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Human Sensory Feedback Research in the Armstrong Laboratory

Janet M. Weisenberger

ABSTRACT

The Human Sensory Feedback Laboratory, park of the Armstrong Laboratory at Wright-Patterson Air Force Base, Ohio, is involved in the development and evaluation of systems that provide sensory feedback to the human operator in telerobotic and virtual environment applications. Specific projects underway in the laboratory are primarily concerned with the information provided by force and vibrotactile feedback to the operator in dextrous manipulation tasks. Four specific research projects are described in the present report. These include: 1) experiments evaluating a 30-element fingertip display, which employs a titanium-nickel shape memory alloy actuator design to provide vibrotactile feedback about object shape and surface texture; 2) studies of a fingertip force-feedback display for 3-dimensional information about object shape and suface texture; 3) use of a force-feedback joystick to provide "force tunnel" information in pilot pursuit tracking tasks; and 4) evaluations of a 7 degree-of-freedom exoskeleton used to control a robotic arm. Both basic and applied research questions are discussed.

Speech and Hearing Science Ohio State University

Human Sensory Feedback Research in the Armstrong laboratory

The Human Sensory Feedback Laboratory, part of the Division of Biodynamics and Biocommunication in the Armstrong Laboratory at Wright-Patterson Air Force Base, Ohio, is involved in the evaluation of teleoperated systems. The basic mission of the Human Sensory Feedback(HSF) Laboratory is to investigate the role of sensory feedback in improving human-in-the-loop control of telerobotic and virtual environment applications. Although all kinds of sensory feedback are of interest in these applications, work in the HSF Laboratory focuses primarily on haptic feedback, specifically force, vibratory, and kinesthetic cues generated in object manipulation tasks.

The study of haptics, or active touch, encompasses a variety of cues generated from normal human sensing of objects. First, contact with objects generates stimulation of mechanoreceptors located under the surface of the skin. These cues, primarily of pressure and vibration, are referred to as *tactile* feedback. Second, object lifting and manipulation create forces exerted by the weight and stiffness of the object, that are directed back to the fingers and hands of the operator. These cues are referred to as *force* feedback. Finally, some cues about object shape and surface features are generated by the movements made by the operator in the act of sensing. These cues, consisting of information from joint and muscle receptors about the location and movement of limbs in space, are referred to as *kinesthetic* feedback. All of these sources of feedback combine to provide a rich sensory representation to the operator in object manipulation tasks.

Research Applications of Haptics

The utility of haptic feedback in research applications has not received as much attention as that of visual and auditory feedback. This lack of attention may be attributable in part to technical difficulties in creating high-fidelity displays to provide haptic feedback to the operator. The design of versatile, high-quality vibratory and force-reflecting actuators has proven to be technologically challenging. In addition, for many years researchers were convinced of the preeminence of visual feedback in object sensing tasks. Kalawaky(1993), for example, states that "the visual channel is the most important interface in a virtual environment system"(p.44). And in many situations, visual feedback dominates feedback from other sensory systems, particularly touch(e.g., in estimations of object shape, see Warren & Rossano, 1992). However, anyone who has attempted to perform a fine manipulation task, such as picking up a coin, wihile wearing thick gloves or while the hand is anesthetized, receives a powerful demonstation of the utility of haptic feedback. Even when visual feedback is present, the loss of tactile, force, and kinesthetic cues renders the operator clumsy and inefficient in even the simplest object manipulation task.

A further area in which the role of haptic feedback remains relatively unexplored is in virtual environment systems. Here again, many researchers assert that a high-quality visual display is all that is necessary to create a compelling virtual environment(NSF, 1992). However, Gilkey and Weisenberger (1995) recently argued that, if one of the goals of a virtual environment is to create a sense of "presence" or "reality" for the operator, a high-quality visual display alone is likely to be insufficient. Instead, they suggest that it is important to provide multimodal feedback, even if each individual modality is imperfectly rendered. Although the nature of the feedback provided to each sensory modality may vary across specific applications, haptic feedback is a crucial element of virtual environments designed for training in any dextrous manipulation task. Thus, there is an urgent need for the development of reliable, high-fidelity haptic feedback displays for virual environment applications.

These arguments apply equally to the development of telerobotic systems. In these systems, a haman operator controls the actions of a robot located at a distance from the operator. Telerobotic systems are of particular utility in situations where dextrous manipulation is needed, but the environment might be hazardous or inaccessibile to a human operator. Although a number of highly sophisticated master systems have been developed to allow control of robotic hands(see Hasser, 1995 for a review), the performance of fine manipulation tasks is impeded by the lack of sensory feedback provided to the human controller's hand. It is clear that the speed and accuracy of task performance will be enhanced when such sensory feedback is available.

A third area of application for haptic feedback is telemedicine, a term that covers a variety of situations in which the surgeon is either not physically present in the operating room, or is performing a surgical procedure at a location distant from his hands, i.e., with an endoscopic tool of some sort. In these situations, the end effector may be a considerable distance from the surgeon's hands, and the loss of haptic feedback from such an arrangement has been a common complaint. The transmission of force, stiffness, and textural cues to the surgeon's hands from the end effectors could provide considerable additional information to the surgeon, positively affecting the outcome of telemedical procedures.

Current Projects in the Human Sensory Feedback Laboratory

The research activities underway in the Human Sensory Feedback Laboratory are designed to address both basic science and applied questions, The general basic science question is, "How do humans process haptic information?" Recently-developed displays to provide vibratory and force feedback to the fingers and hand can be used to address this basic question, with the premise that if we can vary force and vibratory parameters to simulate the perception of a particular object or surface feature, we may gain some understanding of how humans use those same physical parameters in real object sensing. The more applied studies in the laboratory all address the fundamental question, "How can haptic feedback enhance task performance?" Implicit in this question is the notion that haptic feedback can improve speed and/or accuracy of performance in situations where available auditory and visual cues may be insufficient, or in situations where so much information is already conveyed through visual and auditory displays that the operator may suffer from sensory overload. In either case, the addition of haptic cues may supplement or substitute for cues provided via other sensory displays. In the following sections, several research activityies in the Human Sensory Feedback Laboratory are described, that address either the basic science question or the applied question raised above, or both.

