LOCALIZATION OF AN OBJECT USING A BAT MODEL, INSPIRED FROM BIOLOGY[#]

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Abstract. A model of the bat sensorimotor system is developed using acoustics, signal processing and control theory to illustrate the fundamental issues in accomplishing prey capture with echolocation. Using such a model, we can develop a system that can detect objects, like bats which employ echolocation for prey capture by emitting a series of acoustic pulses and processing the echoes.

Key words: bat model, sensor.

INTRODUCTION

Many researchers have proposed ultrasonic sensor systems that make use of bats and the way they capture their prey. Bats employ echolocation for prey capture by emitting a series of acoustic pulses and processing the echoes. Using a model like "bats", researchers have proposed different systems that use at least three receivers. Part of the explanation why biological systems have retained superiority in these more involved tasks may lie in nature's ability to create well-integrated systems comprising many components, each of which contains evolutionarily embedded knowledge about the particular tasks it performs and the control loops it belongs to [7]. Both the morphology of the sonarhead and the measurement strategies it employs are modelled on aspects of the bat's echolocation system. The biological system seeks to reproduce - at a functional level - the biosonar system found in bats. Biosonar outperforms man-made sonar technology in its ability to support versatile, fully autonomous navigation as well as a variety of other tasks in often demanding natural environments as a sufficient far sense. In order to provide

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a robotic platform capable of reproducing these skills, the biomimetic system couples sensing with actuation and integrates peripheral with neural processing by feedback loops spanning all stages.

BIOMIMETIC SONARHEAD

The biosonar system of bats uses intertwined acoustic and neural signal processing with various feedback control loops spanning both domains to achieve an unparalleled performance. Although the ways in which the animals achieve this performance remain largely unknown, some basic system specifications have been determined and are given in Table 1 [5]. The animals have high power ultrasonic emission systems combined with very sensitive reception. The sites of emission and reception are often surrounded with elaborate baffle shapes.

Table 1

Specifications of a current state-of-the-art robotic models (S1 [3], S2 [1], S3 [2], S4 [7], S5 [3], CIRCE [8]) and the bat sonar system

	S1	S2	S3	S4	S5	CIRCE	Bats
Scale[1]	~10	~1–2	~4	~4–5	~4–5	~1	1.0
N rot. DF for ears[2]	0	0	1	2	2	2	2
Variable chirp[3]	No	No	No	Yes	Yes	Yes	Yes
Pinnae	No	Yes[4]	No	No	No	Yes	Yes
Var. directivity-width[5]	No	No	No	No	No	Yes	Yes
F-dep. directivity-axis[6]	No	No	No	No	No	Yes	Yes
Max. BW[7] [kHz]	<<10	<<10	~100	~100	~100	160	160
SNR[8] [dB]	?	?	~30	~60	>60	>>60	?
Output SPL[9] [dB]	?	?	?	?	~110	~120	~130
Number of IHC[10]	1	Few	1	Software	Software	~1000	700–2000
Number of SGC[11]	0	Few	0	Software	Software	~10000	13000–55000

[1]A natural bat head is assumed here to have a diameter of 4 cm; [2]number of rotational degrees of freedom; [3]bandwidth and instantaneous frequency as a function of time; [4]applies to one version of the system; [5]directivity pattern can be made wider or narrower; [6]central axis of the directivity pattern depends on frequency; [7]total non-zero frequency band; [8]signal-to-noise ratio as level difference between an echo from a plane in 1 m distance and the noise floor; [9]sound pressure level 1 m distance straight ahead; [10]inner hair cells; [11]spiral ganglion cells.

While each of the various systems which have been developed over the last 10 years has been successful in reproducing some of the interesting aspects to biosonar function, so far none of them has integrated all known functional features of a bat head. Being much larger than natural biosonar systems renders these models incapable of duplicating the diffraction effects around the head which facilitate sonar sensing in their biological counterparts. Those model systems which have been approximately to scale [1] have achieved this at the expense crucial functional features like ear mobility. In terms of transducers, all existing systems have been using standard, commercially available technology [2, 3] either narrowband piezo-electric transducers [1, 3] or comparatively more wideband capacitive transducers [5, 7].

It is evident from the specifications summarized in Table 1 that there is a wide gap between the current robotic models and natural sonar heads and that realizing a more realistic functional reproduction of the biological system requires several challenges to be addressed:

BIOMIMETIC ANTENNAE SHAPES

In bats, sonar emitters (mouth or nose) and receivers (ears) are surrounded by often elaborate baffle shapes. These shapes are hypothesized to serve as beam-forming aperture tapers. Both, the beam-forming mechanisms and the resulting beam properties need to be understood in order to be able to mimic the acoustic signal processing that is performed by biosonar systems before the signals are transformed into a neural representation.

