command and control signals for other systems incorporated into the system architecture. The majority of research done in the area of telepresent audition is in the area of simultaneous multiple stimulations and their effect on tactile displays. Quality of the aural/audio systems can be easily tested for voice quality at remote and local sites using objective electronic measures such as signal to noise ratio and frequency response measurement. Human factors engineers are involved in psychoacoustics research, this is concerned with the intersensory interactions and perturbations affecting tactile and visual communication using various methods (Sherrick, 1976). Research has been going on since the early 1960s in this area.

Tactile Displays

Gescheider (1970), a scientist who has done research with auditory methods of tactile stimulation, concludes that "comparisons between cutaneous and auditory sound localization has revealed that the skin can be used for sound localization with accuracy nearly as good as that for hearing." Thus, this is another possibility for aiding the development of cutaneous interfaces in teleoperators. Feedback to the operator is of the utmost importance in teleoperations. With visual and auditory feedback already introduced, attention will now be focused on tactile sensing, the major point of this paper.

The most significant determining factor in the success of a tactile display is its ability to utilize the natural capabilities of skin. Systems today do not fully utilize this capability. Cutaneous interface can be accomplished by a variety of methods, hwoever, the two most common are vibrotactile and electrotactile stimulation, respectively. Electrotactile is accomplished by passing an electronic current through the skin whereas vibrotactile stimulation uses mechanical stimulation in the form of vibrations.

TACTILE FEEDBACK

Measurements of the vibration sense have been conducted empirically by clinicians for several decades (Detre & Bunney, 1961). In fact, tactile research has been going on since the early 1940s. Tactile feedback in teleoperator systems is considered one of the most important research areas, but it represents also the biggest hurdle to overcome in development of a sensory complete teleoperator. Much tactile research has taken place and contributed enormously toward the development of a working tactile feedback system for teleoperators but at the present none have been implemented (Shoemaker, 1985).

Research in fields that are coincident to teleoperators is being conducted and progress is being made that overlaps into the areas of teleroperators. Sherrick (1975) states: "increased interest on the part of behavioral scientists will assure continued improvements in the quality of devices an methods for aiding the handicapped." Noll (1972) writes about a three dimensional man-made machine communication tactile device and says "you can 'feel' a three dimensional object that exists only in the memory of a computer." The possibilities of this breakthrough are immense coupled with the recent advances in microcomputer technology. This makes it possible to take tactile stimulation information, encode it digitally, then transmit and reconstruct the information at the remote interface for operator display. Geldard and Sherrick (1972, 1974) at Princeton have done much research on different effects of tactile stimulation such as:

sensory inhibition, phantom sensations, computer generation of vibrotactile patterns, anomalies of cutaneous localization and contactor size. As the state of the art advances the stimulation devices will become smaller and exhibit more characteristics of real skin. This is another limitation in tactile displays, constructing devices that elicit the same results as neurons in skin and that are also of comparable size. The next section will describe the psychophysics of tactile communication.

Psychophysics of Tactile Sensing

As already mentioned, there are both electrical and mechanical methods of tactile stimulation. Mechanical stimulation of the skin activates several receptor organs dependent on the characteristics of the stimuli. Three of these receptor organs are: intracutaneous receptors (IC), Pacinian corpuscles, and touch pads (TP) in hairy skin (Lindbloom, 1970). Of major concern are certain properties of these receptors, namely thresholds, rate of sensitivity, static sensitivity, critcal slope, and receptive field. The types of tactile displays used in a teleoperator system must be designed according to psychological stimulation parameters and the type of receptors involved in the display. An example would be the frequencies used in frequency discrimination of Pacinian corpuscles should range from 50-300 Hz, if this aspect is accounted for then one has to consider the overal frequency sensitivty of the area. According to Carlson and Spalla (1972), mechanostimulators have severeal advantages: they are bulky and difficult to attach firmly to awake subjects such as monkeys. Furthermore, the onset and offset times of stimulation are relatively slow, being governed by mechanical properties of both the device and the skin. Carlson and Spalla then proceeded to describe a system of electrocutaneous stimulation without the disadvantages of mechanical stimulation. Hawkes (1960) studied the circumstances under which a change may be expected in the slope of a line fitted to electrical cutaneous magnitude estimates and found it was possible to make explicit predictions about the change. Rollman (1969) discovered problems with sensory excitations caused by noise in the systems having a greater effect than the excitation of an added stimulus. These and other studies show electrical and mechanical stimulation are subject to psychological aberrations and that these aberrations must be considered when designing tactile stimulation systems. The next sections are devoted to discussions of electrotactile and vibrotactile stimulation.