1. Use of vibratory cues to convey shape and texture information

One set of experiments currently underway in the HSF Laboratory investigates the role of vibratory feedback to the fingertips in the perception of object shape and surface texture. This research employs a specially-constructed display designel by the TiNi Alloy Company (San Leandro, CA, USA). This display contains 30 actuators, arranged in a 5 column by 6-row array, that contact the index fingertip of the operator. The distance between actuators is approximately 3 mm, such that the overall display dimensions are about 1.2 cm by 1.5 cm. This display is shown in Figure 1. Each of the acuators is an L-shaped cantilever beam constructed from a berylliumcopper alloy, to which a length of titanium-nickel wire has been attached. The titanium-nickel combination is a shape-memory alloy, which alters its length in response to heating, accomplished here by the application of current. Contraction of the shape-memory wire causes the cantilever to pull upwards, contacting the fingertip. In the present design, a pulse-width-modulated current is employed, allowing the operation of the actuator at vibration rates between 1 and 200 cps. A more detailed description of this design is found in Hasser and Weisenberger (1993).

For the present investigations, the display was interfaced to the pointer(mouse) of a digitizing pad, such that the operator could place the fingertip on the display and move it about the digitizing pad in a manner analogous to real surface texture sensing. Virtual vibratory patterns, or surface features, could then be activated at various locations on the digitizing pad when the display arrived in the appropriate location. All of the

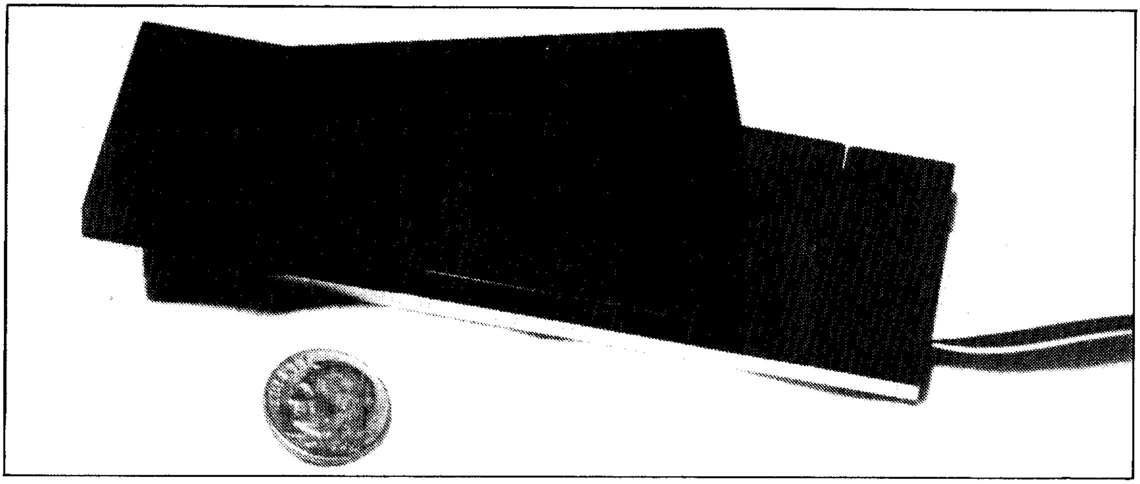

Figure 1. The fingertip shape-memory alloy display used in experiments on the role of vibratory feedback in haptic perception. Display manufactured by TiNi Alloy Corporation

hardware was controlled by a 386-based PC.

The initial work with this diplay addressed the issue of whether the kinesthetic feedback provided by muscle and joint receptors when the display was actively moved about the surface would enhance the recognition of object features. Earlier work in the perception of real textures(e.g., Lederman et al., 1986) indicated that some form of movement, either by the operator or by the surface, was necessary for accurate texture sensing. However, work by Craig (1981) in vibratory pattern identification suggested that moving patterns were actually more difficult to identify than stationary, non-moving ones. Because Craig's moving pattern conditions were accomplished by moving the pattern under a stationary fingertip, the observers in the study were not able to benefit from the addition of kinesthetic cues. Our investigation compared three different pattern presentation conditions : 1) a static condition, in which patterns were activated on the display at some vibratory frequency, remained for a brief time, and then terminated : 2) a passive scan condition, in which a stimulus pattern moved across the display from right to left under a stationary fingertip : and 3) a haptic scan condition, in which the observer moved the fingertip and display around the digitizing pad to sense the stimulus pattern. Figure 2 shows some of the stimulus patterns, which were constructed to resemble letters of the English alphabet.

Results for this experiment are described in detail in Weisenberger and Hasser(1997), and are summarized here. Overall findings are shown in Figure 3, and indicate that performance for the alphabetic stimuli was actually better for the haptic scan condition, across most vibration frequencies. Although this result was statistically significant, and

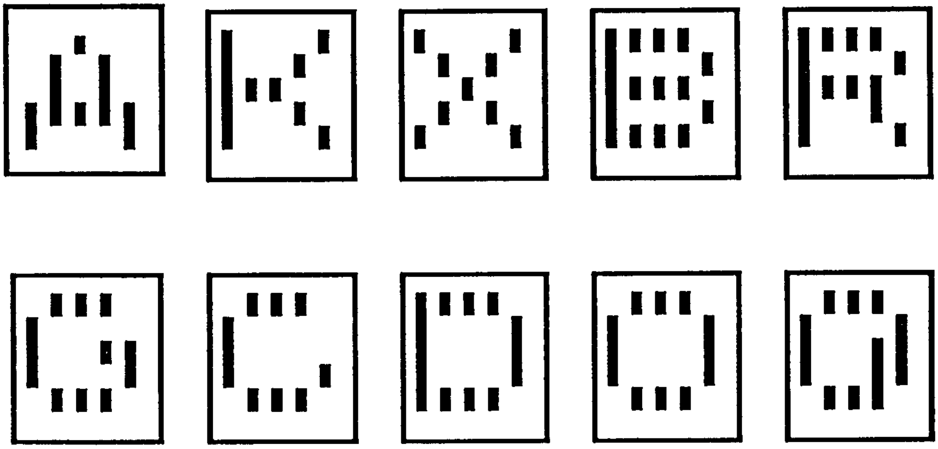

Figure 2. Stimulus patterns used in testing vibratory perception under static, passive scanning and active scanning conditions.

