AUDIO-TACTILE GLOVE

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ABSTRACT

This paper introduces the Audio-Tactile Glove, an experimental tool for the analysis of vibrotactile feedback in instrument design. Vibrotactile feedback provides essential information in the operation of acoustic instruments. The Audio-Tactile Glove is designed as a research tool for the investigation of the various techniques used to apply this theory to digital interfaces. The user receives vibrations via actuators distributed throughout the glove, located so as not to interrupt the physical contact required between user and interface. Using this actuator array, researchers will be able to independently apply vibrotactile information to six stimulation points across each hand exploiting the broad frequency range of the device, with specific sensitivity within the haptic frequency range of the hand. It is proposed that researchers considering the inclusion of vibrotactile feedback in existing devices can utilize this device without altering their initial designs.

1. INTRODUCTION

The integration of haptic feedback into instrument design has been continuously developed since the early works of Goertz in 1953 [1]. Haptic feedback provides the user with both force (hardness, weight and inertia) and tactile (surface contact geometry, smoothness, slippage and temperature) information during the manipulation of digital/virtual devices. The evolution of such appliances has endeavored to reproduce a virtual reality in digital interfaces as well as the forces applied during their use. Whilst interacting with their environment, humans make use of their complex sensory system. However, the somatic system is capable of passive cutaneous data analysis on many levels that are not addressed in certain human interactions with technology. This paper looks at the development of a simple, yet effective, vibrotactile feedback glove capable of delivering tactile stimulation to the user. Tactile and force emulating devices have distinct, differential roles in haptic operations. A tactile stimulator makes use of mechanical skin deformation (pin matrices etc.) or vibrotactile stimulation (voice coils etc.) at one or several locations on the skin. A force stimulator provides mechanical feedback to the user, simulating the passing of an object through a virtual environment. The combination of force and tactile stimulation serve to mediate information between virtual or digital devices through haptics. Therefore, the creation of this device serves as only one part of a larger haptic model.

1.1. Tactile Sensation

Several types of receptor in the skin or subcutaneous tissue act as transducers for tactile information and the biophysical nature of these receptors vary with their location. For the purpose of our application, the receptor systems that lie in or are proximal to the hand are of most interest. These neurons also respond differently depending upon their classification. The tactile system dominates the afferent peripheral and central nervous system pathways, culminating in the overall somatic sensory system. Previous psychophysical experiments have highlighted the role of mechanoreceptors in the perception of tactile stimulation. The four main types of mechanically responsive neurons are outlined below:

- Meissner’s corpuscles
- Merkel’s corpuscles
- Ruffini’s corpuscles
- Pacinian corpuscles

The Meissner corpuscles are located in the upper regions of the skin and are responsible for registering light touch stimulation, stretching and texture perception. Merkel’s corpuscles are located in the same region and detect the presence of sustained pressure and low frequency vibrations. Ruffini’s corpuscles lie deeper within our skin and also detect sustained external pressure. The Pacinian corpuscles are the deepest set of mechanoreceptors. They are used to detect deep pressure and high frequency vibrations applied to the skin. The Pacinian corpuscles will fire in response to high-speed displacements of the skin, but not sustained pressure.

1.2. Tactile Range

Human information processing operates as a multichannel sensory system, capable of cognitive operation through qualitative and quantitative dimensions of sensory activity through experience. The tuning of human tactile sensation is finite, capable of receiving information via mechanoreceptors distributed unevenly throughout the skin. Frequencies that are cutaneously detectable fall into a range from 0.3 Hz to 1000 Hz, with a region of 100 to

500 Hz being the most sensitive [2]. More recent studies have further divided this range [3]. Within the range of 20 Hz to 40 Hz, the perception of vibration is independent from the vibration's frequency. However, between the frequencies of 40 Hz to 700 Hz our sensitivity can be dependant on frequency, with peak sensitivity at 250 Hz [4]. An outline of which can be seen in figure 1.