TRANSDUCER TECHNOLOGY

Bats are able to produce high-energy sonar pulses apparently in a very efficient manner. This results in good signal-to-noise ratios even for otherwise unfavorable target ranges and target strengths. On the receiver side, bats can rely on the superb sensitivity of the mammalian hearing system. Coming close to these specifications requires careful design of electro-mechanical transducers systems which uses an integrated approach for designing the transducers proper and matched driver electronics.

ACTUATION

Many bat species possess several degrees of freedom in orienting their outer ears (pinna) as well as controlling the shape of the baffle structures surrounding the sites of sound emission. This enables them to perform adaptive sensing in a configuration space which is made up not only by the position orientation of their sonar heads, but also by the orientation and shape parameters for the sensors.

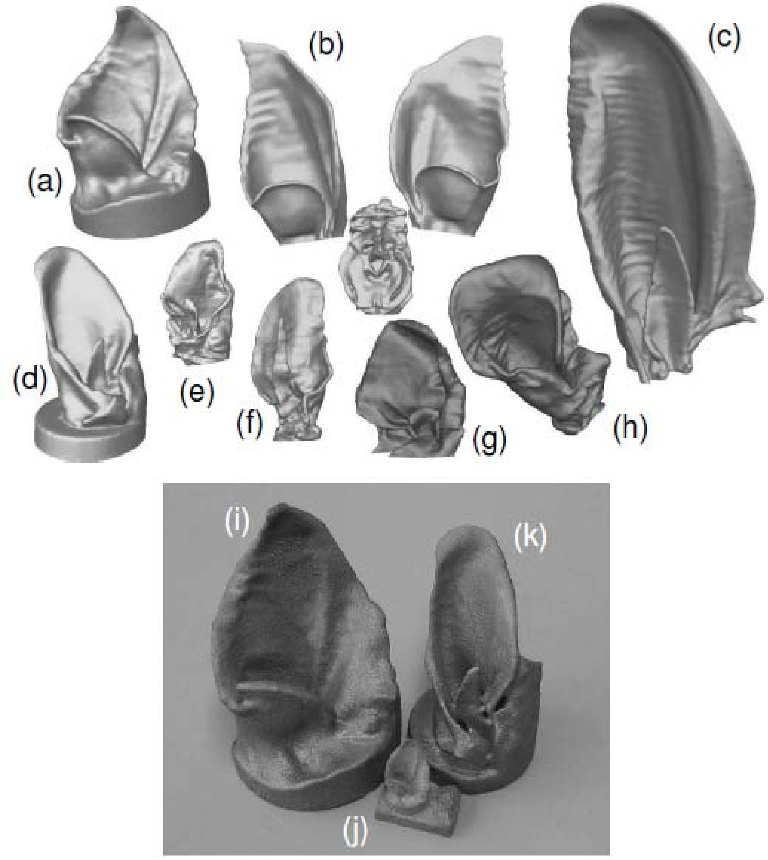

Fig. 1. Example of pinna shapes: a) *Rhinolophus rouxi* (Rufous Horseshoe Bat); b) *Rhinolophus ferrumequinum* (Greater Horseshoe Bat) shown are the two ears and the appendages ("horseshoe") around the nostrils; c) *Plecotus auritus* (Brown Long-eared Bat); d) *Eptesicus fuscus* (Big Brown Bat); e) *Pipistrellus nathusii* (Nathusius' Pipistrelle); f) *Myotis nattereri* (Natterer's Bat); g) *Nyctalus noctula* (Noctule Bat); h) *Tadarida sp*., Physical prototypes made from stainless steel grains in a bronze matrix for two of these shapes; i) *Rhinolophus rouxi* (s, a), magnified 4 times, j) *Rhinolophus rouxi* natural size (for comparison), k) *Eptesicus fuscus* (s, d).

NEUROMORPHIC SIGNAL PROCESSING

Ultrasonic signal processing poses a special challenge for neural systems, because the high bandwidth of the signals has to be adapted to the comparatively low rates at which neural signals can be generated. The principal mechanism to achieve this is a filter bank representation, where each channel codes for the portion of the signal bandwidth which falls into the passband of a bandpass filter, which is much narrower than the entire signal bandwidth. However, the number of primary receptors and nerve fibers making up the auditory nerve in bats (approximately 700 to 2 200 and 15 000 to 55 000 respectively), are still in reach of what digital neuromimetic hardware can match quantitatively.

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ULTRASONIC TRANSDUCER TECHNOLOGY

Faithfully mimicking the sonar system of different bat species requires the ultrasonic transducer to meet a demanding set of specifications.