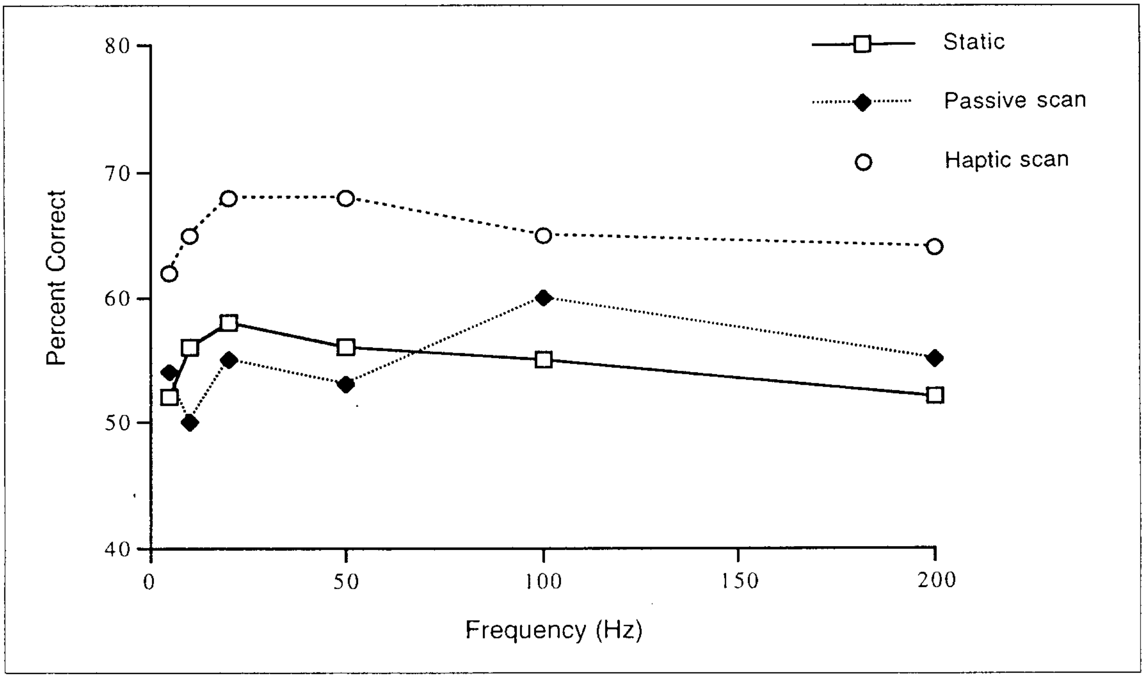

Figure 3. Percent corrent performance for five observers in identifying stimulus patterns, as a function of the vibratory frequency of the stimulus.

suggested that the kinesthetic feedback in the haptic scan condition did enhance performance, there were a number of differences across the presentation conditions that might have affected the outcome of the experiment. First, observers were tested with fixed-duration stimuli in the static and passive scan presentation conditions, but were given unlimited time to scan and examine the pattern in the haptic scanning conditions. Second, only a single stimulus presentation was permitted in the static and passive scan conditions, whereas observers could scan the stimulus repeatedly in the haptic scan condition. Finally, the passive scan condition presented moving stimuli only in the right-to-left direction, whereas in the haptic scan condition, observers could scan the pattern from any direction, thus possibly agining access to additional information.

Accordingly, a number of follow-up experiments were performed. Briefly, these experiments showed that the major factor in the improved performance of the haptic scan condition was the ability to scan the stimulus repeatedly. When observers were permitted to repeat the stimulus pattern as many times as desired in the static and passive scan conditions, performance for these conditions reached that for the haptic scan condition. Slight additional improvements were found for the passive scan condition when the observer could choose the scan direction on repeated presentations. Overall pattern duration per se was not an important factor in performance.

Thus, these experiments showed that the kinesthetic feedback provided by active movement did not provide a substantial amount of additional information for pattern identification. However, in further investigations we attempted to determine whether observers could use this kinesthetic information to compensate when other pattern information was not available. For example, in the experiments described above, all of the stimulus patterns were constructed to fit on the tactile display. But obviously not all stimuli that an obsever might encounter in real life would be the exact size of the fingertip display. Further, the engineering constraints in constructing wearable tactile fingertip displays would suggest that the display be as small as possible, perhaps smaller than the display tested here. If the display size were reduced, such that an entire pattern could not be perceived on the display at any given time, could kinesthetic feedback from active scanning of the pattern be used to supplement the missing spatial information?

This was the focus of the next set of experiments. Much of the literature on virtual displays argues that a large "field of view" is necessary for optimal task performance, as well as for the sense of "presence," or immersion in a virtual display(see Gilkey & Weisenberger, 1995). Here we were concerned with whether reductions in the tactile field of view could be compensated by the addition of kinesthetic feedback from moving the display. Accordingly, pattern identification in the haptic

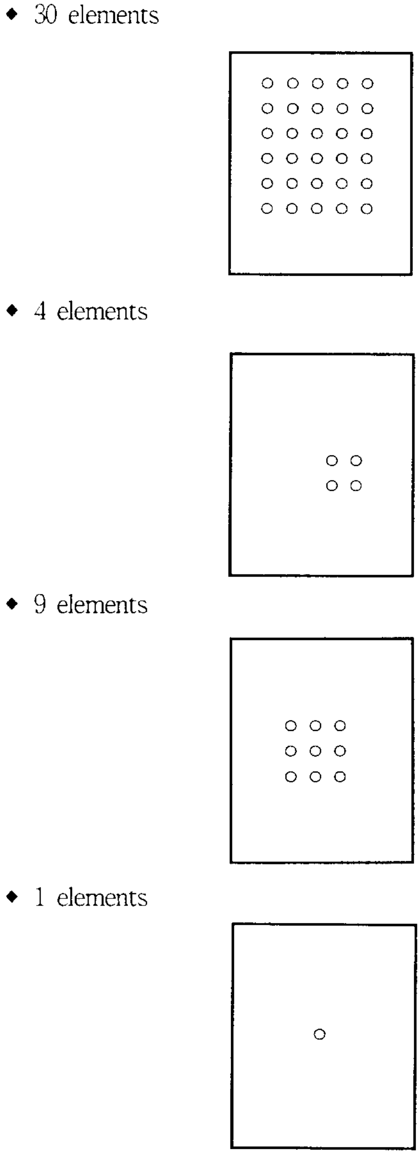

Figure 4. Schematic representation of the reduced field of view displays.

