THE CIRCE BIOMIMETIC BAT HEAD

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1. INTRODUCTION

Despite an ever-increasing speed of technological achievements, biological systems still outperform technical systems in many ways. Part of the explanation why biological systems show superior performance in less structured environments lies in nature's ability to create well-integrated systems comprised of many components, each of which contains evolutionarily embedded knowledge about the particular tasks it performs. In particular, the bat's sonar system outperforms man-made sonar technology in its ability to support versatile, fully autonomous navigation as well as a variety of other tasks in demanding natural environments. As such, bats are a clear example of how the use of intertwined acoustic and neural signal processing with various feedback control loops spanning these stages can lead to unparalleled performance: these animals are capable of satisfying all informational needs pertinent to their highly mobile, predatory lifestyles based on (active and passive) sonar alone.

In order to obtain a better understanding of the role of the different sonar system components (e.g., shape of the emitting and receiving antennae, feature extraction and neural coding, adaptive mobility and reshaping of the antennae) and their interplay in a highly coupled system, an attempt is made to reproduce this system - at a functional level - with a robotic model: the CIRCE head. The primary objective for this biomimetic bat head is to provide hypotheses for biological function. The applicability of these hypotheses can then be tested in experimental work performed with real animals. Besides this objective in basic science, a biomimetic sonar system that would exhibit a bat's navigation and prey-capture skills would lead to orders of magnitude improvements in all areas where technical sonar systems are used nowadays.

To model the acoustic field around the bat's head accurately, the ratio of the size of the important head structures and the sound wavelength has to be kept constant. Hence, the CIRCE head has to combine in a small space (Ø=4-8 cm) actuated antennae for emission and reception,

	CIRCE prototype	Bat
Rotational DoF. for each ear	2	?
Pinnae	rigid + orientable tragus	Deformable
Non-Zero Bandwidth [kHz]	20-200	0-200 (over all species)
SNR (plane at 1m. / noise floor) [dB]	>> 60	?
Output SPL at 1m. [dB]	100	130
Number of Inner Hair Cells	700	700-2000
Number of Spiral Ganglion Cells	10000	13000-55000

Table 1: Functional specifications of biomimetic bat head.

transducers (one transmitter, two receivers) and signal conditioning electronics in a way that meets a demanding set of functional specifications (Table 1). This results in various technological challenges, which are detailed in the remainder of this paper.

2. BIOMIMETIC ANTENNAE SHAPES

The approximately 1000 species of bats have evolved a highly diverse set of baffle shapes which surround the sites of sound emission (mouth or nose) and reception (ears). Most likely, these shapes act as beamforming antennas, optimized to suit the different sonar tasks these animals have to solve. The CIRCE project is the first attempt to systematically analyse the functional properties of some of these shapes and use the insights arising from this analysis to design a set synthetic baffle-shapes for a biomimetic sonar system.

Information on the biological shapes has been gathered [1] from nine different species of bats. Samples of the outer ears (pinnae) were subjected to micro-tomography (Skyscan 1072 scanner) generating sets of shadow images of 1024x1024 pixels. Shadow images were taken across a half-circe (180°) with 0.9° resolution; the cross-pixel resolution was between approximately 8 and 30 micrometer, depending on total ear size. From the shadow images, object cross-sections were reconstructed using the Feldkamp's fan beam algorithm. The reconstruction results, 8-bit cross-section images, were manually cleared of noise and obvious reconstruction artifacts. Stacking the thresholded cross-section images, yielded a three-dimensional voxel-array representation ("structured grid") of the ear shapes.

A functional analysis of these shapes was performed with a, time-domain, finite element numerical simulation of the diffraction effects, using the CFS++ software developed at the Department of Sensor Technology, University of Erlangen-Nürnberg. The boundary of the computational domain of the finite element analysis, i.e. a cuboid enclosing the immediate vicinity of the ear shape, was covered with two-dimensional absorbing boundary elements approximating reflection-free outward propagation. The ear shapes were simulated to act as loudspeakers, with a sound source placed in the proximal preserved cross-section of the ear canal. By virtue of the reciprocity principle, this allows for determination of the receiver directivity as well. The results computed for the boundary faces of the cuboid were then transformed into the frequency domain. Next, for each frequency, the solution on the faces was projected forward using a Kirchhoff integral formulation [2] to a set of points located on a sphere. The normalized wavefield amplitudes at these points were taken as an estimate of the ear's directivities.

