OMAR - A haptic display for speech perception by deaf and deaf-blind individuals

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ABSTRACT: A system for haptic (i.e. kinesthetic and cutaneous) stimulation of the hand is described. While our immediate application involves display of speech information, a number of other man-machine interface applications may be feasible, including force-feedback devices for computer interaction and human pattern extraction from multiple datastreams. Our work is motivated by the observation that devices for conveying speech to deaf-blind or deaf individuals via tactile stimulation have not attained nearly the level of benefit demonstrated by some deaf-blind individuals using the Tadoma method of haptic speech reception. The Tadoma user places a hand on the talker's face to sense various speech articulatory motions. In an attempt to model more closely the information streams available via Tadoma, OMAR was developed to stimulate kinesthetic as well as tactile receptors, by moving and vibrating fingers in one or two dimensions using hard-disk head-positioning actuators. OMAR is being used in experiments involving basic haptic perception and supplementation of speechreading with haptic codings of speech correlates obtained via x-ray microbeam measurements.

INTRODUCTION

Ever since the pioneering efforts of Gault (1924), researchers have attempted to develop vibrotactile devices that could allows deaf individuals to fully receive speech, or, as a more modest goal, enable deaf individuals to speechread with improved comprehension. Various other sensory channels have also been explored to aid speech communication, including vision (e.g. using special eyeglasses that superimpose colored lights over a talker's face [Upton, 1968]) and audition (via electrodes that directly stimulate cochlear auditory nerves). (For a good selection of reprints, see Levitt et. al. 1980.) Experiments using vibrotactile devices have

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evaluated a variety of speech information and codings (Summers 1992; Mason & Frost, 1992), ranging from largely unprocessed speech (conveying speech "rhythm") to highly processed speech characteristics. Results suggest that the information presented and coding scheme used must be carefully matched to the receptive and integrative capabilities of the sensory modality, that learning to use alternate modalities for speech reception requires extensive training, and that performance may be highly dependent on subject, stimuli, and training/testing paradigms used.

While such work has resulted in a number of commercially-available wearable devices and sophisticated tactile laboratory instrumentation, these devices have not been as effective in conveying or augmenting speech as the non-instrumented method of Tadoma (Bernstein, 1992). By placing his or her hand on a talker's face, a Tadoma user can sense various physical correlates of speech production such as voicing, vocal tract shape, mouth opening, and nasal and oral aspiration (Reed et. al., 1992). Skilled users have learned to receive speech at near-normal rates with good comprehension. This existence proof for haptic speech reception continues to provide considerable encouragement to the tactile speech community and has resulted in novel devices such as MIT's artificial talking face for the study of Tadoma (Reed et. al., 1985).

One obvious difference between Tadoma and vibrotactile devices is that Tadoma involves stimulation of kinesthetic receptors in addition to cutaneous. In this report we describe instrumentation, which we have called OMAR, that was developed for the purpose of stimulating both receptor types, primarily for the display of speech information. Actuators are used to control the large-scale movement of fingers on one hand and to superimpose high-frequency, low-amplitude vibratory signals onto these motion trajectories. Currently, OMAR controls motion in the vertical direction only, although we have built a prototype channel for two-dimensional motion, and have designed the control electronics for two-channel operation. In the sections below, we describe OMAR's hardware and software components, and planned initial experiments.

INSTRUMENTATION

OMAR can be configured for a maximum of 10 channels of one-dimensional motion or 5 channels of two-dimensional motion. The actuator, the head-positioning (D.C.) motor assembly from Micropolis 1355 hard disk drives, was selected based on considerations of torque, displacement, its relatively small curvature, and availability on the surplus market. An analog circuit board was developed that implements motor drive electronics and a positional feedback control system that uses actuator position as measured by a high-quality linear potentiometer (ETI LCP-12A-25). A sample three-channel, one-dimensional system is shown in Figure 1. A plate attached to the end of the actuator arm, serving as a finger guide, has a maximum vertical displacement of about 9 cm. Each actuator can be easily repositioned via a velcro mount.

