

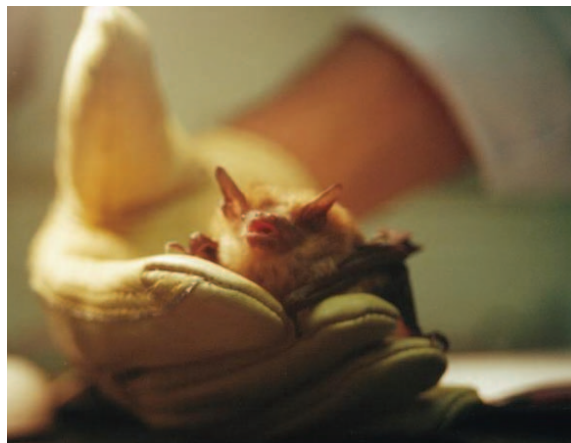
## “Seeing” in the Dark: Neuromorphic VLSI Modeling of Bat Echolocation

Echoes are a major part of our daily auditory lives. Yet, very few of us are even aware that we use them constantly to understand the space around us. The bats of the suborder *Microchiroptera* have made echo detection their primary sensory modality for guiding agile flight in cluttered, three-dimensional (3-D) environments and for capturing flying insects in complete darkness.

The attempt to understand this fascinating sensory modality has captured the attention of researchers in fields as diverse as psychology, biology, physics, electrical engineering, and aeronautics since the discovery in the 1790s that bats could fly in cluttered rooms even when blinded. The development of underwater sonar during World War I, as well as that of radar during World War II, has driven many advances in signal processing techniques and technology that continue to occupy engineers today. While modern sonar and radar processing systems are constructed using large sensor arrays that have incredible imaging and localization capabilities, the question of what bats experience and how they process echo data with only two ears and a pea-sized brain remains a major mystery. The exploration of this question and the attempt to construct a functional model of the bat's neural signal processing using neuromorphic very large scale integration (VLSI) techniques and robotics have provided an interesting framework for our laboratory's research program.

The acronym SONAR comes from SOund Navigation and Ranging, which

includes echolocation. It is most commonly associated with underwater sensing in submarines and dolphins, but the most common example around us is the behavior of the insect-eating bats (see Figure 1) we find in the dark skies on a warm summer evening almost anywhere in the world. Although modern-day sonar and radar are superior in many ways, the study of biosonar



[FIG1] The big brown bat, *Eptesicus fuscus*.

remains important to engineers for many reasons. Even backed by powerful mathematical tools and decades of experience, our best underwater sonar systems still do not rival some of the perceptual capabilities of dolphins. Using an airborne echolocation system, bats have incredible aerial agility, flying in complete darkness through branches and caves while hunting evasive insects. These animals perform such tasks with total power consumption (including flight) measured in watts, not hundreds of watts [1], [2]. In addition, both bats and dolphins live in very social environments, using echolocation in group situations without any obvious problems with interference. These capabilities are

exactly what engineers developing micro-aerial vehicles (MAV) are trying to achieve. Such devices need to operate in environments where global positioning system (GPS) signals are unreliable and obstacles are unmapped. While bat echolocation is a relatively short-range sensory modality due to signal attenuation, it is appropriate for the close-quarters navigational problems and flight speeds (1 to 6 m/s [1]) that bats (and MAVs) encounter.

### WHY DO ROBOTICISTS STUDY BRAINS?

In spite of the phenomenal growth in the usefulness, connectivity, and computational power of the conventional digital computer, we are still not very close to building an intelligent machine. The more we learn about the brain, the more it is clear that the computations being performed and the hardware being used are quite different from our desktop computers. Our best efforts at speech recognition, vision-based navigation, and limbed motor control, while functional, are still basic and fragile, consume large amounts of power, and ultimately have become increasingly based on biological concepts. Ironically, we are literally surrounded by functional examples of the very type of intelligent machine we would like to build.