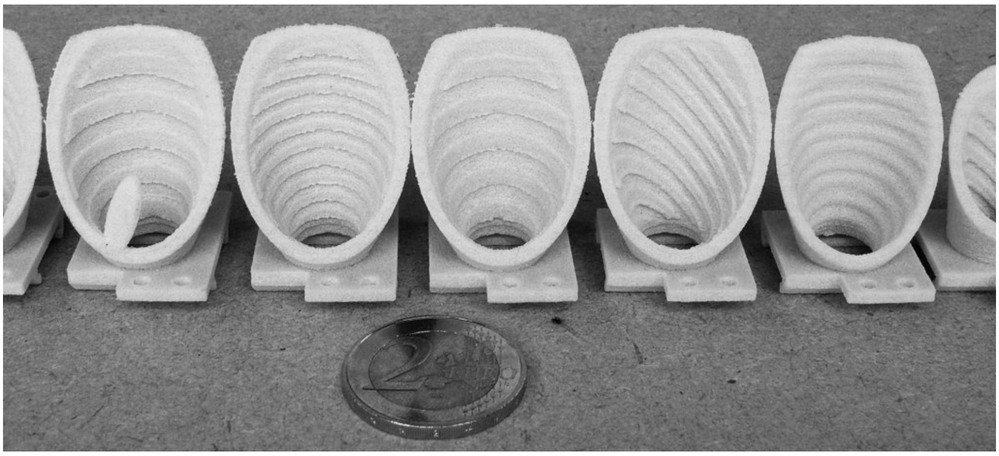


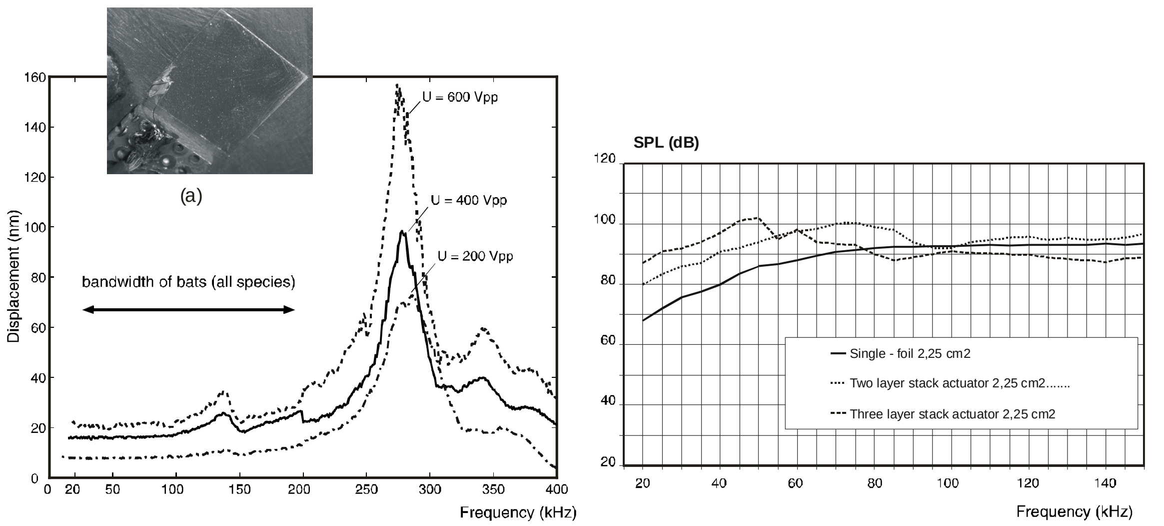
Figure 1: Example of manufactured prototypes of parsimonious pinna shape models.

These simulations have shown that the tragus, a frontal flap which can be very prominent in bats, has a systematic effect on the shape of the directivity pattern. Furthermore, in experimenting with simpler shape models it has become apparent, that there is an interaction between the effect of the tragus and the presence of a surface ripple on the inner surface of the pinna. To validate these results it was decided to design and fabricate a family of artificial ear shapes (see Fig. 1) which use the basic shape of an obliquely truncated horn proposed as an idealized pinna model by Fletcher [3] and augments it with a flap modelling the tragus and a ripple pattern. The fabricated ear shapes are made out of Nylon 7000 using a rapid prototyping tool (selective laser sintering) and are mounted on the transducer using a snap-fit allowing for easy switching between them.