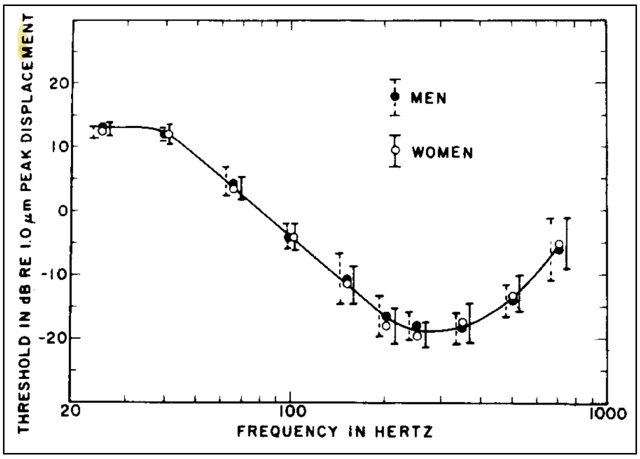

Figure 1: *The absolute threshold of perception for mechanical vibration of the fingertip as a function of frequency [5].*

2. AUDIO-TACTILE GLOVE

The vibrotactile glove has been developed as a tool to present the importance of tactile stimulation in the manipulation of new technologies. The glove is equipped with six independent audio haptic exciters placed purposefully throughout the glove (see figure 2). This device presents tactile information to the user through the stimulation of nerve endings in the skin. The exciters are 9 mm miniature transducers capable of delivering a significant resonant output at frequencies most sensitive to haptic information. The transducers are also capable of producing a nominally flat frequency response across its audio frequency bandwidth [*]. Although the underside of the hand is most sensitive to tactile perception [6], the actuators have been distributed on the back of each finger and the palm. This allows for direct contact between user and device, uninterrupted by the vibrating mechanisms. This permits the user to freely grasp the master device comfortably and maintains consistent pressure against the skin surface. Flexible sub-surfaces run from the actuators to deliver tactile information as close as possible to the areas of the hand most sensitive to vibration stimulus. These flex surfaces are capable of producing structural bending waves, delivering both audio and vibrotactile frequency stimulation to the hand.

The logical linking of tactile feedback through the use of vibrotactile transducers allows the user to sense vibrations through the skin. Tactile localization is achieved through the application of audio signals to the hand, correlating audible feedback with tactile, thusly reducing latency through computer processing of the feedback channels separately and closing the interaction loop. The sensor array is capable of producing simple vibration sensations such as pulses or sustained stimulus supplied from a separate signal source. The combination of these two methods can be used to create complex, virtual tactile patterns, allowing for freedom in designing actuation profiles for various applications.

Figure 2: *The Audio-Tactile Glove*

2.1. Specification (per hand)

- 6 x vibrotactile actuators; one on each finger, one on the palm.
- Capable of producing a tactile resonant frequency range of 150 – 300 Hz.
- Offers independent control of frequency, amplitude and waveform shape in the audio frequency range of 300 – 15000 Hz.
- Continuous power handling of 0.5 W with a force factor of 1 Tm.
- An individual DC resistance of 7.7 Ohms at each actuator, allowing for matching of audio signals from a sound generator or an easily derived audio signal from elsewhere to be applied.

3. APPLICATION

Traditional acoustic instruments convey feedback to the user in the form of audio, visual and haptic stimulation. The physical properties of vibration generation in acoustic instruments cause the interface to vibrate in sympathy to the actions applied to them. These vibrations qualify as tactile feedback, creating a tight relationship between the instrument and the person using them. In addition, some interfaces require no direct contact with the control surface, returning zero tactile feedback to the user. By combining both tactile with kinesthetic feedback from a digital/virtual instrument, haptic information can be passed to the user, allowing for increased control in articulation. As the method of sound synthesis in digital interfaces (DI) and virtual instruments is usually dealt with separately, DIs often fail to close the feedback channel loop.

Interfaces that require no physical contact with an instrument are often controlled via captured hand gestures, which are then used to control synthesis parameters within external processors. These bodiless (or open-air instruments) make use of video cameras and motion capturing software to manipulate synthesis specifications elsewhere [7, 8]. Other methods include ultrasonic or infrared sensors contained within a central transmitter [10, 11]. The most common forms of bodiless interfaces incorporate a glove [12, 13]. These allow for the capture of finger, hand and arm movements. The capture of such small movements with no feedback to the performer present some interesting performance and design challenges. The performer is presented with visual, sonic and proprioceptive feedback relating to their body position along with the audio response of their actions. This is adequate for most applications, but it has been proven that performers who have mastered their instrument make use of haptic feedback cues in performance [14]. Additional to this, instruments that lack haptic feedback can also present a “disconnect” between performer and device, creating a sense of loss in the sound produced and how they are derived [15].

The simplest method of introducing tactile feedback (a major factor of the overall haptic feedback system) is by allowing the instrument itself to take control of sound generation, for example, via embedded speakers [15]. The use of vibrotactile feedback for the control of physically modeled sounds allows performers to distinguish between different modes of vibration, creating a virtual, tactile parameter range to operate within [15]. For bodiless controllers, the introduction of vibrotactile feedback creates virtual space for determining position, assisting in the positioning of the hand. This has been achieved via Tactile Simulation Events as seen in [16]. These techniques highlight that direct audio vibrotactile feedback is not necessarily meaningful to the performer, but new vibration signals can be introduced to create meaningful feedback. Another negative aspect of these techniques is the fixed or narrow band frequency actuators applied in creating the vibrotactile messages, as seen in [16].

