CRCNS: Innovative Technologies Inspired by Biosonar

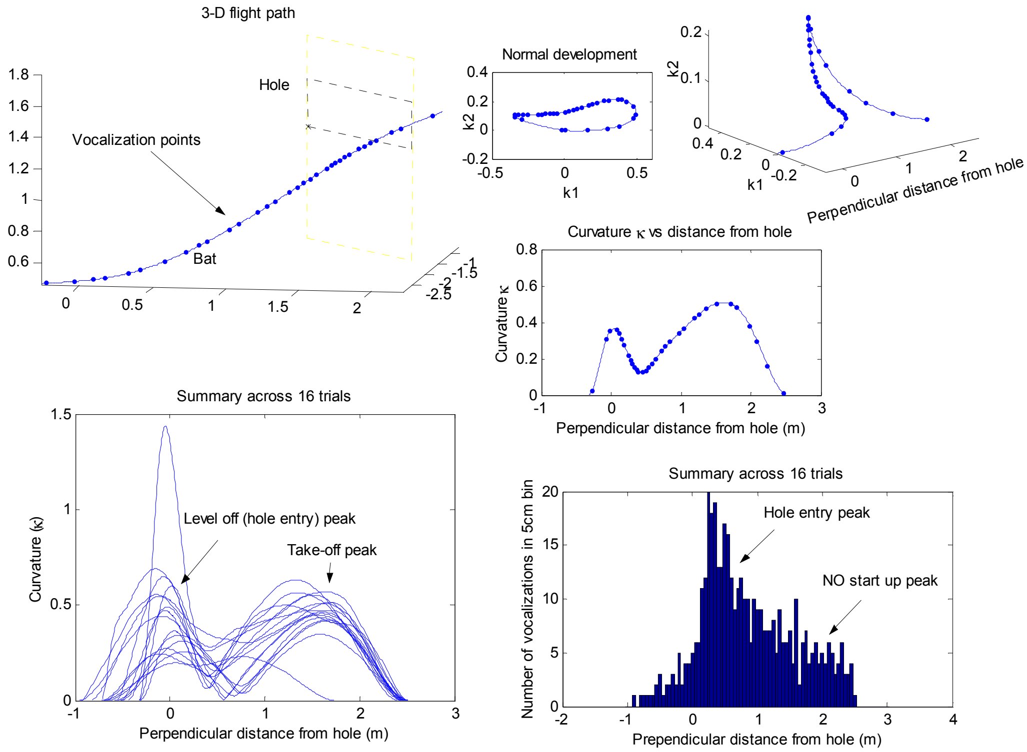
Our collaborative research group combines empirical and theoretical work to develop and test models of central nervous system (CNS) control in adaptive sensorimotor behaviors. In turn, these studies are used to guide the fabrication of artificial neural systems whose architecture and design principles are based on those of biological nervous systems. Our empirical studies employ an animal model that has evolved a highly successful adaptive sonar-guidance system, the echolocating bat. This mammal actively controls the temporal and spectral characteristics of its sonar vocalizations as it negotiates obstacles and pursues flying insect prey. We can therefore utilize the animal's flight trajectories, dynamic patterns of sonar signal production and CNS recordings to measure and model behavioral state changes that vary with task and information load. Our project includes three inter-related research thrusts: 1) Behavioral and neural recording telemetry studies of free-flying echolocating bats engaged in insect capture and obstacle avoidance tasks. 2) Control systems modeling of flight trajectories and vocalizations of echolocating bats to characterize changing behavioral states in a dynamic environment and 3) extracting control systems synthesis principles for applications in robotics and neuromorphic engineering. Collectively, our research has wide-ranging impact on neuroscience, neuroscience techniques, robotics design, control theory, and the design of assistive medical devices.
Below is a summary of the research activities carried out in the first year of our funded project, with a start-date of August 1, 2004.

I. Echolocation in a dynamic environment: Behavior and neural recordings in free-flying bats

As a bat engages in insect capture and obstacle avoidance, it exhibits dynamic vocal-motor patterns and flight trajectories in response to changing acoustic input. High speed video and sound recordings of bats engaged in sonar tasks yield rich data on these adaptive behaviors, which provide a platform for our computational and neurophysiological research. For this arm of the project, we are developing a sophisticated, light-weight telemetry device that permits neural and microphone recordings from animals engaged in adaptive behaviors. This work emphasizes the study of dynamic patterns of CNS activity that occur with changes in the animal's behavioral state, as it detects, localizes, tracks and intercepts insect prey on the wing. In these recordings, we apply modern signal processing techniques to anticipate, isolate, and adaptively extract noise and signal artifacts. Also part of this project, we are also developing VLSI-based neural and EMG telemetry, which have clear implications for future miniature, low-power wireless prosthetics. Technological advances achieved through our work in RF telemetry have the potential to transform research and biomedical applications in the field of neuroscience, by opening up opportunities for the broader scientific community to study neural activity in other small, freely moving animals.