scan condition was tested for several display sizes : the original 30 elements, a 9 element display created by "masking" the activity of all but 9 of the actuators, a 4-element display, and a 1-element display. These displays are represented schematically in Figure 4. The same stimulus sets as those for the original scanning experiments were employed, and all stimuli were presented at a vibration rate of 20 cps. The stimuli were fixed in size to fit on the 30-element display, and thus were larger than the other display sizes, such that an entire stimulus pattern could not be sensed at any one time with these smaller display sizes. Results are shown in Figure 5, showing percent correct across display sizes. As can be seen, reductions in display size from 30 elements to 9 elements, and again to 4 elements, did not substantially affect pattern identification. These findings suggest that the kinesthetic feedback available in active movement could be used to compensate for the loss of spatial information with reductions in display size. However, when the display size was reduced to a single element, effectively eliminating spatial information in the pattern, performance dropped to a much lower level. This result suggests that although kinesthetic feedback can compensate for reductions in spatial information, it cannot replace spatial information completely.

In our more recent work with this shape-memory display, we have begun to investigate whether vibratory cues can be used to convey aspects of surface texture. A first question requiring study was whether observers could discriminate among surfaces that contained different areas of high-and low-frequency vibration(analogous to different

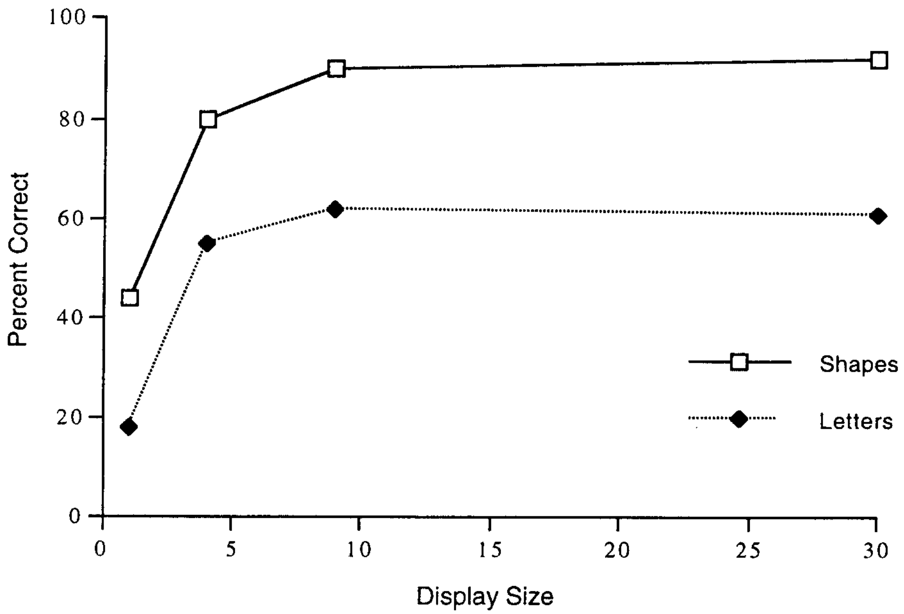

Figure 5. Percent correct pattern identification for five subjects, as a function of display size

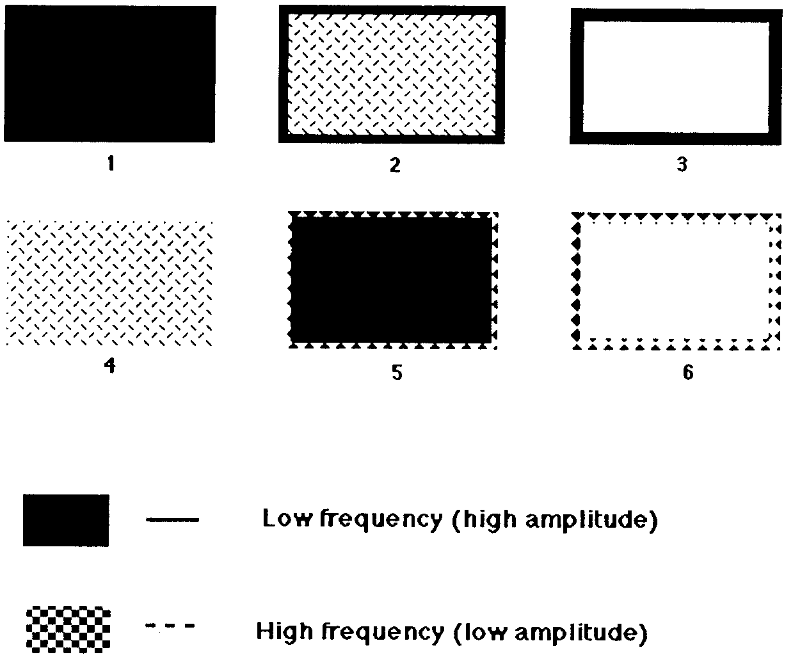

Figure 6. Schematic representation of the high-frequency and low-frequency areas of stimuli used in the texture discrimination experiment.