With the Audio-Tactile Glove it is possible to modify the frequency input of the glove so as to create differences between vibrotactile feedback and instrument sound production. When using similar, or atypical signals for sound generation and vibrotactile feedback it should be possible to achieve a multitude of special digital audio effects.

- Filtering of audible frequencies to within the tactile range of human skin detection.
- Simulation of vibrations relating to other instrument within an ensemble.
- Amplitude compensation between audio and tactile receptors.

Tactile information is an important factor of Virtual Reality (VR) and Computer-Aided Design (CAD) [17]. In these immersive environments, feedback is usually applied through audio or visual channels. However, the inclusion of haptic feedback here has been shown to improve virtual task efficiency [18]. The Audio-Tactile Glove can easily be integrated into such design processes, allowing for vibrotactile stimulation to be an issue for consideration when doing so. This is especially important when virtual devices are models of real-world acoustic musical instruments. Rapid tactile feedback is important here due to the inherent nature of vibrating musical devices and the previous experience of the musician with real-world instruments. The inclusion of a tactile feedback network from a virtual device will allow for faster, more accurate playing of these VR devices [19, 20].

The glove offers several advantages over fixed actuator positioning within the new instrument design processes. For one, the variable physical locating of such feedback devices can be overcome by placing the vibrating mechanisms directly in contact with the operator. Also, the glove allows for the use of subtle vibrotactile feedback, which is much harder to implement in touch screen interfaces [21, 22]. Touch surface/screen devices do not intrinsically contain any tactile or kinesthetic feedback as there is no haptic indication of having pressed the screen, vibrotactile feedback can be applied here without having to physically alter the interface mechanism. The inclusion of vibrotactile feedback in this circumstance can be applied to increase the quality of the users experience with touch-based devices [17, 23].

Recent advances in touch surface technology are investigating the application of electrovibration for tactile feedback [24, 25]. These interfaces rely on constant movement and continuous contact between device and operator. Whilst this is advantageous in some applications, it is restrictive in many others. The ability to gauge the level of interaction and contact is made difficult by the requirements of the system.

4. EXPERIMENT: VIBRATION PERCEPTION

This experiment was conducted in order to confirm the possibility of successful vibrotactile feedback through the application of the Audio-Tactile Glove. The results of this experiment were expected to reinforce the characteristics of tactile sensation [3, 6] and indicate the minimum signal magnitude detectable across the frequency range of the glove. The findings were used to chart the threshold of “just detectable” intensity levels of signals applied to the glove, outlining the minimum amplitude of frequencies detectable by the subject wearing the glove.

Participants were asked to indicate their minimum perception of tactile stimulation applied across the vibrotactile range, as outlined earlier. Three contrasting waveforms were utilized to indicate if this minimum detection level was dependent on the complexity of the wave-shape. The experiment was conducted in a studio environment with audio isolation ear defenders worn to mask any incidental sounds produced by the glove.

4.1. Participants

Ten postgraduate students (4 women, 6 men) aged 24-45 from University College Cork participated in this experiment. None of the participants had previous experience interacting with digital musical instruments, but all had a nominal background in traditional music performance. None of the participants were familiar with the Audio-Tactile glove.

4.2. Apparatus

Vibrotactile stimulus was presented to the test subjects via the Audio-Tactile Glove. A signal generator was applied to drive the glove with three differing waveform types. The researcher, via an audio amplifier, gradually increased the amplitude of the signal generator. The resultant input signal to the glove was metered and recorded via an oscilloscope.

4.3. Procedure

The subjects were seated with their forearm and dominant hand resting on a hard surface. To prevent visual cues, the subjects were positioned facing 90°s from test equipment. Three wave shapes provided the audio stimulus: sine, ramp and square wave. The tones were presented as continuous waves, one at a time, across a frequency spectrum of 5 to 1000 Hz in twenty-one predetermined steps. The frequency of the tone selected was set at the signal generator and the amplitude was raised from zero until the participant could detect the onset of tactile stimulation. Prior to the moment of detection no tactile stimulation would have been perceived. At the point of initial perception, the signal amplitude was lowered until the awareness of the signal was lost. These steps were repeated until a definitive threshold was acquired for each of the test frequencies. The amplitude of the signal was recorded and the frequency adjusted. This procedure was repeated for all three wave-shapes.