3. TRANSDUCER TECHNOLOGY

Bats are able to produce high-energy sonar pulses in a very efficient manner. In addition, bats can rely on the superb sensitivity of the mammalian hearing system on the receiver side. The specifications set out in Table 1 can not be achieved with commercially available in-air ultrasonic transducers as they are too large to fit on the biomimetic bat head and lack adequate bandwidth. Hence, new transducer technology is required. Based on an assessment [4] of the pros and cons of the various transducer technologies EMFi based transducers were selected. EMFi is a polypropylene film, thickness 30−70 μm, that has a cellular structure which results from its manufacturing process [5]. During manufacturing voids created in the non-polar material are internally charged by inducing micro-plasma discharges. The resulting build up of internal charge at the surfaces of the voids turns the latter into macroscopic dipoles. The cellular structure and the associated macroscopic dipoles result in relatively high piezo constants d_{33} = 130−450 pC/N.

A prototype comprising a patch of EMFi (15x15mm) mounted on a copper plate as backing (see Fig. 2(a)) was used for investigating the properties of the EMFi material. The polymer was fixed on one side using conductive glue making the piezo material oscillate in the thickness mode. Actuated with an a.c. voltage of up to 600Vpp, the film's deflection was measured as a function of frequency (Fig. 2(b)). The measurement clearly shows an increase of the amplitude of the displacement with that of the applied driving voltage. Experiments with multiple layer stacks (Fig. 2(c)) show that we have to use a two layer stack to achieve the required Sound Pressure Levels (see Table 1).



(b) (c)

Figure 2: (a) EMFi transmitter (15x15 mm); (b) frequency response of transducer surface displacement; (c) frequency response of acoustic output on transmitter axis at 1m.

The reciprocal nature of the transduction mechanism allows to use the same material for designing broadband receivers. Furthermore, the good impedance match between EMFi and air guarantees a much more efficient transduction than would be possible with standard piezo materials. Finally, EMFi foils are light, thin and flexible making them easy to process, e.g., cut them in arbitrary shapes, but have a relatively low temperature at which the material looses its electret properties, i.e. Tmax < 90^0C, forcing the use of conductive glue instead of soldering for contacting.

4. ACTUATION

Many bat species posses the capability to orient/deform their outer ears (pinna) at will, enabling them to adapt their perception apparatus to the task at hand. The actuation subsystem of the biomimetic head needs to provide the means for duplicating the essential features of such real bat head actuation capabilities. In particular, we have chosen independent panning and tilting of each of the two outer ears (specifications: range=60^0, bandwidth=1-10Hz, accuracy<0.1^0) as well as tragus (specifications: range=60^0) tilting for reproduction in the biomimetic bat head.

The mechanical design of the biomimetic sonar head is to a large extent determined by the actuator technology. Comparing accuracy, drive voltage levels, ease of control, response speed and commercial availability for the different candidate micro-actuator technologies it was concluded that the most suitable actuators are electromagnetic motors, in particular, the DC-Minimotor 0816. The motor, reduction and 32-pulse encoder has a size of Ø=8×80 mm.

An overview of mechanical systems has led to the adoption of a differential architecture (see Fig. 3(a)) combining the movements of two motors to move the ear with the required two rotational degrees of freedom. If both motors have the same rotation sense, the ear makes a pan movement; if both motors have opposite rotation senses, a tilt movement is executed. The differential, apart from being very compact, shares the larger inertia of the tilt movement between the two motors.