Using Curvature Methods to study bat flight through obstacle array

An elementary flight obstacle consisting of a curtain of thin wires with a gap has been used in studies this first funding year. Bats have been trained to fly through the obstacle from a fixed starting point. Our analysis shows that the bat goes through phases of high curvature. In the first phase the bat takes off and turns to an initial heading direction. It keeps this heading until it detects the obstacle and then finds the gap in the obstacle. At that point the bat turns sharply to fly through the obstacle, creating a second phase of high curvature.



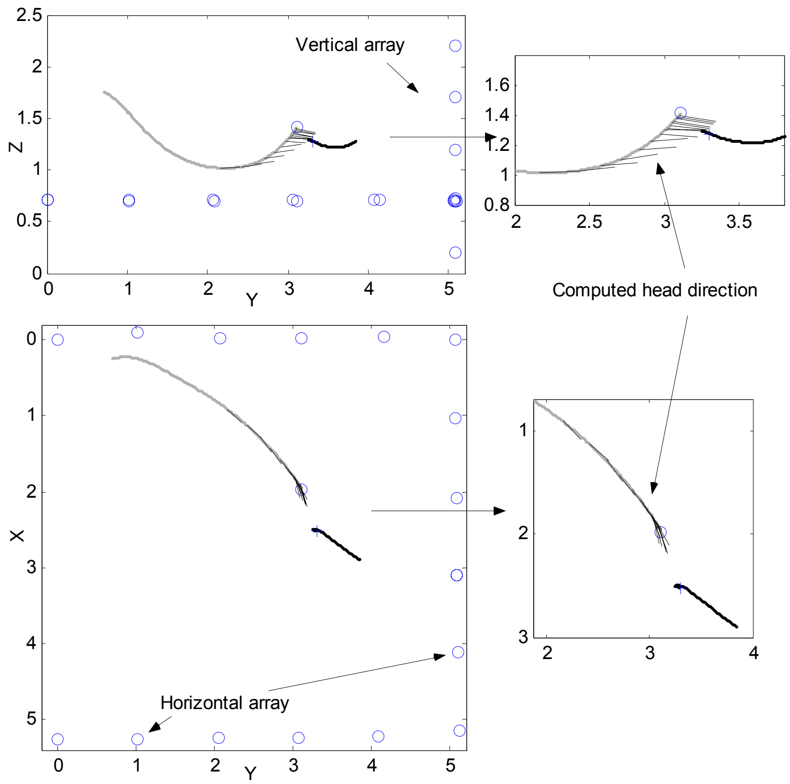
During the first phase of high curvature the vocalization rate of the bat is low. We believe this is due to the fact that the bat is not responding to any obstacle in its flight path, but is taking off from its start point and selecting a flight heading.

During the second phase of high curvature, when the bat is actively navigating the obstacle, the bat produces vocalizations at a higher rate, indicating that it is attempting to get more detailed information during this critical navigation phase.

Future experiments will incorporate a series of arrays of wires, forcing the bat to repeatedly undergo phases of high flight path curvature. By studying the kinematics of the bat flight path in relation to its distance to the obstacles and in the context of its vocalizations we hope to uncover steering strategies the bat may be using while navigating obstacles.

Using the vertical array to study the vertical head orientation of the bat during insect pursuit

In a previous study we have shown that the bat points its head at its target in the horizontal plane during flight. We measured the direction of the bat's vocalizations using a horizontal array of microphones. We have now setup an additional vertical array that enables us to simultaneously measure the vertical aspect of the bat's sonar beam aim. We are in the process of collecting enough data to show whether the vertical tracking accuracy of the bat is as precise as its horizontal tracking accuracy. In an ongoing study we have linked the bat's horizontal flight path planning with the horizontal direction of its head. We hope to extend that study to investigate whether the bat links its vertical head direction to its vertical flight planning in a manner similar to what has been discovered for the horizontal direction.



