Aural Antennae

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ABSTRACT
Aural Antennae are portable devices which translate sound impulses into vibrotactile stimulus. By swapping audio sensation for haptic sensation we illustrate one variety of artificial synesthesia. The compact devices can be worn to act as electronic travel aids for the hearing-impaired or used for augmented reality applications. Using a simple model of the audio scene's background noise, the device triggers when there is a large change in sound intensity from a specific direction.

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augmented reality, haptics, sensory substitution, hearing aids

ACM Classification Keywords
H.5.2 Haptic I/O
H.5.5 Sound and Music Computing
B.4.2 Input/Output Devices

ARTIFICIAL ANTENNAE
Suppose for a moment that your body was covered with several extremely long antennae. Like an insect, you use these antennae to probe about space, tapping and feeling the world that surrounds you.

For some, such a scenario is just a much-reduced plot of a Kafka story. However, we view this scenario in another light; our research group is preoccupied with how the precepts can be transformed to reproduce atypical experiences. We find motivation to create sensation similar to what the antenna-endowed insect feels.

Indeed, there are some surprising upshots to having antenna. It has been observed, for instance that cockroaches "use their antennae to detect a wall and maintain a constant distance" [2]. Antenna and cilia provide a variety of tactile spatial awareness. Some crude televised experiments with house cats and duct tape also show that felines use their hair to modify their gait and assess the space surrounding them [9].

Now suppose that you were covered with antennae which could pick up and localize minute aural signals. What would it be like to feel higher frequency audio signals in a manner to similar to how we already feel low-frequency bass?

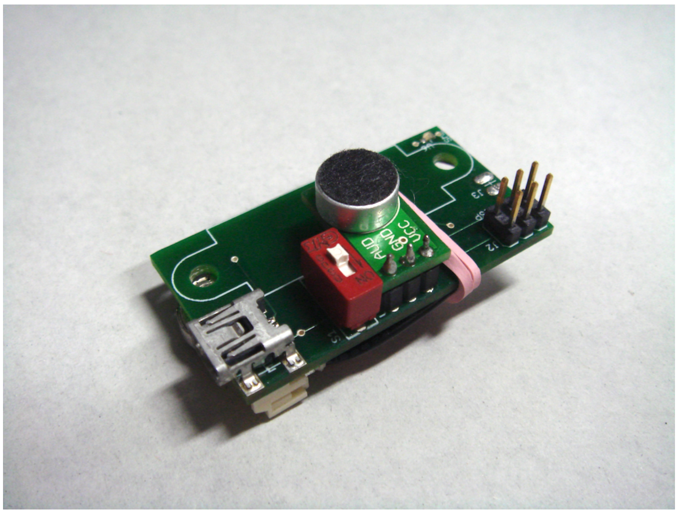

Figure 1. An Aural Antenna converts a signal from an electret microphone into vibrotactile stimulus.

HEARING IMPAIRMENT AND PROSTHESES
The Tadoma or Hofgaard method is a simple technique where those suffering from hearing loss feel the movements of a speaker by touching the parts of the face and neck used in speech production [17]. It has been used since the 1890s as a method for speech-reading [14].

As early as 1936, Gault discussed "hearing through the skin" and worked to develop mechanical apparatus for sound localization [7]. The development of vocoding techniques in the 1940s in turn spurred a variety of haptic audio systems modified to provide haptic stimulus at various loci on the body [17]. By the 1980s, wearable systems were constructed in which "speech sound generates a characteristic tactile pattern that observers can learn to identify" [20].

Wearable auditory systems gave way to implantables which were capable of "direct electrical activation of the auditory nerve" [24]. Further information about the neural basis of audition has been provided by studies of macaque monkeys using fMRI giving evidence integration of tactile and audio stimuli in the auditory cortex [11].

TRANSFORMATION OF PERCEPTION
Portable electro-mechanical systems make possible the creation of pattern converters or intermediaries that sit between our sense organs and the real world. The somatic nervous

system, reflex arcs, and even muscles are organs whose artificial stimulation allows the transformation of perception.