### BAT ECHOLOCATION AND THE BRAIN

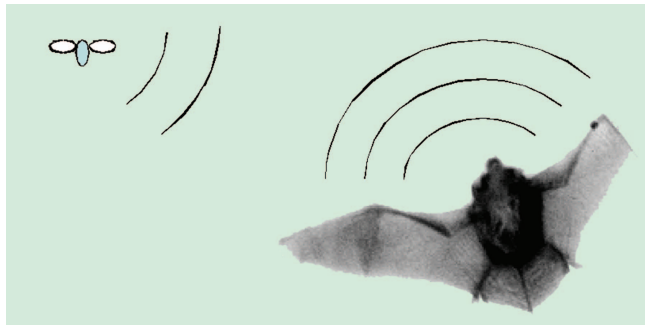
While most creatures can determine the direction of an arriving sound, bats extend this ability by emitting their own sound, which produces echoes of objects that are then localized

(Figure 2). The time of flight (or echo delay) provides information about range, and changes in the spectrum and temporal structure can provide information about the shape, size, and motion of objects. The exact selection of the sound to be emitted represents an active choice in optimizing the measurement of one feature over another. For example, big brown bats emit a short, harmonic, downward sweep in the ultrasonic frequency range and actively modulate the bandwidth, loudness, duration, and repetition rate.

From a neuroscience perspective, bats are remarkable due to the very short time scales at which their sensory systems must operate. The barrage of detectable returning sonar echoes from a bat's near environment lasts about 30 ms following a sonar emission, with any one target's echo lasting a few milliseconds. At this time scale, any one neuron (the putative computing element of the brain) has the opportunity to fire only one or two action potentials (voltage pulses, or "spikes") to represent the echo. Unlike the "traditional" view of neural processing in the neocortex, where action potentials from a neuron are integrated over tens to hundreds of milliseconds to estimate a firing rate, the bat must rely on tens to hundreds of *neurons* that respond with only a few spikes. In such neural circuits, the details of action potential timing, neuron interconnection (synapse) dynamics, and the internal dynamics of a neuron become extremely important. In spite of all this behavioral and sensory specialization, the bat brain is still organized like other mammalian brains; it provides a valuable comparative viewpoint of mammalian auditory processing in general.

#### NEUROMORPHIC VLSI AND ROBOTIC IMPLEMENTATION

Electronic models of neural systems and robot models of behavior both have



**[FIG2]** Bat echolocation relies on the reflection of emitted ultrasonic sound pulses off objects in the environment. By varying the temporal and spectral properties of the pulses, as well as their timing, echolocating bats appear to actively analyze their world as they fly.

a long history in the demonstration of our understanding of biological systems. In most cases, however, these two endeavors have been pursued separately due to a lack of knowledge of the underlying neurobiology at the cellular and systems levels (neuroscience), limitations of electronic realizations (fabrication technology), shortcomings of available robotic technology (materials, actuators, batteries), or the limited appreciation of the critical synergy between brain and body. Continuing advances in the fabrication of microelectronics, recent advances in neuroscience, and the latest consumer focus on low-power, portable electronics are driving technologies that will create new opportunities in biologically inspired robotics. Hardware implementations provide a reality check for computational models that attempt to explain how neural circuits can control behavior in realistic sensorimotor environments. Such implementations can also create new technology and devices for commercialization.

While early efforts to model neural circuits with discrete electronic components provided limited insight due to small numbers of cells and functionality, the development of a toolbox of analog VLSI primitives for describing neural structures launched a field of engineering known as neuromorphic VLSI [3]–[5]. This approach involves the design of analog and digital VLSI circuits that mirror neural algorithms in both signal representation and mor-

phology. Using commercial silicon foundries, large arrays of analog and digital circuits can be (relatively) inexpensively fabricated on a single chip to perform the massively parallel signal processing known to occur in neural structures like the retina [6]–[8], the cochlea [9]–[13], the auditory mid-brain [14], the cortex [15], [16], the spinal cord [17], and other sensorimotor structures [18]–[20]. By utilizing dedicated parallel ana-

log circuits, low-precision computations can be performed in real time (or faster than real time), with power consumption that is many orders of magnitude less than in a general-purpose computer. While the challenge of translating these devices into useful neural modeling tools remains, the speed of computation and the small physical size promise to enable real-time modeling of complex sensorimotor interactions that were previously impossible (e.g., echolocation-based flight control). VLSI-based neural models also stand out as useful tools where a large range of time constants are desired; they are suited for use in spike-based synaptic learning rules or in spike-based models of motor control, where neuron-to-world interactivity is desired.