Vibrotactile Stimulation

Vibrotactile stimulation is accomplished by subjecting the skin to periodic mechanical vibrations. The useful range of frequencies in vibrotactile stimulation is 10-300 Hz. Frequencies above this range tend to blend together and are not discerable as freqencies *per se*. The optimal range of stimulation is 150-300 Hz. The Just Noticeable Difference (JND) in amplitude is 1.5 dB or 20% change. This JND is not uniform throughout the body, however. The fingertips, for example, are more sensitive to vibrotactile stimulation than the thigh. Perception of vibratory stimuli by tactile means is sharper than by visual means. The largest area of concern in tactile stimulation is that of adaptation to stimuli.

Sensory adaptation is another factor which must be considered when designing vibrotactile displays. Hahn (1966) found that although there is much less adaptation to prolonged vibratory signals that to prolonged pressure signals, there is still enough vibratory adaptation that it must be considered significant. Masking also requires attention. This is the tendency to perceive areas of stronger stimulation and not notice areas of weaker stimulation. There are other types of illusions such as phantom sensations in areas between two vibrotactors. Early vibrotactors were electromagnetic devices such as relays or solenoids. Today, piezoelectric bimorph benders' oscillations are passed to transducers that affect a mechanical ouput to the skin.

Electrotactile Stimulation

Electrotactile stimulation is accomplished by electronic stimulation of nerve fibers. This form of stimulation is complicated by variations in skin impedance at differing times caused by sweat and vasodilation. Moore and Mundie (1972) found that experimental conditions commonly employed in psychophysical and neurophysical investigations of the tactile system may influence the mechanical characteristics of the skin-tissue system. Plutchik and Bender (1966) also found significantly different skin resistances according to gender. This may further support the possibility that gender differences in pain threshold reflect real differences in skin properties between men and women. Characteristics of this type of stimulation are dependent upon the type of waveform involved. Various types include: sinusoidal, monopolar, bipolar, and on/off bursts of bipolar. Szeto (1982, in Larsen 1985) found that monopolar pulses were less comfortable but produced clearer sensations. Saunders (1974, in Larsen 1985) found electrochemical changes in the skin associated with the monopolar pulses. Monopolar pulses also result in less adaptation. Problems associated with vibrotactile stimulation also occur in electrotactile phenomena such as phantom sensations and masking. Also, if the two stimuli are used in conjunction, electrotactile stimuli tend to mask the vibratory stimuli more effectively than vice-versa.

Coding Schemes

Coding schemes for information transfer of tactile sensory perceptions are numerous. These include: amplitude modulation (AM) and various frequency modulation (FM) techniques such as pulse width modulation, pulse rate modulation, and burst FM. Frequency modulation seems to be the better method of information transfer because of the wider range available. Szeto (1982, in Larsen, 1985) suggests simultaneous frequency and puls width modulation as the best technique for information transfer. Locus modulation is another technique available, this involves shifting the location of an active tactor in relation to the modulated signal. This technique more closely utilizes the skin's natural sensory function. There are other tactile display methods, including airjets, inflatable bladders, and braille. The most successful application of tactile displays other than braille is Optacon. The Optacon converts images from print to patterns on a vibrotactile matrix applied to the finger. Similar methods also used the abdomen and back. Although much research has been done with vibrotactics there has never been a tactile application in teleoperators (Shoemaker, 1985).

