Estimation of Elevation and Azimuth in a Neuromorphic VLSI Bat Echolocation System

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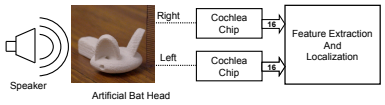
Introduction

To support our ongoing work in modeling bat echolocation, an artificial bat head was designed and fabricated using a 3D printer, an ultrasonic cochlear filterbank with 16 channels has been designed with moderate quality (Q) factor, and 128 spiking neurons convert these signals to spike trains. A two-dimensional address-event arbiter is used to transmit these spikes off of the chip. Two feature extraction chips were designed and fabricated to extract the acoustic features used in localization. We demonstrate that the response of the feature extraction chips can be decoded to estimate the azimuth and elevation of ultrasonic chirps. All chips were fabricated in a commercially-available 0.5 µm CMOS process.

System Block Diagram



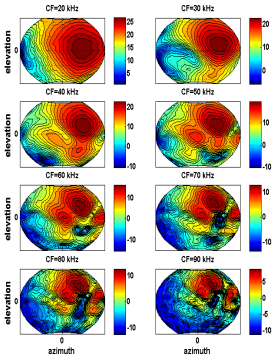
A speaker emits an ultrasonic sweep. The acoustic signal is transformed by the head-related transfer function (HRTF). The two (right & left) microphones (inserted at the back of the head) generate the electrical signals that are amplified and stored (not shown). The signals are played back to the right and left cochlea chips. Each cochlea chip has 16 cochlear filters. Two feature extraction chips extract the acoustic features used in localization from the spiking cochlear outputs.

Artificial Bat Head

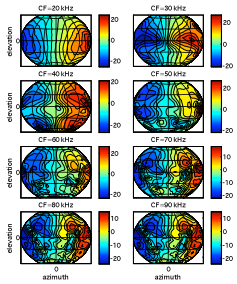
The artificial bat head was designed with SolidWorks™ software and fabricated using a ZCorp 310 3D printer. The head has an elliptical cross section with a height of 10mm and a width of 25mm. The two pinnae are pointed outwards by 45 degrees and tilted forward by 20 degrees. The pinna cavity has a height of 12.6mm, a width of 9mm, and a depth of 2.5mm. The ear canals (holes inside the base of each pinna) lead to microphone (Knowles FG6163) mounting holes at the back of the head. Other mounting holes are for head positioning during characterization.

HRTF Measurement

A 5ms hyperbolic FM frequency sweep (120 kHz-20 kHz) was played from a speaker at a distance of approximately 83cm from the bat head. The speaker was scanned in the horizontal plane (azimuth) from -90 to 90 degrees in steps of 5 degrees and in the vertical plane (elevation) from -67.5 to 67.5 degrees in steps of 7.5 degrees. The right and left microphone signals were amplified and recorded.

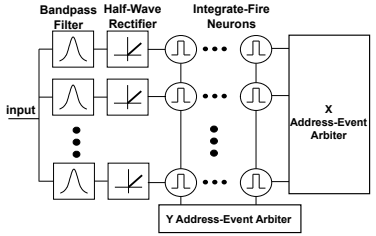


Spatial contour plot of the magnitude (in dB) of the FFT of the sound received at the right ear at difference frequencies (CF). The grid lines have a separation of 30 degrees.



Spatial contour plot of the interaural level difference (ILD) (in dB) at difference frequencies (CF). The grid lines have a separation of 30 degrees.

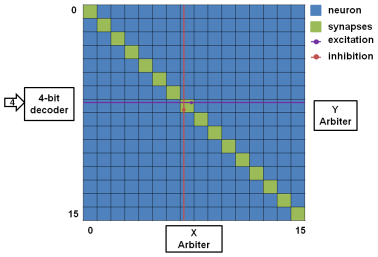
Cochlea Chip



Block diagram of the cochlea chip. The cochlea is a 1D array of 16 bandpass filters. The filter output voltage is converted to a current, half-wave rectified by a p-type current mirror, and mirrored to all eight integrate-and-fire neurons associated with that filter. The spikes are transmitted off of the chip using a 2D address-event arbiter.

Spectral Difference Chip

The first of two feature extraction chips, the monaural spectral difference chip compares the activity of pairs of cochlear filters comparing the activity of neurons associated with one cochlear filter with those associated with another cochlear filter.

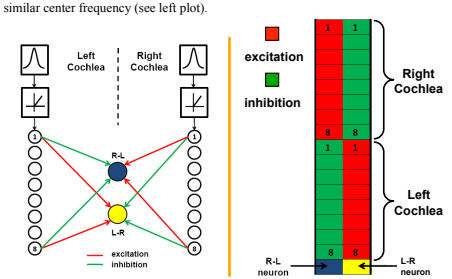


Block diagram of the monaural spectral difference chip.

- The chip has 240 neurons (blue boxes) arranged in a 16 by 16 grid. Each neuron has an excitatory synapse and an inhibitory synapse.
- Sixteen timing blocks (green boxes) lie on the diagonal. Each timing block is connected through the address event system (and the 4-bit decoder) to one of the 16 cochlear filters.
- Each timing block has 2 identical timing circuits that are activated simultaneously; one timing circuit controls all excitatory synapses lying on the same row, the other controls all inhibitory synapses lying on the same column. Each row (column) receives excitation (inhibition) from a single cochlear filter.
- A 2D address-event arbiter is used to readout the neural activity.