#### THE "MICROCHIPOPTERA" PROJECT

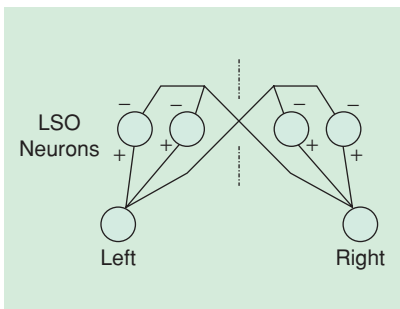
While roboticists have been using and researching sonar for decades, there have only been a handful of efforts to truly mimic the behavior of the bat. Fewer still have attempted to model the neural circuitry underlying bat echolocation in a closed-loop fashion. Two recent examples include work to understand the computational significance of scanning pinna movements of the horseshoe bat [21] and the new European CIRCE project ([www.circe-project.org](http://www.circe-project.org)) to build a bionic bat head with initial results in analyzing pinna shape [22].

In the Computational Sensorimotor Systems Laboratory at the University of

Maryland, we are focused on the neural circuitry underlying bat echolocation to understand and distill the fundamental computations performed by the bat auditory system. We aim to develop low-power neuromorphic VLSI circuits (fabricated through the MOSIS Service) that mimic this remarkable system in real time. We plan to demonstrate the success of our understanding through the construction of a small, sonar-guided aircraft. The motivating theme of our laboratory is the investigation of how sensory information is extracted by neural systems and how neural activity is ultimately transformed into system-level behavior. In the following sections, we highlight some of the bat echolocation subsystems we are studying and describe what challenges we face in implementing them in silicon.



**[FIG3]** An example binaural sonar head with two ultrasonic microphones mounted on top, with an ultrasonic loudspeaker below. The assembly is shown mounted on a rotating platform.



**[FIG4]** LSO neurons receive excitation from one ear and inhibition from the other ear. Differences in logarithmically encoded input strength and thresholds produce sensitivity to different sound directions.

### SHAPE MATTERS: THE HEAD-RELATED TRANSFER FUNCTION

Echolocation begins with the bat (or robot) emitting a short (e.g., 2 ms), but loud, ultrasonic vocalization. This sound is transmitted out from the head and produces echoes from small objects at distances as far away as 5 m, a significant distance given the small size of the animal. After the echoes return to the bat (or robot), the head, snout, and pinnas (or microphone sensitivity curves) all combine to produce directionally dependent spectral filtering for each of the two ears (or microphones). While this binaural, head-related transfer function (HRTF) has been well characterized in humans, existing measurements for bats are coarse, and only a few examples exist. A number of groups have recently been pursuing these measurements (such as the CIRCE project and the Moss Laboratory at the University of Maryland), and we hope to soon have a better understanding of which physical features are important for sculpting the sound spectrum. Although the big brown bat head is considerably smaller than a human head, the wavelengths of the frequencies it uses are smaller as well. As a result, the HRTF of this bat, at the frequencies of interest, looks remarkably similar to those of humans.

In humans, where the ears are far enough apart to create as much as 1 ms of interaural time difference (ITD), timing is used to estimate the arrival angle at low frequencies. Echolocating bats, in contrast, have small heads (less than 2 cm in diameter for the big brown bat), and the distance between the two ears of a typical insect-eating bat generates an interaural time difference of less than 70  $\mu$ s. While a few bats have been shown to be sensitive to such tiny interaural time differences, most bats do not seem to utilize this cue. The dominant cues for directional localization in echolocating bats appear to be binaural comparisons of intensity and monaural spectral cues.

To explore the use of these directional cues, we are modeling two different types of neurons thought to be impor-

tant for localization: 1) a type that receives binaural narrowband input and responds to interaural-level differences and 2) a type that receives monaural broadband input and is selective to spectral notches at different frequencies. Figure 3 shows our narrowband sonar system, which produces interaural intensity cues.