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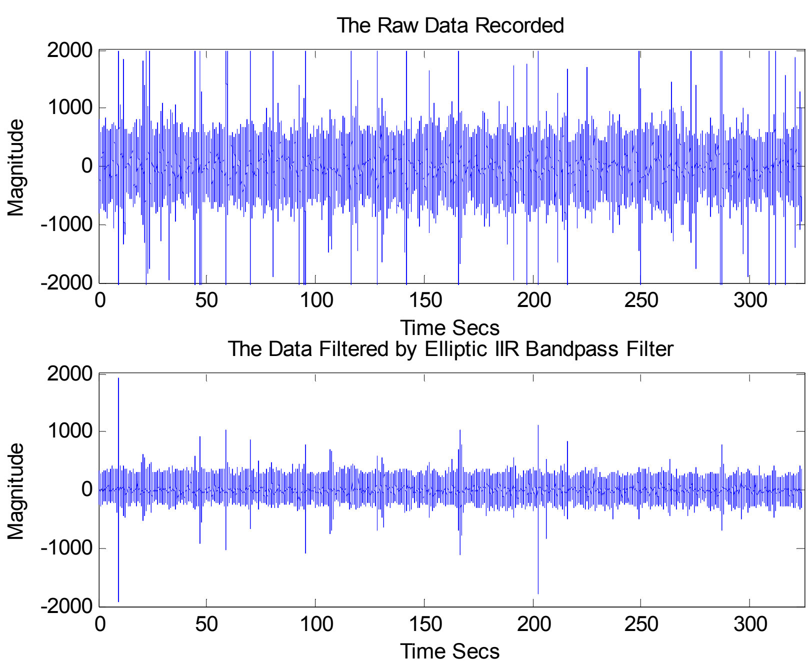
RF telemetry recordings of sonar cries/echoes and CNS activity in free-flying bats
This year, we have been working to refine hardware for more reliable neural telemetry recordings. Neuralynx, a company providing us with a custom, lightweight system for neural telemetry recordings, has made several developmental changes to our system. In the most recent system:

- Neuralynx changed the transmitter design to a "SAW Resonator" that provides a stable transmission frequency, and Epson is scheduling delivery of the custom SAW parts for April, 2005.
- Neuralynx changed the headstage design to consist of their standard input op amp design to avoid a problem with electrode offset voltages.
- Neuralynx changed the receiver system design to use commercial "Black Box" radios from ICOM. These are PC software-controlled receivers that are a very high quality design. We are using 8 of these receivers per system, which allows us to receive each of the 4 channels from two antennas for added reliability.

- Neuralynx changed the headstage design to allow use of their "Warp 16" drive and allow selection of the 16 electrode channels for the 4 transmitted channels and the common reference.

With all of these modifications to the system, we anticipate exciting results from radio telemetry recordings in the upcoming funding year.

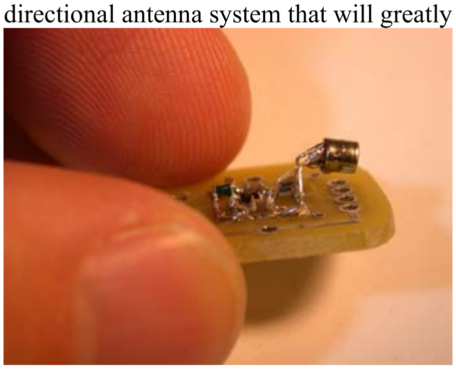
We have also been working on methods to process multiunit neural recordings taken from a free-flying bat. Spikes from neural recordings from the midbrain of a freely behaving bat were first filtered between 300-8000 Hz to remove any baseline fluctuations and Low-frequency field potentials. The resulting traces were generally quite clean and yielded 1-3 simultaneously active single units. Spike sorting of the traces was done off-line using a sophisticated MATLAB based program that allows the user to trace manually templates (constructed with multiple amplitude-time windows) for each spike shape. The average spike waveform from each sorted class of units was then estimated and checked to ensure that at least one time-amplitude window was fully separable from all other templates by a standard deviation. Furthermore, the program allows us to inspect several properties of the spikes trains to ensure that they conform to expectations. For instance, we check that the spike rate for each class remains relatively constant throughout the experiment, or at least that it varies in a similar to all other classes indicating, for instance, general effects of arousal. If spike rates change suddenly or vanish during the experiment, appropriate measures are taken to combine or break up the affected classes. We also inspect the inter-spike intervals of each class to make sure that very small intervals are minimal or absent, and that the distribution has an exponential tail to ensure that we are, in fact, analyzing single unit responses. Finally, data from different electrodes are analyzed and various checks are performed to ensure that the data is maintained at the same time-base of the vocalization recordings.



Once spikes are sorted, we generate a variety of raster displays that are time-locked to different aspects of the bat calls and echoes. For instance, spike times might be displayed relative to each individual FM sweep, or relative to the final in a series of sweeps with increasing rate. We are currently investigating whether these stimulus features evoke stereotypical responses indicating their behavioral significance. Finally, cross correlations of spike trains across electrodes will also be conducted to explore whether any synchronization or enhanced timing precision is present during calls relative to other epochs.