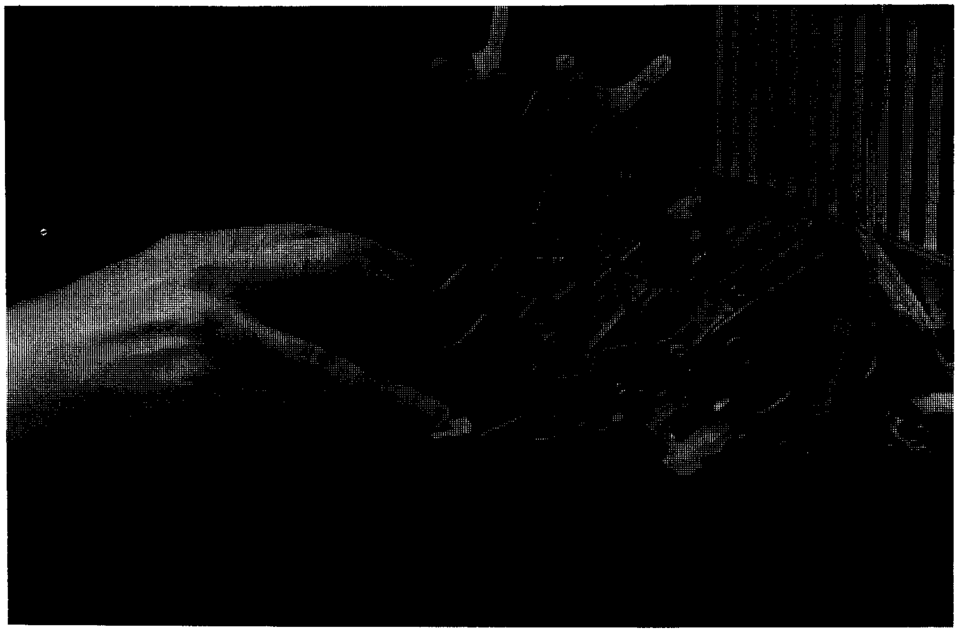

Figure 1. Three one-dimensional OMAR actuators. Each actuator arm has a vertical displacement of about 9 cm. Attached to each shaft is a linear potentiometer for position measurement.

A digital microprocessor board was developed to process and deliver signals to the actuators. It incorporates a 10 or 16 MHz Motorola MC68000P microprocessor, 64 Kilobytes of random-access memory (RAM), a 16-bit counter, two 16-bit digital-to-analog converters (DACs) for driving one or two actuators, and one each 12-bit DAC and 12-bit analog-to-digital converter for auxiliary functions. Board decode circuitry allows up to 15 boards to be independently accessed by a host computer via 16-bit input and output ports and a 6-bit control port. Software modules have been developed for controlling the actuator with arbitrary waveforms, either by realtime transmission of sample points from the host computer, or by preloading samples in the microprocessor's RAM and specifying an output data rate. The microprocessor system is also capable of superimposing arbitrary low-level pulses onto the larger-scale positional trajectories, primarily for vibratory stimulation of cutaneous receptors. By using the least significant bit in the position samples to trigger a pulse rather than superimposing the pulses onto the samples directly, stimulus storage requirements and PC-to-microprocessor board bandwidth are reduced dramatically.

Among the more interesting issues addressed during OMAR development was how to obtain a large dynamic range while avoiding perceived noise. While kinesthetic receptors are capable of sensing motion over the full range of finger extension, over a decimeter, some tactile receptor groups can sense vibration with a fraction of a micrometer displacement. To obtain a reasonably wide range of motion, a 16-bit DAC was used. (However, due to the limited resolution in the position potentiometer and analog drive electronics, low-level vibratory signals essentially operate open-loop.) Also, a gain control in the drive electronics allows mapping the DAC's full range over only a portion of the actuator's displacement, allowing a tradeoff between amplitude resolution and maximum displacement. A related issue is that highly sensitive receptors may effect perception of quantization steps in the low-bandwidth position samples, despite the lowpass filtering (i.e. smoothing) inherent in the drive electronics and finger-loaded actuator. Therefore, another function of the microprocessor system is data upsampling, by linear interpolation, for increasing sampling rate and reducing quantization effects.