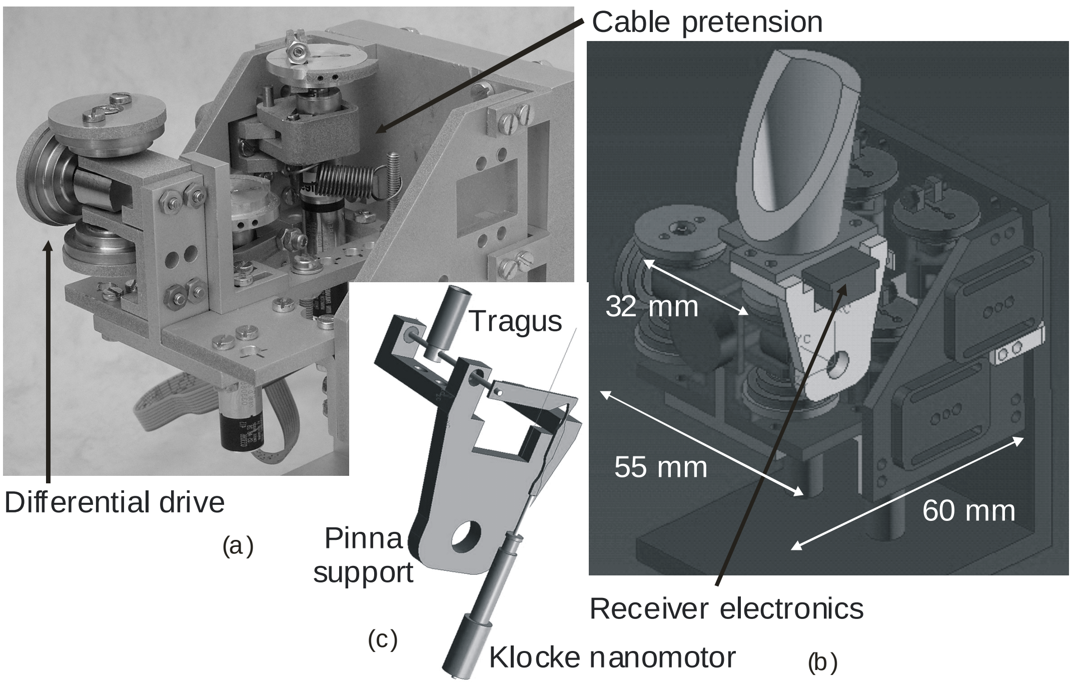


Figure 3: (a) Prototype of biomimetic bat head; (b) biomimetic bat head showing pinna/receiver fixture ; (c) mechanism to rotate tragus.

To guarantee the required accuracy in the absence of end-effector position information, the differential mechanism makes use of cables instead of gears. This approach results in a backlash-free motion of the ear at the price of increased complexity, e.g. pretensioning of the cables. The mechanism that transforms the linear motion of the Klocke piezomotor into a tragus rotation is shown in Fig. 3(c). As required, the complete biomimetic head (Fig. 3(b)) fits inside a 55×60×55 mm cube, i.e. similar to the head sizes of the larger bat species, while providing independent pan and tilt capabilities for both ears plus a tilt capability for the tragus.

5. NEUROMIMETIC SIGNAL PROCESSING

The bat's auditory system is structured in the same way as that of other mammals [6]. The pinna (outer ear) directs the incident sound towards the ear canal. Movement of the tympanic membrane, positioned at the end of the ear canal, is then converted by the middle ear into movement of the membrane at the oval window thus generating pressure waves in the fluid inside the cochlea, i.e. the inner ear. In the cochlea, transduction from sound stimuli into neural activity is performed by the inner hair cells (IHC). The hair cells' response is non-spiking i.e., the magnitude of the pressure wave travelling through the cochlea grades the amount of neurotransmitters released towards the spiral ganglion cells (SGC). Each of the 700-2200, depending on the species [7], inner hair cells synapse with up to 20 spiral ganglion cells of which there are 13000-55000, again depending on the species. The latter are spiking neurons and their axons form part of the auditory nerve that transfers their spiking responses into the bat's brain.

Very little is known about the functional significance of many features of the mammalian hearing system in the context of biosonar and data from bats is, in general, unavailable for choosing the parameters of detailed neuronal models. Hence, we have preferred a simple, efficient cochlear model, which selectively reproduces functionally significant features of the neural code but generates a quantitatively correct representation of the code in the auditory nerve allowing for the study of code properties on a neural population level. The CIRCE neuromimetic cochlea (see Fig. 4) consists of a pipelined parallel architecture of 700 filter banks with a frequency span from 20 kHz to 200 kHz, demodulation in each frequency channel by a combination of half-wave rectification and low-pass filtering and spike generation by thresholding.