In addition, we have begun to develop and test our ultrasonic microphone transmitter system in the laboratory and have been designing mounting systems that can survive the animal's efforts to remove the device, yet make it simple enough to easily replace the batteries. We have recently switched to a 3V battery and have been adapting our circuit to handle the different supply and different physical battery size.

On the receiver side of the system, we are awaiting the release of a new model of the WinRadio (www.winradio.com) system that allows software-controlled, frequency tracking to follow the temperature-related drifts of the simple RF transmitter. In addition, we have been constructing a directional antenna system that will greatly improve rejection of external sources of noise.



II. Modeling of target tracking and obstacle avoidance by sonar

Our team is currently involved in the task of developing control-oriented geometric models of echo-locating bat behavior. The model under development uses the language of differential geometry to describe bat trajectories in three dimensions and how they are shaped by in-flight perception of the environment and tracking of an evasive prey. An essential ingredient of the model is the use of continual modification of trajectory curvatures as the encapsulation (or higher level abstraction) of flight control. Such a model is expected to be simpler than detailed models (see for instance: P. Watts, E. Mitchell, S. Swartz (2001), *The Journal of Experimental Biology*, **204**: 2873-2898) based on the bio-mechanics and aerodynamics of bat flight that require information on wing-beats, body deformation and orientation among other things, - information that is very difficult to infer from digitized and sampled video imagery of flight. In collaboration with graduate student Kaushik Ghose and faculty colleagues Tim Horiuchi and Cynthia Moss (thesis advisors of Ghose), he is investigating the problem of how trajectory curvatures (i.e. controls) are coupled to sonar vocalizations. Working from the hypothesis that, during the tracking phase of bat flight towards prey capture, head-aim is directed at prey location, Ghose and Moss have shown in a recent preprint (*Steering by Hearing*), that there is a strong correlation between instantaneous *turning rate in a plane* and the time lagged value of angular offset of flight direction from head aim. This suggests a corresponding sensory-motor feedback loop at work and Ghose and Moss determine estimates of feedback gains in different flight behaviors. Accurate measurements of head-aim have been achieved thanks to the availability of distributed array of ultrasonic microphones in the flight room and the ability to register the vocalization recordings from these microphones with the video imagery. One of the primary aims of the modeling efforts of Krishnaprasad is to take advantage of such measurement capabilities and extend this type of sensory-motor feedback loop model to fully three dimensional flight. In the three dimensional setting, the geometric techniques are essential.

In the differential geometry of curves, (see for instance, R. S. Millman and G. D. Parker, *Elements of Differential Geometry,* Prentice Hall, 1977), the Frenet-Serret (FS) apparatus allows one to propagate a moving orthonormal frame of tangent *T*, normal *N* and binormal *B* vectors in the arc-length parameterization, given two functions of arc length, the curvature κ (s) and the torsion τ (s). The apparatus consists of the differential equations

$$\begin{aligned} T' &= \kappa N \\ N' &= -\kappa T + \tau B \\ B' &= -\tau N \end{aligned} \qquad \text{(FS)}$$

with $\gamma' = T$. Here $\gamma = \gamma(s)$ denotes the trajectory in 3 dimensions as a function of arc-length *s* and $'$ denotes derivative with respect to *s*. Since bat trajectories are collected in the laboratory as sampled time functions, one converts to the arc-length parameterization by the formula $s = \int_0^t \left\| \frac{d\gamma}{dt} \right\| dt$, where $\left\| \frac{d\gamma}{dt} \right\|$ is the speed. Under the natural physical assumption that speed > 0, this change of parameterization is a strict monotonic one and hence invertible. In that case $T = \gamma'$ is always a unit vector.

If the Frenet-Serret apparatus (FS) is used as a model for the dynamics of a bat then κ and τ are control functions encapsulating the complex sequence of physiologic activity that generates the observed trajectory γ. Given a trajectory γ it is possible to recover from it unique functions κ and τ under the additional non-degeneracy and smoothness assumptions that $\gamma'' \neq 0$ and γ''' is also continuous. The corresponding inverse formulas involve up to three derivatives of the bat trajectory and *hence susceptible to measurement noise in video data*. Bearing this in mind we have considered another apparatus (which does not require the above additional assumptions) for framing a space curve, discussed in an influential paper of R.L. Bishop ("There is more than one way to frame a curve," *American Mathematical Monthly,* **82**(3):246-251, 1975). The idea is that it is possible to construct an alternative basis for the normal plane spanned by *N* and *B*, i.e., the plane perpendicular to *T*. This alternative basis is well-defined for all s provided (a) we pick an initial $M_1(0)$, a unit vector perpendicular to T(0) and define $M_2(0) = T(0) \times M_1(0)$ to get an initial (natural) frame $(T(0),\ M_1(0),\ M_2(0))$; (b) the curve γ is twice (piecewise) continuously differentiable.