That electrical activity has the ability to interact with the human percepts has been long known: "In his 1820 dissertation, Bohemian physiologist Johann Purkyne reported that a galvanic current flowing through the head upset balance and equilibrium" [6]. This technique has recently been employed by researchers who have built wearable devices to alter sense of balance as well as provide a "virtual sense of acceleration" [13].

Cutaneous rabbit illusion is an interesting perceptual illusion in which a series of taps produced by actuators at discrete locations feel as if they are interspersed between the actuators under particular timing conditions [8]. This phenomena has been exploited by a variety of haptic devices to provide stimulation in areas between actuators. For instance a 3 x 3 "rabbit" display composed of vibrator was used to communicate directional cues [22].

Another phenomena which has been exploited to transform perception is that of sensory substitution. Early attempts looked at using vibrating stimulators to convey visual pictures using an array built into a dental chair [1]. Experiments showed that visually impaired participants could "learn to recognize ... the layout of objects on a table in depth and in correct relationship."

Synesthesia (literally: joining of perception) has been induced in humans using a variety of methods, including electrical stimulation [5]. Less invasively, it may also be simulated through the use of devices which map the information of one senses onto another. This is the case with Fingersight devices, including one that allows wearers to feel optical edges as oscillations of a solenoid mounted above the fingertip [21].

We have developed a number of systems that seek to augment the percepts and specifically make use of the body or reflexes as part of interaction [18]. Earlier work on laser-based tracking systems [15] led us to think of how optical based information might be felt by users, which led us to radar and antennae as metaphors for interaction.

HAPTIC ANTENNAE

We began to experiment with the concept of artificial antennae as part of device illustrating another concept: Haptic Radar [4]. This is a project that seeks to augment spatial awareness by creating radar out of sensors which act to extend the range of touch for the skin.

As most humans have a copious amount of hair located on their head (at least at some point in their life), and our heads are something we wish to protect, we reasoned a headband device would be a good first form factor to test.

We devised a system linking pairs of infrared rangefinders to motor vibrators into a circular arrangement. An earlier paper, Augmenting spatial awareness with Haptic Radar, details experimental results concerning the Haptic Radar. Most saliently, we found that 86% of untrained participants could use the system to move to avoid objects they could not see [3].

Following these initial experiments, we began a redesign with the aim to make individual, compact, Haptic Antenna. To replace the Arduino board, we selected an ATMEL ATtiny13 RISC microcontroller for its compact size (4 mm x 4mm). The process of reading from infrared rangefinder and controlling a vibrating motor requires a minimum of computational resources so this 8-bit microcontroller operating at 20 MHz is adequate.

After recreating and testing the system on breadboard, we added a 100 milliampere-hour lithium-ion polymer battery as well as charging circuitry. After testing this through-hole technology circuit, we designed and fabricated a surface-mount technology printed circuit board (using the freely available Eagle printed circuit board CAD software.)

After further testing and circuit board revisions, we have arrived at a Haptic Antenna in a much more portable instantiation. The device melds a microcontroller, infrared rangefinder, motor-vibrator (a common part in portable phones), battery and electronics. Altogether, these components occupy 25 cm^3, which is a factor of 34 times smaller than the previous version's electronic system.

AURAL ANTENNAE

During this process we came to ask ourselves: what if people felt directional sound as opposed to distance information? Imagine that a car is honking behind you but that you cannot hear it because of a hearing impairment or environmental noise. Now imagine that the honking could be felt on the body at the location nearest to the car's horn.

As a starting point to test this concept we have been building prototype audio-to-touch sensory substitution devices. Aural Antennae are compact, worn modules which produce vibrotactile stimulus in response to audio signals emanating from a particular direction.

Principle of Operation

Our current prototype builds upon the precious Haptic Antennae platform. Instead of a range finder, we attach a daughter board containing an electret microphone, conditioning resistors and capacitors as well as an OPA344 operational amplifier configured with a gain of $G = 100$.

The analog voltage output of the amplifier is digitized using the ATtiny's internal 10 bit analog to digital converter. The microcontroller's firmware samples the microphone at approximately $f_s = 9000Hz$.

After each sample, the microcontroller computes a simple moving average (SMA) over the previous $k = 10$ samples (1). The absolute difference (δ) is then computed between the current sample s_t and SMA (2).