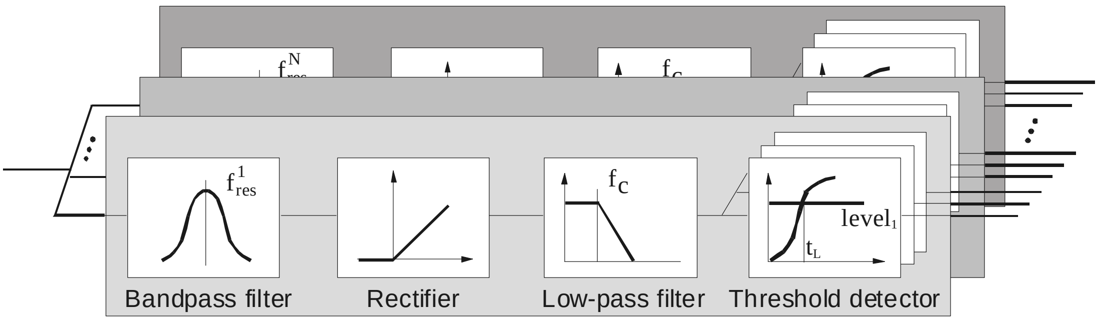


Figure 4: Neuromimetic cochlea: filterbank with a frequency span from 20 kHz to 200 kHz, demodulation by half-wave rectification + low-pass filtering and spike generation by thresholding.

To make possible the modelling of different bat species requires that, in addition to a high processing speed, the system should be flexible and allow for the incorporation of changes to the specifications. A general purpose programmable DSP chip has the flexibility but does not have sufficient speed for this application. Field programmable gate arrays (FPGAs) on the other hand combine the advantages of custom functionality, required speed, and possibility to modify the design after production. The architecture of the neuromimetic cochlea as implemented on Xilinx Virtex II hardware (Fig. 5) allows for user programming of the coefficients of the Butterworth bandpass and lowpass filters, the gain stage and the thresholds of the spike generation stage.

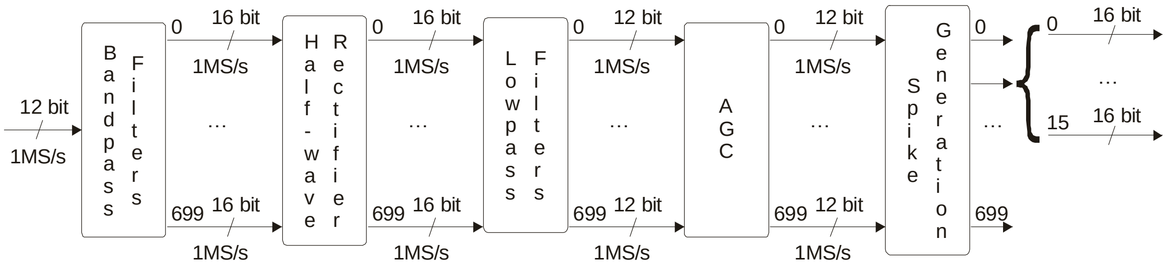


Figure 5 Neuromimetic cochlea: data flow specifications for the FPGA implementation; the numbers given are for a single echo data stream from one ear.

6. CONCLUSION

On top of the technological innovations resulting from the building of the biomimetic bat head, as described here, the head makes possible systematic study of the active sensing strategies evolved by bats for coping with the complex echoes arising while flying/hunting in the foliage. Indeed, by attaining an unprecedented level of realism both in acoustical and in neural signal processing (Table 1) the biomimetic head is an ideal test bed for the implementation of hypotheses concerning the function of biological sonar systems. In addition, it provides the opportunity to tap into the large pool of biosonar experience built by millions of years of natural selection presenting a valuable extra source of information for robotic sensor designers attempting to build the next generation of more advanced robotic echolocation systems [8].

7. ACKNOWLEDGEMENTS

This work is supported by the European Union, IST Program, Life-like Perception Systems Initiative (IST-2001-35144). The work reviewed here is the collective effort of the six-partner consortium of the CIRCE project, more information on the project can be found at the URL: http://www.circe-project.org.

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