Nowadays, PZT (Lead zirconate titanate) or PVDF (Polyvinylidene Fluoride) transducers are commonly used, but for this type of work the best material is ElectroMechanical Film (EMFi).

EMFi is a polypropylene film, its thickness for sensor and actuator applications is typically 30 – 70 μm. The film has a cellular structure which results from its manufacturing process [5]. Charge is injected into the polypropylene film by a corona method making use of a strong electric field with $E_{\text{polarization}} \sim 10\,\text{kV/cm}$. The resulting buildup of internal charge at the surfaces of the cavities turns the latter into macroscopic dipoles, see Fig. 2, which retain their dipole moments after the polymer cools to room temperature. The cellular structure and the macroscopic dipoles result in relatively high piezo constants $d_{33} = 130 - 450\,\text{pC/N}$.

The directivity pattern of the Polaroid transducer at frequency f is approximated by that of a circular piston placed in an infinite baffle:

$$D_{\text{piston}}(\theta) = 20\log\left(\frac{\left|J_1(ka\sin\theta)\right|}{\left|ka\sin\theta\right|}\right) \tag{1}$$

with a being the radius of the transducer, $k = 2\pi/\lambda$, and θ is the angle between the maximal sensitivity axis of the transducer and the object’s line of sight.

Using the wave propagation speed, time of reflection information can be converted into distance of reflection information. If the transmitting-receiving wave transducer has suitable directional sensitivity, the direction of the reflected signal can be measured and a two-dimensional reflection-signal image formed [4]. To determine the strength of an echo arriving at one of the receivers of the bionic sonarhead we have to take into account the spreading losses, absorption in air and reflection losses, in addition to the directivity of both the transmitter and the receiver.

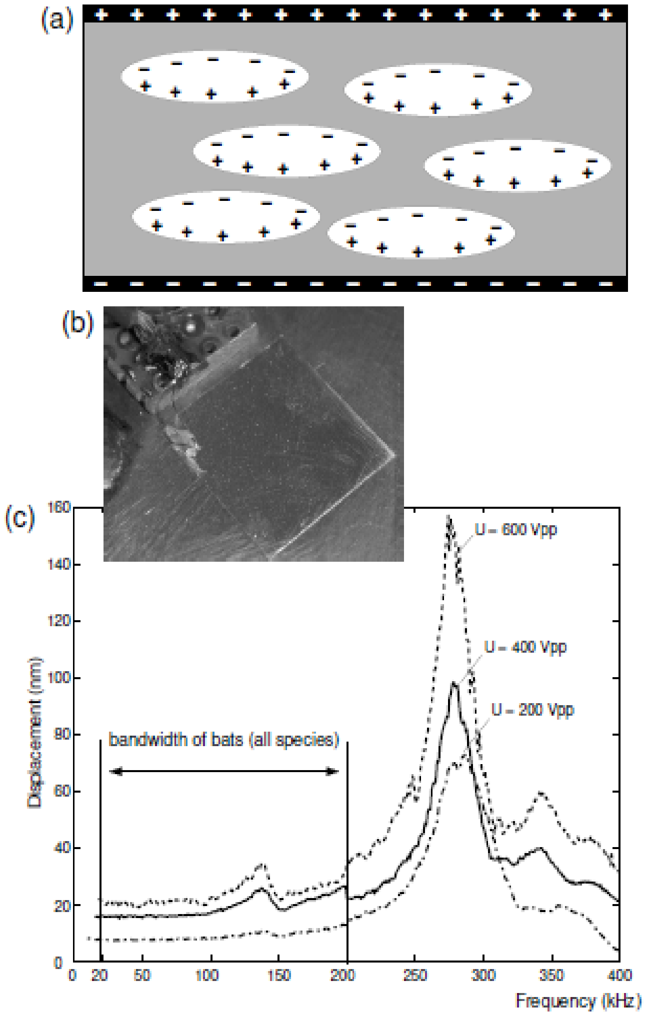

Fig. 2. EMFi transducer technology: a) the presence of permanent dipoles in the polymer film gives EMFi its electret properties, b) test setup for evaluation of EMFi transducer technology, c) frequency response for the displacement of the EMFi transmitter surface.

When the mouth is modeled as a circular piston of radius a_{m} vibrating with frequency f in an infinite baffle, the emitted acoustic pressure distribution in the far field forms a beam described by a Bessel function. The standard field pattern is modified by including a term, $\alpha(f, r)$, to account for the frequency-dependent acoustic absorption of air. The emitted pressure amplitude at range r and angle β relative to the piston axis is then approximated by

$$P_{\mathrm{E}}(f,r,\beta)=\frac{\rho c}{2}U_0\frac{ka_{\mathrm{m}}^2}{r}\alpha(f,r)\left(\frac{2J_1(ka\sin\beta)}{ka\sin\beta}\right)=(\rho\pi U_0)\frac{fa_{\mathrm{m}}^2}{r}\alpha(f,r)\left(\frac{2J_1(ka\sin\beta)}{ka\sin\beta}\right) \quad (2)$$

where ρ is the density of air, c is the speed of sound, U_0 is the source strength, $k=2\pi/\lambda=2\pi f/c$, and J_1 is the Bessel function of the first kind.