To avoid the possibility of actuator-induced injury, actuator force must be limited. An important issue is selection of the force maximum, since insufficient force results in mistracking from finger stiffness and muscle tension, whereas too large a force may cause injury. We have taken a conservative approach whereby the steady-state force limit was set to about 150 grams, a force easily overridden by the finger muscles. For comparison, we have measured the weight of a relaxed finger at 28 grams. Informal experience has demonstrated that some individuals must learn to relax the fingers being manipulated by OMAR in order to avoid mistracking. Limit values for transient signals are somewhat higher than those for steady-state, allowing the actuator to overcome inertia and to initiate motion quickly and cleanly. Current limiting (to about 1 Ampere) is achieved via a light bulb (which exhibits a resistance proportional to temperature) in series with the actuator. Filament temperature builds up over a finite time interval, allowing the larger transient current spikes. The bulb can also be used to indicate to subjects the degree to which they are loading the actuator.

To evaluate OMAR's capabilities to manipulate fingers, measurements were taken using an adjustable dashpot to model effects of finger loading. The dashpot was set to give the same overall damping as a finger, when a triangular waveform was presented. Frequency response curves were obtained for initial peak-to-peak displacements of 0.25, 0.5, 1.25 and 2.0 cm. Response curves were flat to cutoff, with 3 dB cutoff frequencies of, respectively, 19, 11.5, 7.5 and 5.5 Hertz. Informal experimentation suggests that these cutoff points are sufficiently high that the finger's ability to track the actuator is exceeded.

INITIAL EXPERIMENTS

Experiments are being carried out to characterize basic perceptual capabilities of the haptic system and to evaluate OMAR's potential for conveying speech via the haptic channel, as a supplement to lipreading. A first series of studies, performed at Indiana University under the direction of Dr. James C. Craig, consists of psychophysical evaluations of the device and the haptic system. The detectability of tactile stimuli (250-Hz haversine pulses) in the presence and absence of large amplitude finger movements will be measured to determine if kinesthetic stimulation interferes with tactile stimulation. A second study involves measuring the discriminability of finger movements of the same frequency but different amplitudes and finger movements of the same amplitude but different frequencies. Finally, the extent to which subjects can attend to changes in finger motion with three fingers, as compared with a single finger, will be evaluated.

The results will provide guidance for stimulus design for subsequent experiments in haptic presentation of speech. The most critical issue in evaluating OMAR's capability for conveying speech is choice of speech information. A point of departure, suggested by Tadoma, is to present articulatory position information. As there is no reason to believe that Tadoma supplies the optimal coding for haptic speech reception, the stimuli can be manipulated so that the subject's hand lies not on a virtual face (as in the instrumented Tadoma case), but, for example, along the inside of a virtual vocal tract, so that thumb position might correspond to lower lip position, elevation of the index finger to upper lip position, middle finger to tongue-tip height, fourth finger to tongue blade height, and fifth finger to dorsal tongue height. Furthermore, superimposed vibratory signals might be used to convey voicing, fundamental frequency, and/or nasality. Fortunately, such information is available from x-ray microbeam recordings that have been generated by tracing the movement of metal beads placed on various articulators (e.g. lower/upper lip, tongue). Several microbeam traces have been converted to OMAR stimulus datafiles for initial experiments. These experiments will evaluate the ability of subjects to differentiate between patterns of haptic movement corresponding closely to movement of a talker's articulators.

CONCLUSION

While the work described here was motivated by a desire to extend our previous research in tactile and visual-tactile speech perception to include kinesthesia, knowledge about the haptic system may be much more broadly applicable to man-machine interfaces. In particular, the computer-human interface has traditionally been conceptualized exclusively in terms of vision (with limited auditory signalling) and the only role that haptics has played is in manipulation of keyboard and pointing devices. Given the impressive capabilities demonstrated by the haptic system, might it not be worthwhile to extend the computer-human paradigm to include haptic stimulation by the computer?

Certainly, haptics is an important component of the new "computer-created worlds" paradigm, and experiments in force-feedback have been carried out for specialized applications such as telerobotics and display of intermolecular forces (Brooks 1992). But even the current (computer) graphical user interface paradigm might benefit from a haptic stimulation component that could be as simple as vibrotactile signalling by the pointing device whenever the cursor is positioned over a selectable objects, or as complex as a force-feedback mouse or a multichannel haptic display for human extraction of patterns in multiple simultaneous datastreams. The research outlined here may give a general indication of the capability of the haptic system to receive, from instrumentation, multiple streams of data.

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