KINESTHETIC COUPLING OF TELEOPERATORS

There are controllers that make limited and direct use of knesthetic senses such as the NOSC head motion tracker, NASA-Ames arm and NOSC torso. True kinesthetic coupling of .teleoperators, however, is done only through bilateral force reflection systems (Shoemaker, 1985). These truly represent the state of the art. Controllers and manipulators of bilateral force reflecting systems exhibit a master/slave relationship, where controller is the master and the manipulator is the slave. Early systems were linked by cables and pulleys, but to be truly remote and have enough power to operate, bilateral servomanipulators are used now. These are equipped with servoactuators for each degree for freedom and the amount of force used is either one to one or in some ration with the slave. In order for force reflecting teleoperators to be effective they must be capable of following operator motions and exhibit a high degree of coupling. Gravity, weight, and inertia of the slave should be minimized so the operator can only feel a portion of the external force being applied, which can be accomplished by counter-balancing the slave. .

There are two types of control schemes in use today: position-position and position-force control. Position-position control forces exerted by master and slave units are equal and opposite. In the position-force control scheme, however, position error is a command signal sent back to the master. There must also be some degree of compliance when the slave comes in contact with a rigid object. Numerous compensation techniques are applied mainly to allow the operator to "feel" only the external forces and not those produced by the system. With the use of today's new microprocessors, such as the Motorola MC68000 (the central processor in Apple's MacIntosh), distributed digital control systems will greatly enhance stability and allow various operating parameters to be run simultaneously and adjusted by the software.

SUGGESTED FUTURE RESEARCH

Recommended future activities include the following:

1. Carefully examine Shoemaker's (1985) review of literature in this area.

2. Attached is an extensive computer search for resources related tactile and kinesthetic displays in teleoperation. Determine those most relevant and obtain the necessary manuscripts.

3. Write a research proposal (draft) and then schedule a visit to Carl Sherrick's Princeton laboratory before making the final copy. This visit may be the most important of all of the suggestions.

4. By whatever means necessary, get a data collection system operational as soon as possible. Let the obtained data dictate subsequent directions in which to focus. Along this line, the following proposed study may be useful.

Tactile feedback is of the utmost importance in teleoperator systems, since there are no existing tactile displays it is proper to suggest a few proposed research experiments. One experiment would be to add force transducers to the grippers on an existing teleoperator and interface them with the operator via strain gauges with digital readouts. Studies of the strain involved in picking up various items of different sizes could be done to produce a temporary, but functional, tactile display. If one wanted to go farther, the visual tactile displays bimorph benders and force transducers could be added to existing grippers and torsos without much difficulty. The gripper interface is self-explanatory, but including the force transducers on the torso could provide a display to assist operators in determining complian in force reflection systems. This may add a true representation of the force encountered by the back of the arm or other areas where the transducers and tactors are placed, thereby assisting the operator in assessing compliance.

SUMMARY

Contributions in coincidental research areas has helped to advance the quality of life for handicapped individuals and has contributed greatly to the development of teleoperator systems.

Telepresence is the ability to project one's sense of being into a remote environment by use of teleoperators that have sensory projections interfaced with the operator. Senses involved are primarily visual, audio, and tactile. There are systems today that use all except tactile feedback.

There are two methods of tactile interface: vibrotactile stimulation and electrotactile stimulation. Kinesthetic coupling may be accomplished through bilateral force reflecting systems.

Research and development in the area of tactile and kinesthetic senses is of paramont importance to accomplish development of a true teloperator system. There are no working tactile displays in a teleoperator system today (Shoemaker, 1985). This fact alone should awaken us to the necessity of tactile research if we are to stimulate teleoperator technology.

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LITERATURE SEARCHES

The attached literature searches (computer retrievals) were obtained through the Graduate Libraries of The University of Southern California. Ten databases were explored, including Psychological Abstracts, Medline, ERIC, INSPEC, NTIS, COMPENDEX.

The keywords used in these searches were:

Tactile, Vibrotactile,	|	Teloperator,
Electrotactile,	|	Robotic
Somatosensory,	|	Remote
Sensory,		Telepresence
Proprioceptive,	AND	Telechir?
Kinesthetic,		Telemanipulator
Electrocutaneous,	|	
Force Reflection	|	

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