### INTENSITY CUES FOR AZIMUTHAL LOCALIZATION

If we limit our sound directions to the horizontal plane and analyze a single frequency band, the difference in sound level at the two ears [interaural level difference (ILD)] will be correlated with different directions. In the bat, as in other mammals, information about the ILD is known to be coded at the earliest stage of binaural processing by neurons in the lateral superior olive (LSO). The LSO receives excitatory inputs from the ear on the same side of the brain and inhibitory inputs from the ear on the opposite side of the brain (Figure 4). Roughly speaking, this means that LSO neurons on the right side of the brain respond to echoes coming from the right side of the animal, and vice versa. When the excitation created by an echo is stronger than the inhibition to a particular LSO cell, the neuron will fire a single spike for an echo. With an array of cells with different thresholds, a range of ILD thresholds is created. By observing the response of this array of cells, the brain can determine the sound direction. As each echo arrives, the array responds to indicate echo direction.

We have designed a population of LSO neurons in VLSI (a commercially available, 1.5- $\mu$ m CMOS process) and have demonstrated direction-selective responses with our sonar system [23]. This circuit is designed to operate in the MOSFET subthreshold region of operation, consuming only microwatts of power.

### SPECTRAL CUES FOR AZIMUTH AND ELEVATION

Another important cue for sound localization utilizes the fact that the pinnas produce a spectral notch, the frequen-

cy of which varies moderately with sound elevation and weakly with sound azimuth. By detecting the notch frequency binaurally, a combined estimate of both azimuth and elevation can be made. To model this technique for localization, we are constructing and testing an ultrasonic cochlea chip and different pinna shapes that produce direction-dependent frequency notches like bat pinnas.

Echolocating bats specialize in high-frequency hearing using ultrasonic sounds that have the most power in the frequency range of 20–100 kHz [24]. While some bats are specialized for specific frequencies with very sharp cochlear threshold-tuning curves ( $Q_{10dB} \sim 400$ ), we are studying bats that use a broadband vocalization; they are ultrasonic frequency generalists (e.g., *Myotis lucifugus*) with threshold-tuning curves of modest sharpness ( $Q_{10dB}$  values in the range of 10–30 [24]) throughout the ultrasonic frequency range. Good frequency resolution is important for detecting and estimating frequency notches.

To address this need, we have been designing a binaural, ultrasonic filter-bank chip using a gyrator-based filter that achieves moderate quality-factor ( $Q$ ) bandpass filtering followed by spiking neurons for use in modeling the bat echolocation system [25]. The filter frequencies are spaced exponentially to mimic the frequency spacing in the bat cochlea. We have also designed a neuron circuit that encodes the echo amplitude and produces minimal spike-related power-supply noise (a typical problem for mixed-mode circuits); it reports spike events using a current-mode digital output. This binaural cochlea chip operates on about 500  $\mu\text{W}$  of power.

### USING NEURON DYNAMICS TO COMPUTE RANGE

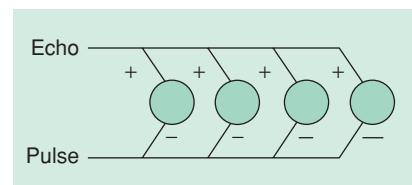
Determining the distance to an object is based on the time of flight of the sonar pulse. At the speed of sound, the distance to objects can be calculated by allowing for approximately 17 cm for every millisecond of delay measured.

In midbrain areas specialized for auditory processing (inferior colliculus), neurons have been found that respond to specific pulse-echo delays with relatively broad tuning. This type of population coding enables the representation of multiple objects at different ranges, provides a substrate for spatial memory, and allows range-specific parameter optimizations. For example, echo signals from faraway objects tend to be significantly lower in intensity and could potentially be optimized for a lower signal-to-noise ratio.