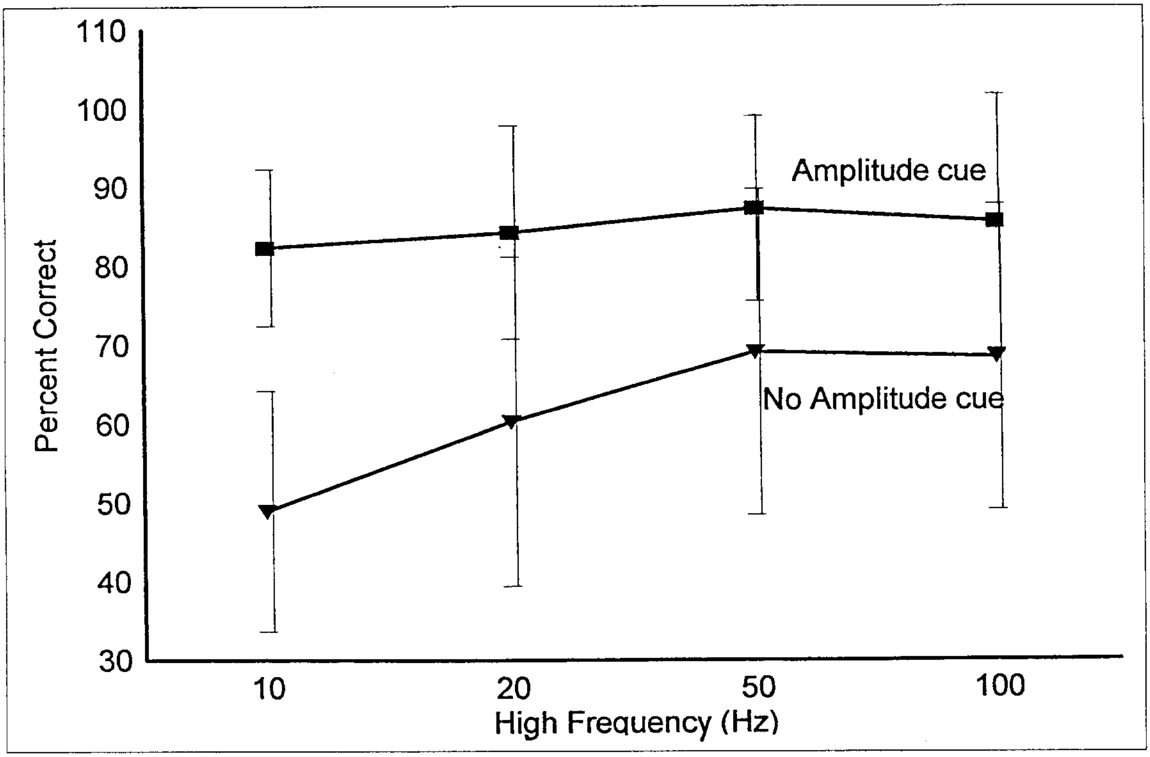

Figure 7. Percent correct identification of textured stimuli, as a function of the values of low and high vibratory frequency

textures for "edges" and interior detail). Accordingly, stimuli were dseigned that had high-frequency or low-frequency deges and high-frequency or low-frequency interior detail. Icons for these stimuli are shown in Figure 6, and observers were asked to identify the pattern sensed on each trial. The values for low-and high-frequencies were varied as an experimental parameter, and all patterns were sensed in the haptic scan mode. In addition, in some conditions an additional amplitude cue was employed, such that the low-frequency portion of the stimulus also had a higher amplitude than the hgih-frequency portion.

Results for the first of these experiments are shown in Figure 7, and show percent correct identification for the pattern set as a function of the value of the low and high frequencies in the stimulus. In the top panel, the high frequency was fixed at 100 Hz, and the low frequency varied. In the bottom panel, the high frequency was fixed at 200 Hz. In both panels, a similar finding emerges. Observers can reliably identify the assorted patterns when the frequency separation between portions of the stimulus is large, but as this frequency separation is reduced, performance levels drop. In addition, the amplitude cue appears to provide supplementary information in this task, such that even when the frequency separation is small, the amplitude cue can aid performance. Of course, when the low and high frequencies are equal, performance is based only on the amplitude cue.

We are continuing this line of research, but the initial results suggest that different combinations of vibratory frequency and intensity can be used to differentiate surface features. In future studies, we will attempt to determine whether these cues can be used to simulate the perception of "real" surfaces, thus increasing the utility of this display for virtual sensing applications.

2. Use of force feedback cues to convey object and surface qualities

In a second line of research in the HSF Laboratory, we are investigating the effectiveness of force feedback cues in conveying information about object shape