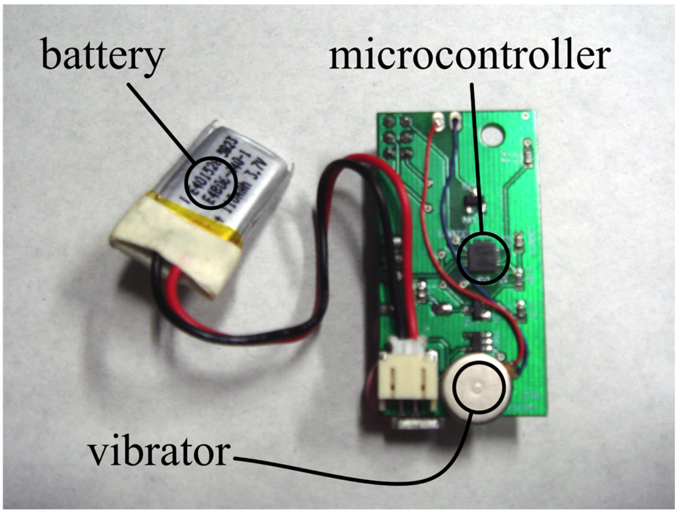

Figure 2. An Aural Antenna module incorporating lithium-ion polymer battery, 20 MHz, 8-bit microcontroller, and vibrotactile motor.

$$SMA = \frac{s_t + s_{t-1} + \cdots + s_{t-(k-1)}}{k} \quad (1)$$

$$\delta = |s_t - SMA| \quad (2)$$

If δ is greater than $\frac{2^{10}}{10}$ (10% of the dynamic range of the analog to digital converter), then the vibrator is activated with 100% duty cycle until the next sample is processed. This moving average works as an extremely rudimentary adaptive background noise filter. The vibrating motor is controlled by a MOSFET transistor whose gate is tied to a digital output pin of the ATtiny microcontroller.

Our initial experiments with Haptic Antennae indicated that blindfolded participants readily interpreted the vibrotactile stimulus and associate it with approaching objects. We expect that similar phenomena will be observed in forthcoming experiments with the aural antennae.

The device exploits our innate ability to process (in a parallel manner) haptic stimulus applied to skin or the Vellus hair which covers most areas of our bodies. Other recent work on electronic travel aids [16] as well as the use of vibrotactile cuing in virtual environments [12] make use of this phenomena. Experiments have also documented that strong haptic stimulus can induce a startle reflex [25], which may be useful in emergency situations.

EXTENSIONS

While independent modules may be worn simultaneously, when networked together the augmentations provided by the devices would be greatly enhanced. We are in the process of evaluating low-power wireless chips such as Zigbee to incorporate into the modules. We anticipate that wireless antennae would be able to work together to provide “rabbit” perceptual illusions of motion between the actuators.

Making use of shotgun-type microphones has improved the directionality of our initial prototype. The use of laser-microphones might increase range significantly. With network capabilities we could create a worn antenna array capable of sound localization using time-of-arrival.

One can imagine a type of wearable simultaneous localization and mapping (SLAM) system. This could be a fusion of antenna-array sound localization and laser ranging and detection (LADAR). Such a system might use a Bayesian network to estimate object location based on data provided by both audio and optical sensing systems.

Another extension of this work is in the area of actuation. The “pancake” style vibration motor we are using (KOTL C1030B028F) has the advantage of being compact, but presents substantial initial friction which makes response somewhat limited. Other researchers have reported on the use of air puffs and acoustic cues to elicit startles [23]. Still other researchers have thoroughly investigated using electrical stimulation to provide haptic cues [10].

AS OTHER SPECIES HEAR

We have developed an example of aural antennae which provide haptic feedback. Often thinking about haptic devices is constrained by our experience of our existing senses. We have instead sought to break with this convention by seeking to emulate insect perception.

Thinking more openly, we can imagine a myriad of new biomimetic ways of seeing the world. Compound eyes and ocellus suggest worn garments that have thousands of cameras. Mimicry of insect’s abilities to acutely detect subtle vibrations [19] and act on this information could lead to extension of touch in the manner that optics have extended the sight.

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