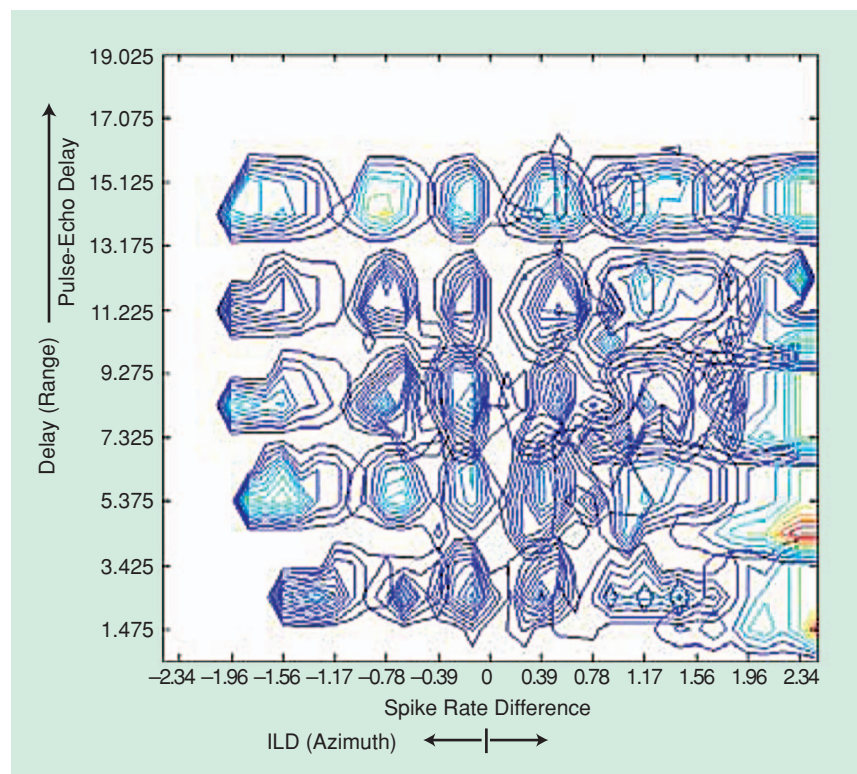
How does a neuron become tuned to a particular pulse-echo delay (i.e., range)? Neurophysiological experiments have shown that these neurons have slightly underdamped membrane potential dynamics that provide a timing cue. During the outgoing sonar pulse, these neurons are inhibited, thus reducing the membrane potential (Figure 5). As the membrane potential reverts back to its resting state (each neuron with its own time constant), it momentarily overshoots its resting state (“rebounds”); hence, a narrow

window of opportunity exists for a temporally coincident excitation from an arriving echo to push the potential above its spiking threshold. Since these range-sensitive neurons fire at the time of the arriving echo, like the azimuth-sensitive neurons described in the previous section, it is possible to “bind” the two pieces of information together using temporal coincidence.

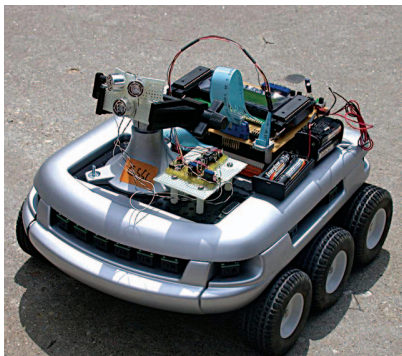
To model these neurons, we designed an array of low-power ( $\sim 500 \mu\text{W}$ ) VLSI neurons ( $0.5 \mu\text{m}$  CMOS process) with similar rebound dynamics that respond to pulse-echo delays in the 1–30 ms range [26]. To model the “binding” of range and azimuth, we



**[FIG5]** Range-tuned neurons are differentially inhibited by the outgoing pulse; if the echo arrives at the time of the postinhibitory rebound, the neuron will produce a spike.



**[FIG6]** By using the temporal coincidence of spikes from the LSO neurons and the delay-tuned (range-tuned) neurons, 2-D receptive fields can be created.



**[FIG7]** The binaural sonar head shown mounted on a Koala mobile robot (K-Team, Switzerland) is used to test neurally plausible, multiple-object collision avoidance algorithms based on sonar data.

have recently designed and fabricated a chip that detects the temporal coincidence between the firing of azimuth-sensitive cells and these range cells to create “two-dimensional cells” that respond to specific combinations of range and azimuth (see Figure 6).