The essential idea of the construction of $M_1(s)$ at s is that we transport $M_1(0)$ to $M_1(s)$ at *s* by requiring that M_1 turns as little as possible, or is a relatively parallel adapted field along γ. More precisely, we ask that

$$\tfrac{dM}{ds} = f(s)T(s)$$

at each *s* and for a suitable *f(s)*. Such a process in fact, remarkably enough, leads to an orthonormal triad $(T,\ M_1\ ,M_2)$ that is essentially unique except for the choice of the initial $M_1(0)$ which gives a single degree of (rotational) freedom. The equations to construct this *natural Frenet* frame are

$$\gamma(s)'' = \frac{dT}{ds} = k_1(s)M_1(s) + k_2(s)M_2(s)$$
$$\frac{dM_1}{ds} = -k_1(s)T(s)$$
$$\frac{dM_2}{ds} = -k_2(s)T(s)\,.$$

If we denote $h = (T, M_1, M_2)$ then:

$$h' = h\xi_{NF} \qquad \text{(NF)}$$

where,
$$\xi_{NF} = \begin{pmatrix} 0 & -k_1 & -k_2 \\ k_1 & 0 & 0 \\ k_2 & 0 & 0 \end{pmatrix}$$

The skew symmetric matrix ξ_{NF} is to be compared with the matrix ξ_{FS} that generates the usual Frenet-Serret frame. The *natural curvatures* k_1 and k_2 take the place of κ and τ and we also have the relations

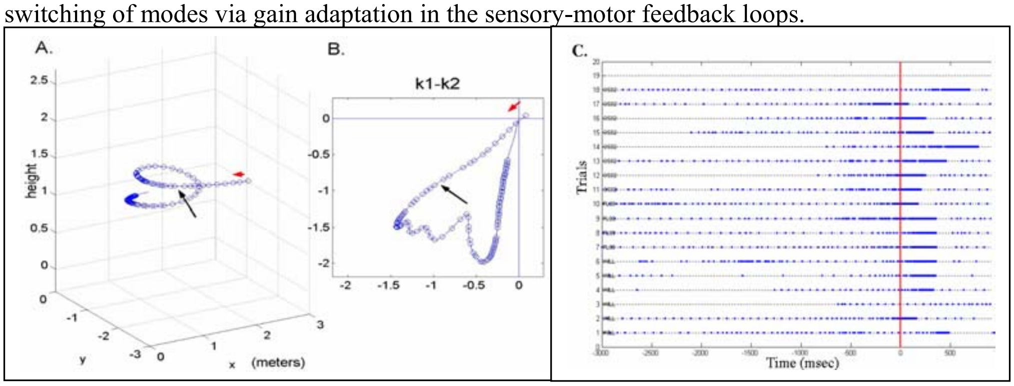
$$\kappa = \sqrt{k_1^2 + k_2^2} \qquad \theta' = \tau\text{, where} \quad \theta = \tan^{-1}\left(\tfrac{k_2}{k_1}\right).$$

The equations (NF) are a robust alternative to the model (FS) and allow one to understand bat trajectories in terms of the curvatures k_1 and k_2 (viewed as controls). A great deal of information is contained effectively in the behavior of k_1 and k_2 as functions of *s*. Visualizing bat trajectories in the (k_1, k_2) plane (also called the normal development) can be very helpful (see figure below). We need an effective method to extract the curvatures k_i from the trajectory γ. This inverse problem boils down to solving the following uncoupled Volterra integral equations:

$$k_i(s) = \gamma''(s)\cdot M_i(0) - \gamma''(s)\cdot \int_0^s k_i(\sigma)\gamma'(\sigma)d\sigma \qquad \text{i=1,2}$$

These have unique solutions given $M_1(0)$ and $M_2(0) = T(0)\times M_1(0)$. In order to exploit this theoretical framework as a modeling method for three dimensional bat behavior, Kaushik Ghose has created software tools to extract the natural curvatures in a robust manner. As a first step one can explore bat behavior by investigating the patterns observed in the (k_1, k_2) plane. For instance, the normal development of a 3D circular helix is a circle in the (k_1, k_2) plane. A planar motion of γ corresponds to a motion along a straight line through (0, 0) in the normal development plane. A motion confined to a sphere in 3-D gives rise to motion on a line in the (k_1, k_2) plane at a distance = (radius of the sphere)$^{-1}$. See Figure N for natural curvature analyses on selected behavioral trials.