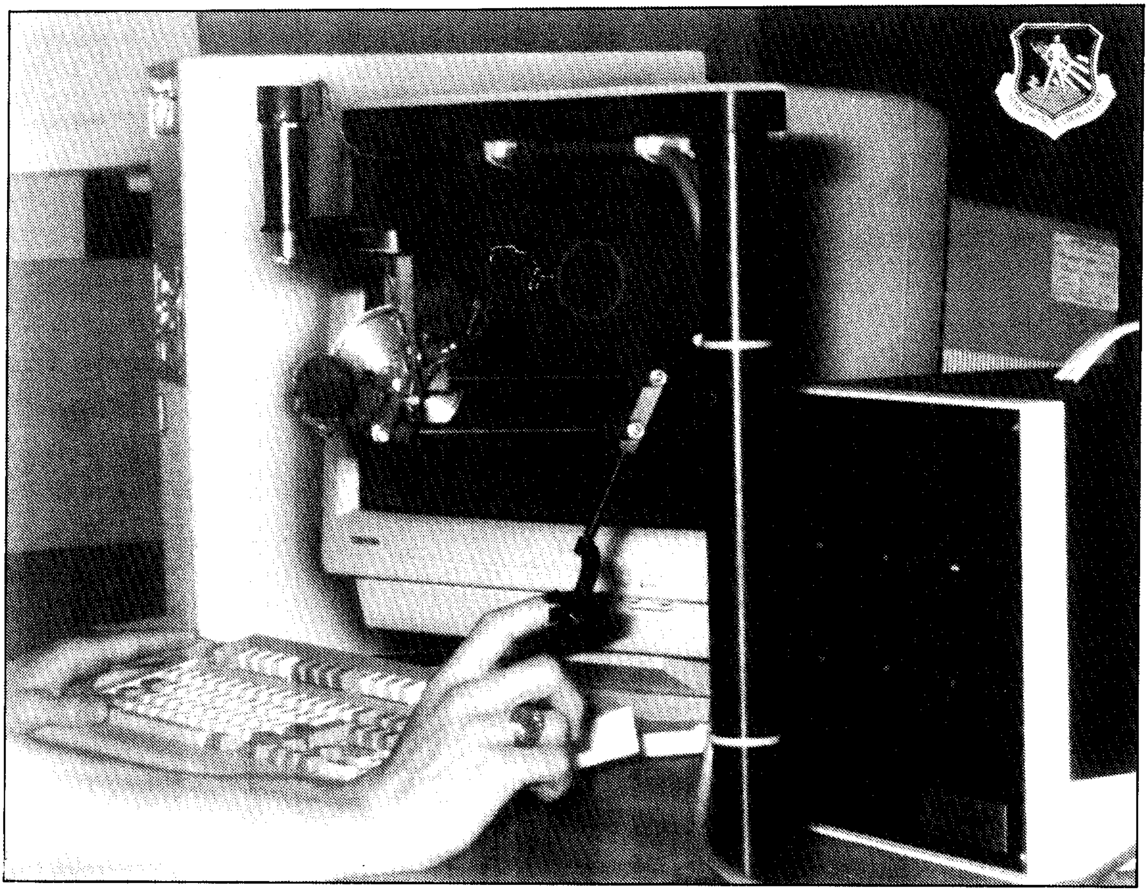

Figure 8. The PHANToM Force Feedback Display (manufactured by Sensable Devices, Inc.).

and surface texture in three dimensions. This work employs the PHANToM Force Feedback Display (Sensable Devices, Inc., MA, USA). This is a 3-degrees-of-freedom display that permits 3-dimensional sensing of virtual objects or surfaces. This device, shown in Figure 8, can be used with either a stylus gripped by the hand, or with a "thimble" into which the fingertip is inserted (this latter configuration is used in the HSF Laboratory). The observer places the index fingertip into the thimble, which is connected to a series of three motors. As the observer moves the fingertip about in space, the motors can be programmed to provide resistive force when virtual objects are encountered. Position sensors keep track of the fingertip's location in space. The exerted forces are programmed to simulate the geometry, mass, and material of a virtual object. This device has a high bandwidth, and provides excellent fidelity in force feedback.

In our initial experiments, we addressed the question of whether surface texture features could be conveyed by force cues alone. Earlier work on real surface texture sensing, as cited above, did not fully resolve the question of the relative contributions of force and vibratory cues in texture perception. The PHANToM is an ideal display for studying the role of force cues. In investigating the perception of force-cue textures, it was necessary as a first step to determine whether subjects could discriminate small differences in surface features. Accordingly, a simple surface was defined, based on the equation $z = A(\sin x + \sin y)$, which produced a "bumpy" surface. The size the bumps(i.e., the spatial frequency of the surface) was varied by changing the values of x and y, and the overall height of the bumps was varied by changing the amplitude parameter A.

The observer's task is to feel two surfaces(first one surface, then the second surface), and to determine whether the two surfaces feel "same" for "different." Observers can repeat the stimuli as often as desired before responding. For any pair of surfaces, the two parameters of spatial frequency and overall amplitude are of interest. One of these values(say, spatial frequency) is the same for both patterns, while the other parameter (amplitude) is variable. An adaptive procedure is used, wherein if two surfaces are judged to be different, the value of the experimental parameter being varied in that condition (either amplitude or spatial frequency) is altered to make the two surfaces closer to physically identical for the enxt trial. If the observer judges two surfaces to be the same, that parameter is varied to make the two surfaces more physically different for the next trial. Data collection for the discrimination studies is currently underway. To data initial results are available for a range of values of amplitude and spatial frequency variation, and are shown in Figures 9 and 10. In Figure 9, it can be seen that large reference values of amplitude require larger amplitude changes in

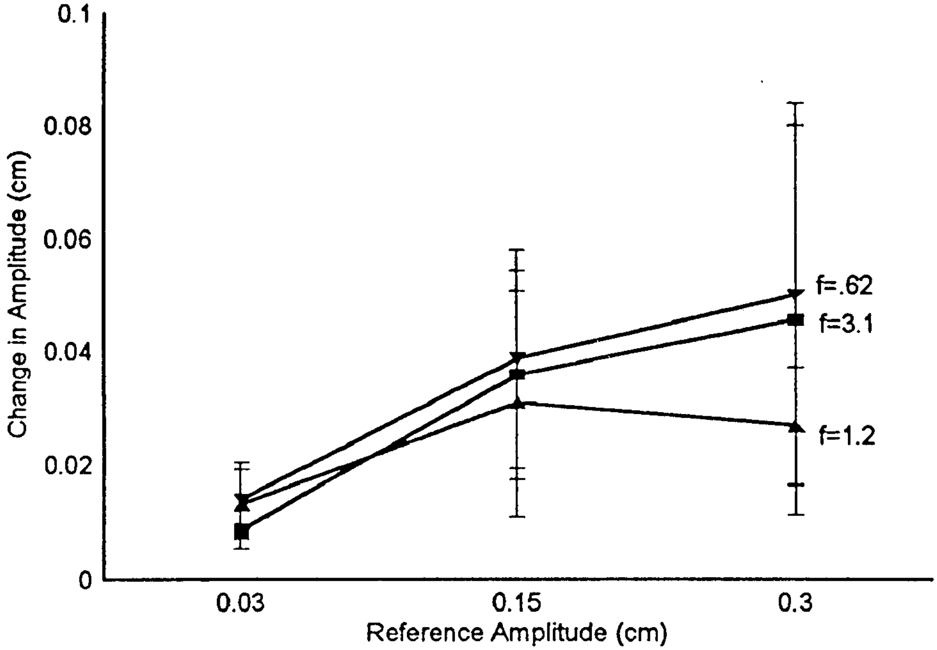

Figure 9. Values of amplitude change required to discriminate two textured surfaces, for different starting amplitudes and different spatial frequencies