#### LOOK OUT FOR THAT TREE!

How do we connect low-level computations and data representations to high-level behavior such as collision avoidance and insect capture? How do animals represent the 3-D world to determine where and how to move? Mobile robot studies have struggled with this question for decades, formulating many different types of approaches that ultimately depend heavily on the sensory system used to collect data. While precise mapping and trajectory planning approaches dominated mobile robot research in the early years, recent efforts have been drawing upon new understanding of an area of the mammalian brain known as the hippocampus, where cells are thought to rapidly “learn” to signal when the animal is in a particular location within a familiar environment.

In our laboratory, we are currently focused on the problem of rapid steering decisions that occur during insect pursuit in unknown, cluttered environments. In pursuit problems, the sensory activity generated by a target can be used in a straightforward manner to determine the actions an animal should

take to capture the target (e.g., producing a turning rate in proportion to the error angle). In collision avoidance, however, sensory activity generated by obstacles should only determine actions the animal should *not* take to avoid collision. Given how little is known about the neurobiology of spatial decision making, can we design a *neurally plausible* algorithm that can successfully combine both target pursuit and collision avoidance?

By representing space in terms of emptiness or openness, we have begun to create successful algorithms that can combine information about both goal directions and multiple obstacles to make good choices for navigation. An example software-based testbed that has been constructed to explore these ideas is shown in Figure 7. Constructed by a summer undergraduate research team, the “batmobile” can navigate through a “forest” of cardboard tubes without slowing down. We are currently developing a spiking, neuron-based version of this algorithm in VLSI for high-speed, two-dimensional navigation suitable for model cars and aircraft in the near future.

#### COMMERCIAL APPLICATIONS OF THIS RESEARCH

Beyond research and education, there are many obvious commercial and industrial applications of integrated sensory systems implemented in low-power VLSI. The development of a small, sophisticated, power-efficient, low-cost echolocation system has many potential applications beyond neural modeling. In the biomedical realm, such devices are beginning to be used as another option for collision avoidance and spatial sensing for blind or low-vision patients. These devices, when properly scaled down, could also be used to guide endoscopic instruments or provide additional information about distance to monocular, visually guided surgical tools. Air-coupled sonar, as a basic sensor module for mobile robotics, has not advanced significantly beyond a narrow-beam, closest-target sensor, despite decades

of use. With robotic vacuum cleaners finally hitting the market, a low-power module with significantly more sensing capability at low cost could facilitate a new range of commercial products and toys that have the ability to sense objects in the near-field like a full set of whiskers.

From a micro-aerial vehicle perspective, while GPS has successfully enabled long-range navigation, the final leg of many desirable missions occurs in locations where the lack of GPS signals and unmapped obstacles make navigation untenable; such locations include inside buildings, under the forest canopy, in canyons, and in caves. Obtaining the range to objects directly, while computing azimuth, sonar systems are a natural complement to vision systems for these challenging environments. When combined with an ornithopter airframe, a nearly silent device (to humans), the ability to fly in the darkness seems to be within reach.

Overall, this project is proving to be a wonderful framework in which to pursue different types of scientific and engineering-oriented research and education. Understanding bat echolocation involves many interesting problems of signal processing within the context of biological data representations and neural hardware.

#### AUTHOR

*Timothy K. Horiuchi* received both the B.S. degree in electrical engineering (1989) and Ph.D. degree in computation and neural systems (1997) from the California Institute of Technology. He did postdoctoral work in the Zanvyl Krieger Mind/Brain Institute at the Johns Hopkins University and is now an associate professor with a joint appointment in the Electrical and Computer Engineering Department and the Institute for Systems Research at the University of Maryland, College Park (UMCP). He is also a member of the Neurosciences and Cognitive Sciences Program at UMCP. His research interests are in computational neuroscience and the implementation of neural circuit architectures in

mixed-mode neuromorphic VLSI-based processors. He is currently pursuing the development of analog VLSI chips that mimic the signal processing and sensorimotor control of bat echolocation. He is also involved in efforts to improve the tools and techniques used in neurophysiology.

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