Using the methodology described above, preliminary analyses have been carried out on a number of trials of flight data under prey-capture behavior. Patterns of flight control variations as expressed in variations of natural curvatures have been observed and are under detailed scrutiny. We anticipate developing an understanding of correlations between natural curvatures and angular offset of flight direction from head-aim in three-dimensional flight, analogous to those observed by Ghose and Moss in their planar analysis. Bat flight during prey capture behavior demonstrates significant mode switches in vocalization patterns, perhaps including as many as four modes. We have also begun to explore hybrid models that incorporate switching of modes via gain adaptation in the sensory-motor feedback loops.



Flight path in single trial. Red arrows indicate start of trial. Black arrows denote onset of increased curvature in flight path. **A**. 3-D flight path. **B**. k_1-k_2 plot of same trial. Circles represent the bat's vocalizations. Note higher signal repetition rates during turns and at the end of the trial (insect capture). **C.** Raster display of signals produced across 20 insect capture trials. Each circle represents a vocalization. A peak in κ occurred at time 0 in each trial. Note that vocal repetition rate increases and sonar strobe groups occur 50-100 msec before the peak in κ. For animations, go to http://www.bsos.umd.edu/psyc/batlab/natural_frames.htm

Krishnaprasad, in collaboration with colleagues Eric Justh and Fumin Zhang, is also investigating the mathematical modeling of wall-following and obstacle-avoidance behavior. The mathematics and the control theory involved is pertinent to both animal behavior and autonomous robotic behavior. Two papers, developed with additional leveraged support from DOD agencies, on this topic are:

1. F. Zhang, E. W. Justh and P. S. Krishnaprasad (2004), "Boundary following using gyroscopic control", Proceedings of the 43rd IEEE Conference on Decision and Control, pp. 5204-5209, IEEE, New York.

2. E. W. Justh and P. S. Krishnaprasad (2005), "Natural frames and interacting particles in three dimensions", submitted to 44th IEEE Conference on Decision and Control (under review).

These papers are included with this report. In these papers, information on the curvature of the boundary is used to guide boundary-following behavior. While in robotic contexts such curvature information may be gathered via ultrasonic and optical sensing, it is hypothesized that boundary geometry information is exploited by bats in negotiating cluttered environments. Preliminary experiments in the Batlab using wire-frames are likely to provide test-data to this end.

III. Modeling the transformation from echoes to steering: software and robotic modeling

This arm of the project involves both MATLAB simulations and a binaural, sonar-equipped mobile robot model to implement the closed-loop behavior identified in the bat's flight trajectories. This simulation and robotic modeling work seeks to link known neural representations of echolocation to motor commands necessary for obstacle avoidance and insect capture. There are many environments in which light is not a viable sensing medium, and robots built to operate in such environments can use advanced radar/sonar to navigate. The robotics work carries significance for the design of sonar-based devices, both by the direct creation of systems that can steer through natural environments and by identifying the forms of sensory data that may be most useful for guiding movements in humans.

Neuromorphic Engineering

Modeling the dorsal nucleus of the lateral lemniscus (DNLL) – VLSI

We are continuing to expand our investigation of the sound localization computations being performed by the neural circuits of the bat auditory brainstem and midbrain, specifically the lateral superior olive (LSO), the dorsal nucleus of the lateral lemniscus (DNLL), and the inferior colliculus (IC). We have previously focused on rudimentary models of the LSO and how binaural information was combined to form directional responses to steady-state input, however, our new work focuses on the problems of this approach specifically for the bat echolocation system and the overlooked issues that arise as these computational results are transmitted up to the DNLL and IC circuits as suggested by the current neurobiological literature.

Specifically, we have been exploring the consequences of long duration synaptic dynamics on the formation of these directional responses when a bat receives a rapid succession of echoes as would be expected in a more complex environment like a forest. Echoes from objects separated by 17 cm return to the bat with about 1ms temporal separation; at this timescale, most models of neural refractory period, excitatory synaptic currents, inhibitory synaptic currents, and neuron time constants indicate that the neural response to one object will modify the response to a second target. The implications of this observation has significant ramifications on our interpretation of how the bat can use the information coming from the auditory brainstem.

We will be presenting a paper on some preliminary results at the International Symposium on Circuits and Systems in May of 2005 in Kobe, Japan (Shi and Horiuchi, 2005).