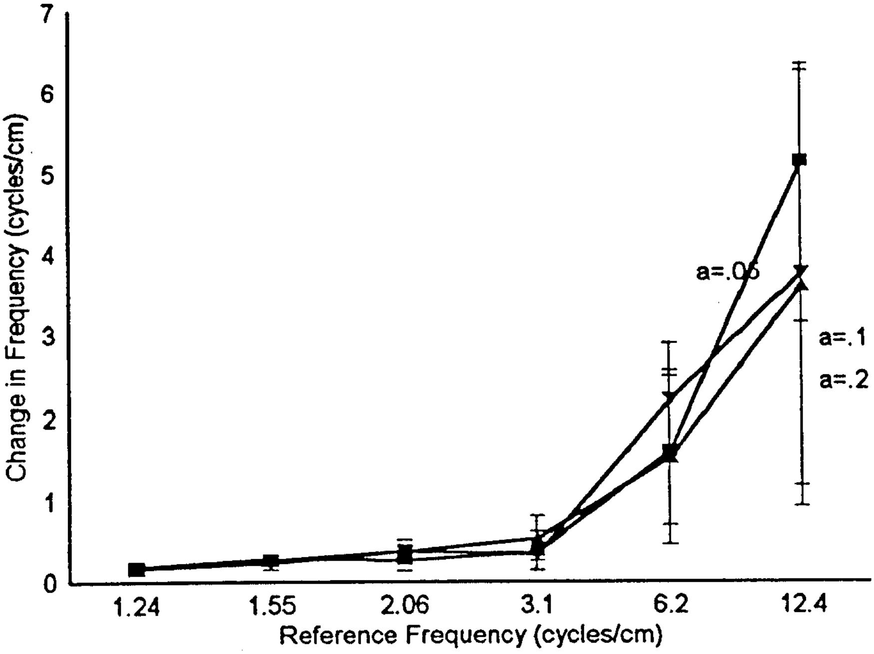

Figure 10. Values of spatial frequency required to discriminate two textured surfaces, tor different starting spatial frequencies and fixed amplitudes.

order to be discrminated, whereas smaller values are necessary when the reference amplitude is small. This result is not surprising, and has some similarity to the Weber fraction for discrimination of intensity in other sensory modalities. A similar pattern emerges for the case in which the spatial frequency is varied, as shown in Figure 10. When the spatial frequency is large(fewer cycles/cm), relatively smalll changes, sometimes less than 1 cycle/cm, are perceptible to the observer, but when the spatial frequency is small(more cycles/cm), a larger frequency change is needed for discrimination.

Overall, the results of this work give us a baseline from which to operate in continuing studies of texture perception with virtual surfaces. Ongoing work begins to address the question of how changes in spatial frequency and amplitude affect the perceived roughness of surfaces. Longer-term goals for this research effort are the devleopment of algorithms for mathematical simulation of "real" surfaces using force-feedback cues. In addition, apparatus to combine force and vibratory cues will be developed, to permit evaluation of how these cues work together in texture and feature perception. Specifically, what is the effect on perception when force and vibratory cues are consistent? What is the effect when these cues are inconsistent?

3. Use of force feedback to enhance performance

A third area of interest in the Human Sensory Feedback Laboratory is how force cues can be implemented to improve performance in manipulation tasks. The PHANToM, described above, has also been used in addressing this issue. Specifically, observers were tested in a task resembling the Fitts-Law task, in which they were asked to move the fingertip thimble first to one location in space, and then to another, as rapidly as possible. Testing conditions included varying the size of the location to be contacted, and the use of force cues to "guide" the fingertip to the correct location (i.e., increased force when the observer overshot the desired location). Results of This testing showed that the use of force cues led to greater speed and accuracy in the movement task.

A related research question was asked in a pilot pursuit tracking task. This study used a different apparatus, the Immersion Force Raflecting Joystick(Immersion Corp., CA, USA). This device is shown in Figure 11. This device is of considerable interest for haptics research, because it can provide both force and vibratory cues to the user. In the present work, only force feedback was employed. Observers were asked to move the joystick to conduct pursuit tracking of a target displayed on the computer monitor in a simulation of target acquisition by fighter pilots.

The problem under investigation was "pilot-induced oscillation," or PIO, a situation in which the response of a mechanical system

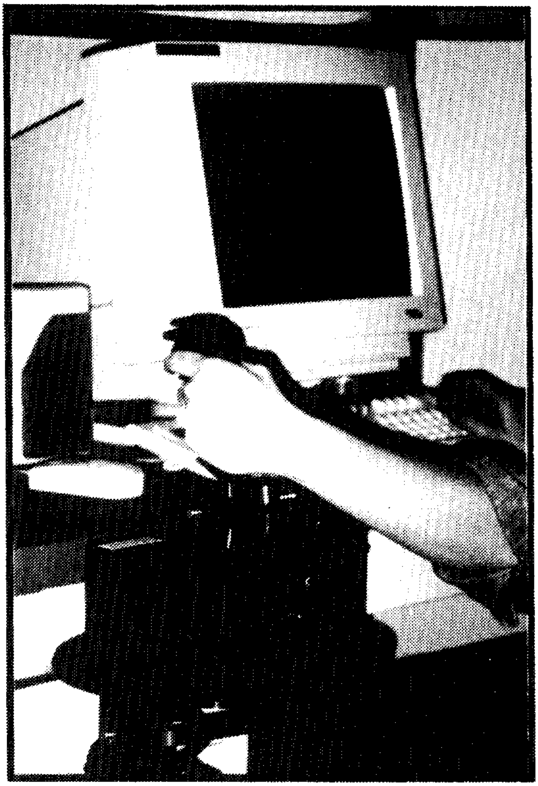

Figure 11. The immersion joystick(manufactured by Immersion Corp.)