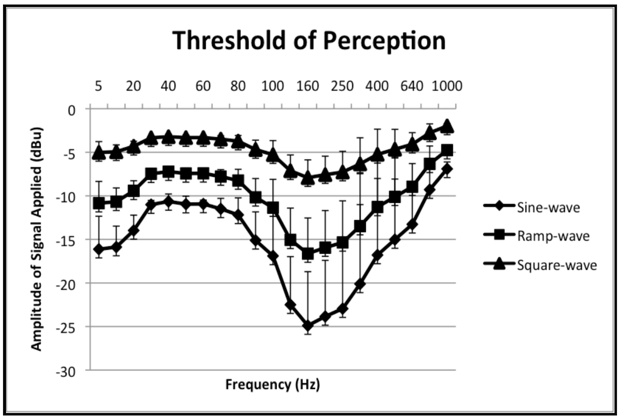

Figure 2: *The absolute threshold of perception for vibrations applied via the Audio-Tactile Glove.*

4.4. Results

The graph in figure 2 shows the mean results for subject sensitivity to each of the wave shapes. Subjects presented with increased awareness of sine wave stimulus across the entire frequency domain tested. The square wave signal was deemed to be the most difficult to perceive across this range. The test subjects perceived frequencies below 20 Hz as simple "clicks". As the signal frequency was increased beyond this point, the perception of vibration was noticeably reduced up to the 60 Hz mark. At this frequency, the sensitivity to applied signals slowly increased. Subject sensitivity to the perception of applied signals reduced sharply above the peak sensitivity range. Participants indicated uncertainty of detection at higher frequencies over lower and were unable to detect frequencies above 1000 Hz. Although our subject indicated no detection of vibrotactile stimulation above 1000 Hz, research has suggested that humans are sensitive to vibrations at frequencies of 2 > 4 kHz [26]. Amplitudes for detection in this range are required to be much higher than for peak sensitivity. As the actuator choice for the Audio-Tactile Glove are capable of producing frequencies in this range, possible application can be investigated.

4.5. Discussion

The experiment findings supported previous research found in tactile perception materials. The peak sensitivity range was found to be between 100 to 400 Hz, as specified earlier.

The findings of this experiment indicate that the Audio-Tactile glove could be applied to haptic models that require vibrotactile elements. This may be relevant for designers of digital musical instruments (DMI), or digital effects researchers, who are considering tactile feedback in their designs, but are investigating different modes that can be applied. The physical perception of tactile information being delivered concurrently with sonic events will allow for designers to explore appropriate feedback techniques without dismantling their interfaces. It is proposed that this will be particularly useful for researchers and designers of new musical interfaces. Allowing end users to experience passive or active tactile feedback.

The incorporation of motion capture and wireless interactivity will allow researchers to investigate the application of vibrotactile feedback in bodiless interfaces. Virtual fields will be highlighted via Tactile Simulation Events and with the frequency response of the Audio-Tactile Glove being much wider than fixed or narrow band actuators, 3D spatialization may be made possible. This will assist in the creation of larger interactive spaces for artists to perform.

The Audio-Tactile Glove may also be applied to assistive technologies. For example, it may possibly assist in the rendering of complex data into tactile information for the visually impaired. Another application in this field could be in the creation of tactile cues for the deaf or hearing impaired. This function could aid in the inclusion of otherwise ignored or dissuaded musicians. Vibrotactile feedback has been successfully applied via fixed vibration matrices for semiautonomous wheelchair guidance and hand rehabilitation, the inclusion of a small, wide frequency, transducer may expand these areas further [27, 28].

Other demonstrations of the Audio-Tactile Glove have indicated that the increased tactile response from digital musical instruments, brought about from wearing the device, can significantly increase user engagement. This has been observed as particularly relevant for users of new musical devices or devices that produce nontraditional audio outputs.

5. FUTURE WORK

Future applications of the Audio-Tactile Glove are to investigate the relationship between haptic and non-haptic musical interfaces and their effects upon musical performance. Performance studies will be conducted in controlled conditions and the results will be used to theorize the use of haptic information by performers. The results are to be used to investigate the importance of the inclusion of haptic information in designing new DMI interfaces and other nonmusical designs. In order to demonstrate this theory, the Audio-Tactile Glove will be used in conjunction with a DMI modeled upon an existing musical instrument that is able to stimulate kinesthetic sensation in performance. Linking all aspects required for haptic feedback on separately controllable output channels.

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