The 'Openspace' Algorithm (& Chip)

As described in the original proposal, part of our work includes the transfer of concepts gleaned from the analysis of bat flight to algorithms that can be demonstrated on robotic platforms and in neuromorphic systems designed to mimic the bat echolocation system. At this early stage in our research, we have been designing a neurally-plausible algorithm that integrates sonar echo information into a common data representation with goal direction information to guide the steering behavior of a robot. While not currently tied to any specific brain area or known recordings, this algorithm uses a hypothesis-testing framework that creates an estimate of "goodness" of different directions that is driven by goal directions and inhibited by detected objects and limitations of the robot. We have recently successfully demonstrated this algorithm in steering a mobile robot operating with a 40 kHz binaural sonar system (see below).

A new spike-timing-based neural model of this algorithm has been developed that is uniquely suited to the bat echolocation problem. By utilizing the natural timing of the returning echoes to trigger weak, but long-duration inhibitory currents, the 'openspace' algorithm can be implemented with spiking neurons, using a 'race-to-first-spike' winner-take-all mechanism. We have simulated this algorithm in MATLAB and in VLSI circuit simulations and have recently submitted a VLSI chip of the algorithm. This chip is being fabricated and will be tested in June of this year.

Mobile Robotics – 'Openspace'

Two undergraduates (as part of the Univ. Maryland MERIT program) in the Horiuchi lab have recently implemented the 'openspace' algorithm (previously only tested in MATLAB) on a mobile robot platform with great success. As a result of this demonstration and new experience with practical modifications of the algorithm, we are rebuilding the system to improve speed and range. This project and associated poster received a 'Best Project Award' from the University of Maryland 2004 MERIT Fair judges.

Sensorimotor model of sound localization

Two experimental fields make the major contribution to our current understanding of how auditory system localize sounds. While psychoacoustic studies try to determine the properties of the phenomena and test proposed hypotheses on humans or animal subjects, anatomical and electrophysiological studies focus on the internal circuitry that are thought to participate in the computation of sound localization by the brain. Work in physiology and psychoacoustics are supported and motivated by the studies that are involved in understanding the acoustic properties of the signals received at the two ears. Despite a wealth of knowledge obtained from these efforts, our understanding of sound localization is still far from being complete.

Here we plan a new approach in hope of providing a new avenue to increase our understanding of sound localization. Recent findings in the field suggest that the explanation of how sound localization takes place should include the following properties of the phenomena:

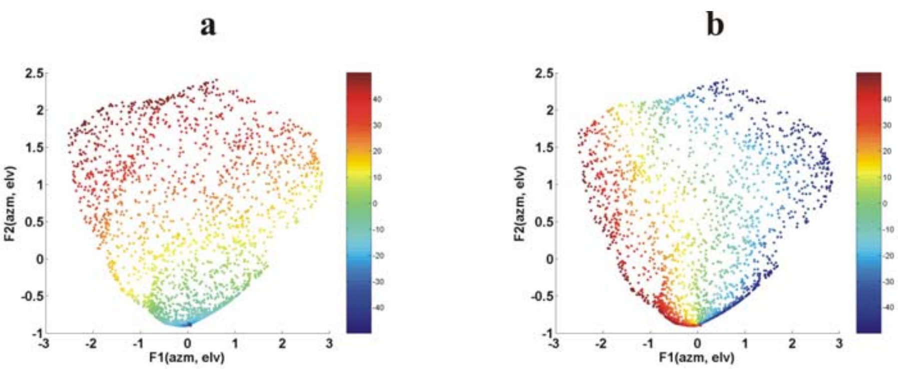
- Independence of sound source spectrum.
- Robustness against the patchy spectral input.
- Necessity of binaural input.
- Self calibration, plasticity.
- Proprioceptive contribution.

Unlike the approaches commonly taken by the researches in the fields, our approach looks at the problem from the angle of the organism that has to localize sounds. An organism from birth faces to the problem of calibrating the system that computes the sound location. Without the knowledge of the head and the ear shape, the auditory system manages to learn how to localize. In fact, perhaps we can even claim that spatial perception of the sound sources only becomes available as a result of this calibration process. We suggest that posing the question of how an organism can built a computational framework to achieve sound localization can be the key to many of the answers that the field is seeking.

We have been able to show that the interaction between the acoustic input and the head movements can provide necessary information to build such computational framework. Under the controlled head movements direction-dependent change in the acoustic input can be induced. A systematic analysis of such changes can give access to the spatial parameters of the sound source. Acoustic changes caused by small head movements are tangential to a smooth 2-dimensional surface embedded in the acoustic input space. Information on the geometry of this smooth surface can be obtained, thanks to the principles of the differential geometry. We have shown that a naive organism can access this information by repeating similar head movements and observing the change in acoustic input. Using echolocating bat head related transfer functions (HRTF) as an experimental platform we were able to obtain two independent spatial parameters that can determine direction of a sound source.