If the prey is small compared to the wavelength, the echo has a spherical wavefront whose amplitude decays with the inverse of the distance propagated. The detection sensitivity pattern of the circular ear aperture of radius a_{e} at frequency f has the same Bessel function form, or directivity factor. If the prey is located at $(r_{\mathrm{m}},\beta_{\mathrm{m}})$ relative to the mouth and $(r_{\mathrm{e}},\beta_{\mathrm{e}})$ relative to an ear, then the echo pressure amplitude at the inner ear is given by

$$\begin{aligned}P_{\mathrm{D}}(f,r_{\mathrm{m}},\beta_{\mathrm{m}},r_{\mathrm{e}},\beta_{\mathrm{e}})&=(k_{\mathrm{e}}\sigma\rho\pi U_0)\frac{fa_{\mathrm{m}}^2a_{\mathrm{e}}^2}{r_{\mathrm{m}}r_{\mathrm{e}}}\times\\ &\times\alpha(f,r_{\mathrm{m}}+r_{\mathrm{e}})\left(\frac{2J_1(ka_{\mathrm{m}}\sin\beta_{\mathrm{m}})}{ka_{\mathrm{m}}\sin\beta_{\mathrm{m}}}\right)\times\left(\frac{2J_1(ka_{\mathrm{e}}\sin\beta_{\mathrm{e}})}{ka_{\mathrm{e}}\sin\beta_{\mathrm{e}}}\right)\end{aligned} \quad (3)$$

where k_{e} is a constant that describes the geometrical properties of the pinnae, the a_{e}^2 term indicates that the sensitivity of hearing improves with the pinnae size. This model assumes that the echo is perceived with a frequency dependent efficiency η_{f}. The echo pressure perceived by the bat is given by

$$\begin{aligned}P_{\mathrm{P}}(f,r_{\mathrm{m}},\beta_{\mathrm{m}},r_{\mathrm{e}},\beta_{\mathrm{e}})&=3000f\eta_{\mathrm{f}}\frac{r_\sigma^2a_{\mathrm{m}}^2a_{\mathrm{e}}^2}{r_{\mathrm{m}}r_{\mathrm{e}}}\alpha(f,r_{\mathrm{m}}+r_{\mathrm{e}})\times\\ &\left(\frac{2J_1(ka_{\mathrm{m}}\sin\beta_{\mathrm{m}})}{ka_{\mathrm{m}}\sin\beta_{\mathrm{m}}}\right)\times\left(\frac{2J_1(ka_{\mathrm{e}}\sin\beta_{\mathrm{e}})}{ka_{\mathrm{e}}\sin\beta_{\mathrm{e}}}\right)\end{aligned} \quad (4)$$

with $\eta_{f_o}=0.9$ for the fundamental and $\eta_{f_1}=1$ for the overtone, r_σ represents the range of the prey determined from the previous echo and $(k_{\mathrm{e}}\sigma\rho\pi U_0)$ set to be 3000.

The time of flight (TOF) of the echoes is related to the range of the prey.

The echo from the first emission impinges on the prey at time $t=r_1/c$, where r_1 is the prey's range at first emission. The echo then contains the information about the location of the prey at that time instant. The echo returns to the ears at approximately $t=2r_1/c$, and its processing is done at $t=\tau_1$ at which time the bat reacts to the heading and produces a new emission. The kth echo is produced at time $t=T_k$, where $T_k=\sum_{n=1}^{k}\tau_n$, where τ_n is the time between emissions n and $n+1$ and is described by

$$\tau_n = 0.044 r_n - 0.008 \text{ s}, \text{ for } r_n \geq 0.32 \text{ m} \tag{5}$$

$$\tau_n = 0.006 \text{ s}, \text{ for } r_n < 0.32 \text{ m} \tag{6}$$

CONCLUSION

The models presented in this paper are inspired from biology and allow for localisation of objects. The use of a robotic system suitable for operation in the real, physical world, ensures that the explanatory power of any such hypothesis is automatically proven by virtue of a working implementation.

In order to build small, actuated, biomimetic bat head, we have presented in this paper our research about the optimal material for transducers, types of pinna and a mathematical model to investigate acoustic information employed from nature.

For future work, we propose a study concerning the shape of the aperture and an optimal type of transducer for this model (flat, 1-D or 2-D array).

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