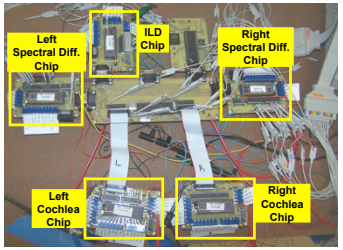
Interaural Level Difference (ILD) Chip

The second of two feature extraction chips, the binaural ILD chip compares the activity of pairs of cochlear filters; comparing the activity of neurons associated with a cochlear filter from the right ear with those from a left cochlear filter of similar center frequency (see left plot).



Each cochlea chip has 16 cochlear filters. The ILD chip has 16 blocks (see right plot); each block compares the activity of a pair of cochlea filters that have the same center frequency. Every ILD neuron receives excitation from one cochlea and inhibition from the other cochlea. The ILD chip has a total of 32 neurons.

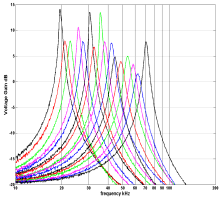
Echolocalization System



Photograph of the system. The spikes from the right and left cochlea chips are sent to the right and left spectral difference chips as well as to the ILD chip.

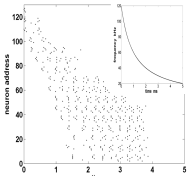
Chip Testing Results

Cochlear Filter Tuning Curves



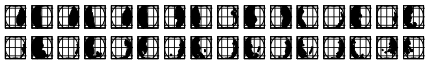
Example cochlear frequency tuning curves: The filters had a mean quality factor (Q) of 14.5 and a standard deviation of 5.4.

Neural Spikes (Spike Raster)



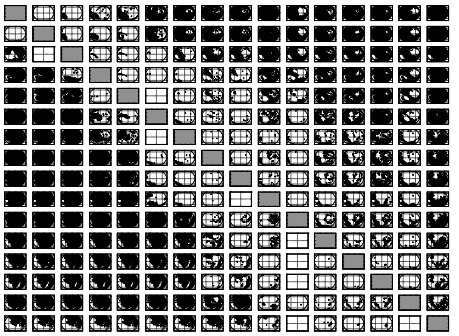
Example spike raster: Response to a 5ms FM hyperbolic sweep (see inset). Spike timing is relative to the first spike.

Interaural Level Difference (ILD) Chip



Spatial receptive fields of the 32 neurons of the binaural ILD chip. The black regions indicate the directions for which a particular neuron fired a spike.

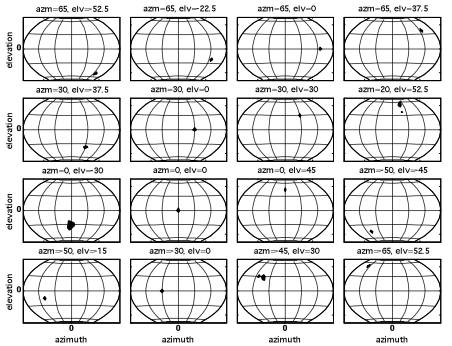
Spectral Difference Chip



Spatial receptive field of the 240 neurons in the right spectral difference chip. The black regions indicate the directions for which a particular neuron fired a spike. There are no neurons along the diagonal (gray boxes).

Localization

Recordings were made at 703 (19 elevations x 37 azimuths) different directions. The feature extraction chips put out a 512 binary code (using ±1) for each direction. For the 703 directions, 703 unique codes were observed. A spatial correlation plot can be constructed by cross-correlating a code from a given direction with codes from all other directions. The maximum correlation is 512 for identical codes and decreases by 2 for every 1 bit difference.



Spatial correlation plots for 16 different directions where azm denotes azimuth and elv denotes elevation. The 512 bit code (using ±1) for a given direction is cross-correlated with codes from all other directions. The maximum correlation is 512 for identical codes and decreases by 2 for every 1 bit difference. Only the correlations for the 50 closest codes (i.e. correlation ≥412) are shown to emphasize the neighborhood relationships. The grid lines have a separation of 30 degrees.

References:

[1] P. M. Furth and A. G. Andreou, "Cochlear models implemented with linearized transconductors," in *Proc. IEEE Int. Symp. Circuits and Systems*, vol. 3, pp. 491-494, 1996.

[2] P. M. Furth, "A continuous-time bandpass filter implemented in subthreshold CMOS with large-signal stability," in *Proc. IEEE Midwest Symposium on Circuits and Systems*, vol. 1, pp.264-267, 1997.

[3] H. Abdalla and T.K. Horiuchi, "An ultrasonic filterbank with spiking neurons", in *Proc. IEEE Int. Symp. Circuits and Systems*, vol. 5, pp.4201-4204, 2005.

[4] H. Abdalla and T.K. Horiuchi, "Binaural spectral cues for ultrasonic localization", in *Proc. IEEE Int. Symp. Circuits and Systems*, pp.2110-2113, 2008.

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