(i.e., the change in pusuit trajectory) is decoupled from the actions of the pilot(i.e., the movements of the joystick). This is accomplished most easily by inserting a time delay between the pilot's movement of the joystick and the resulting change in trajectory on the monitor. This time delay leads the pilot to overcorrect his response, with potentially disastrous results in real situations. In our investigation, the effectiveness of "force tunnels" in decreasing pilot-induced oscillation was evaluated. These force tunnels were simply changes in exerted force feedback by the joystick to guide the observer to the correct location. Observers were tested with and without inserted time delays between joystick movement and visual trajectory change, and with and without force tunnels. The initial results showed that the use of force tunnels did indeed significantly reduce the amount of pilot-induced oscillation. Ongoing studies are focused on optimizing the parameters of these force tunnels for different time delays, to further improve performance accuracy. Because of the flexibility of the Immersion joystick and its ability to transmit both force and vibratory cues, long-term goals also include the use of this apparatus in other manipulation tasks, possibly including some of the texture sensing experiments described above.

4. Hand-arm control of robotic manipulators

A fourth area of research currently underway in the HSF Laboratory concerns the use of force-reflecting exoskeletons to enhance the haman control of robotic arms. This work employs a special-purpose device called the FREFLEX(Force-Reflecting-Exoskeleton), which is a 7-degree-of-freedom exoskeleton for the arm and hand. A series of seven motors encodes and reflects movement of the operator at shoulder, elbow, wrist, and hand pivot positions. The FREFLEX device is used to control a Merlin robotic arm; both devices are shown in Figure 12. In initial studies, basic data on speed and accuracy were obtained from a Fitts-Law task of the

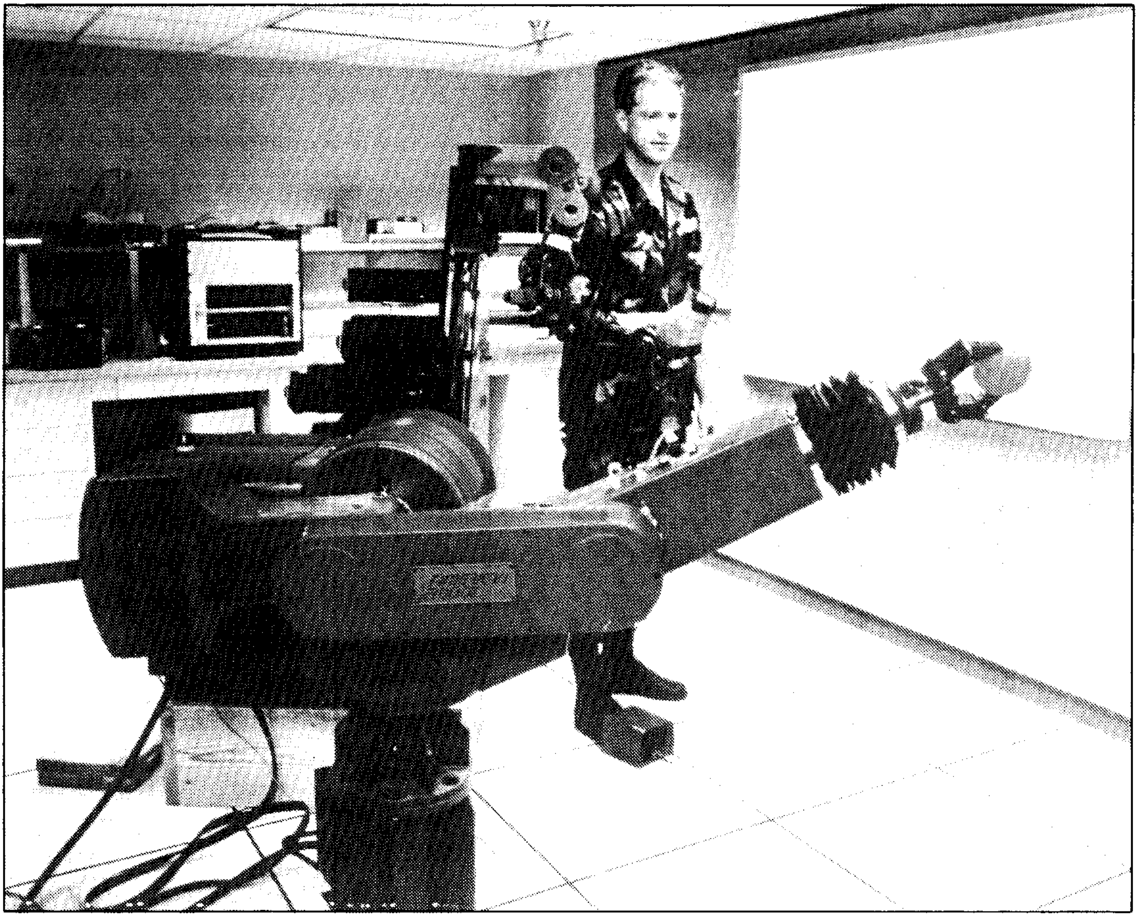

Figure 12. The FREFLEX force-reflecting exoskeleton and Merlin robot

type described above. In this experiment, the observer, fitted into the FREFLEX, was instructed to place a hand-held peg into specific locations sequentially on a pegboard. The basic results indicated that observers could perform this task with some degree of accuracy, and that the addition of compensatory forces from the FREFLEX motors improved both speed and accuracy on the task. Ongoing work focuses on the controlling relations between the human operator of the FREFLEX and the Merlin robotic arm, and on optimizing the force cues provided by the FREFLEX motors. These motors must also compensate for the heavy weight of the exoskeleton, which makes it cumbersome to operate. In the long term, the goals of this project are to improve the coupling between the FREFLEX operator and the robotic arm, to enhance the accuracy of task performance.

5. Summary

The present paper described four areas of research currently underway in the Human Sensory Feedback Laboratory of the Armstrong Laboratory at Wright-Patterson Air Force Base, USA. All of these areas emphasize the utility of haptics, or active touch, in virtual environment and robotic applications, and it is hoped that all are providing useful information in answering both the fundamental basic science question ("How do humans process haptic information?" and the more applied question ("How can haptic information improve task performance?"). Further information about laboratory activities can be found at the following Web address:
http://www.al.wpafb.af.mil/cfb/hsf.html

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