We suggest that an internal model that predicts the acoustic changes caused by specific head movements can remove the need for the head movement for localization. By providing a prediction of the acoustic change the need for head movement to obtain the change can be removed. Localization then can be accomplished by finding the corresponding spatial parameters to the predicted acoustic change. Allowing the internal model to adapt, an organism can cope with the changes that may happen to the ears and the head. Thus, this approach provides a tool to understand all the itemized characteristics of the sound localization above.

In the figure below we show our preliminary results with bat the HRTF. For this application 29 frequency channels per ear spanning frequencies from 30 kHz to 75 kHz is used. The modeled animal took measurements of acoustic changes caused by 1 degree left and 1 degree upwards head movements at random times. Sound source spectra were randomized so that no two spectrum were similar from one measurement to another. The simulated acoustic changes due to head movements were fed to a manifold learning algorithm to obtain the two spatial parameters. In the figure each sound source represented as a point in this two-parameter space. Color indicates sound source azimuth (left) and elevation (right). Note that sound sources with similar azimuth and elevation appears close to each other in the parameter space resulting in a smooth color change. Thus, our naive animal now has a representation of space. We are currently working on building an internal model for this implementation. Investigations of the inner workings of the internal model will allow us to determine what acoustic features were used by this model to localize sound (Aytekin and Moss, 2005).



Significance: Fundamental to healthy human function is the transformation of sensory information to motor commands for adaptive behaviors such as tracking, reaching, grasping and steering around obstacles in the natural environment. A deeper understanding of the mechanisms supporting this vital function of the nervous system will facilitate treatment and rehabilitation when it fails to develop normally or breaks down through disease. Our CRCNS project takes an innovative approach to advance technology and research on this central problem in neuroscience and medicine. Specifically, we are working to integrate miniaturized radio telemetry recordings, advanced signal processing, control systems modeling, adaptive behavior studies and neurophysiology to deepen our understanding of active sensing for spatial localization, obstacle avoidance and target tracking. We have chosen the echolocating bat as a model system for our project, because this animal exhibits rich but well-defined adaptive motor patterns that serve to indicate changing behavioral states. Furthermore, the bat uses a sophisticated biological sonar to build a three-dimensional representation of the environment in complete darkness, and it uses this spatial information to maneuver rapidly as it flies. The choice of this model system therefore presents special opportunities to bridge work on sensorimotor behaviors guided by audition and vision.

The behavioral experiments carried out under 'Specific Aim 1' of the project provide empirical data for computational modeling through which we can gain access to the commands for behavioral control. Moreover, recent developments in technology permit recordings of neural activity and sonar cries from free-flying animals as they engage in the full suite of adaptive behaviors used for obstacle avoidance and insect capture. Given the opportunity to link neural activity profiles with details of the bat's flight path, sonar beam aim and vocal signals under changing task conditions, this work promises to advance systems neuroscience and computational modeling in the context of complex adaptive behaviors.

Our modeling effort under 'Specific Aim 2' focuses on the investigation of control laws and sensory-motor integration in goal-oriented behavior of bats in complex cluttered environments. In addition to the basic science, the use of geometric methods in this arena is expected to lead to important new insights in the design of control algorithms and software for robotic navigation in complex environments. Further development of such robotic technology could be coupled to the development of technology to aid safe movement and functioning of impaired humans in complex environments via active acoustic probing and robust sensory-motor integration.

This simulation and robotic modeling work under specific aim 3 seeks to connect known neural representations of echolocation to motor commands necessary for obstacle avoidance and insect capture. The short-range and sampled nature of the echolocation system and the speed of a flying bat make rapid navigational choices critical. By integrating the ability to manipulate head direction and echolocation rates, we hope to model and understand the choices the bat makes in gathering information. We will soon expand this work into the third dimension to include more of the physics of flight and to begin matching our generated trajectories to those seen in the behavioral experiments. This simulation work, while cast in the bat problem, has application to mobile robot navigation in general where continuous movement is desirable (e.g. for aircraft or in predator-escape situations) and sensory information appears intermittently.

Published papers, manuscripts and meeting abstracts

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Aytekin, M. and Moss, C.F. A sensorimotor model of sound localization by the echolocating bat, *Eptesicus fuscus*. Association for Research in Otolaryngology, New Orleans, 2005.

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Ghose, K. and Moss, C.F. Steering by hearing: Sonar beam direction guides locomotion in echolocating bats. In preparation for submission to the *Journal of Neuroscience*, 2005.

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