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DRAFT: BIOINSPIRATION FROM BIODIVERSITY IN SENSOR DESIGN

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ABSTRACT

Biodiversity is a notable outcome of biological evolution. In the process of adaptive radiation, functional principles of sensing in biology have been adapted to suit different tasks and constraints. The biosonar system of bats is an example of such an adaptive radiation in sensing that also offers particularly advantageous conditions for a biodiversity-level analysis of adaptation principles with potential engineering relevance. The beamforming capabilities of bat biosonar are tied to the geometries of external baffle structures, i.e., the outer ears used for reception and the noseleaves used to shape the emitted biosonar pulses. Since the geometries of these baffles determine their functions, which in turn can also be expressed by a shape (the beampattern), biosonar beamforming can be described by two interrelated shape spaces, one for biological form and the other for biological function. A shape space representation for the outer ears can be obtained by a cylindrical transform of the ear surfaces followed by principal component analysis. The results of this analysis are in a form that is suitable to inform the design of technical baffle shapes. However, additional analysis methods need to be developed for noseleaves, beampatterns, as well as the link between form and function.

INTRODUCTION

The success of numerous bioinspired engineering solutions, not few of them in the area of mechanical engineering, has already proven the value of biological systems as a source of inspiration for engineers [1–4].

Seen from the engineering perspective, the biological systems that have provided these inspirations often give the impression of an unorganized collection of unrelated case studies. For example, one organism happens to have a high-performance sensor while another may be capable of producing a material with unique properties. Hence, the successes in bioinspired technology often appear to have been gifts of serendipity that came about due to a random match between a biological capability and the needs of a technical application area.

Seen from a biological perspective, living organisms are closely linked by their ecological and evolutionary contexts. The resulting ecological and evolutionary [5] relationships between organisms are seen as an essential framework of all biological research. They are key to obtaining meaningful insights from biological systems and their function, no matter whether these insights are related to engineering or not.

One of the most conspicuous outcomes of evolution is an overwhelming diversity of lifeforms [6]. Biological systems

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which share common structural or functional principles may come in a large number of variations that almost always exceeds what is seen in man-made devices by a large margin. Among the evolution processes that give rise to this biodiversity, *adaptive radiation* is of particular interest to engineering. In adaptive radiation, the phylogenetic descendants of a common ancestral species undergo evolutionary adaptation processes that allow them to fit into different ecological niches [7].

The outcomes of these adaptive radiation processes can be highly relevant to engineering because they contain information on how a single set of functional principles can be adapted to multiple sets of specifications and constraints. Replicating this capability could also greatly benefit engineering, because it could inform the customization of technology to match different specifications without a need for individual development in each case. The knowledge that is required to achieve this goal is embedded in the evolutionary outcomes at the biodiversity level. Hence, it cannot be accessed from isolated studies of individual species. Mining such knowledge from biodiversity requires the development of methodology to characterize the variability in biological form and function across species in a quantitative, engineering-oriented fashion.

In the following, approaches to accomplish this goal for the model system of beamforming in bat biosonar will be discussed.

Biodiversity in Bat Biosonar

Bats are an exceptionally diverse group of mammals. Worldwide, there are about 1,000 different bat species [8], which account for about 20% of all mammalian species. This makes bats the second species-rich group of mammals (after rodents) [9]. Besides species richness, another important indication of the evolutionary success of bats is a global distribution which only leaves out the polar icecaps and some isolated oceanic islands [10]. Finally, bats can also be extremely abundant - the largest known aggregations of vertebrates in the world are bat colonies that can contain tens of millions of individuals [11].

Bats are set apart from other mammals by a combination of powered flight and the use of biosonar sensing. It might hence be hypothesized that the integration of these sensory and locomotion capabilities has been a key factor behind the outstanding evolutionary success of the group. Bats have settled successfully in a wide variety of habitats that range from deserts to rain forests [12]. In these habitats, different bat species exploit a diverse set of food sources that include crawling arthropods and insects, insects on the wing, fish, amphibians, and terrestrial vertebrates, birds and other bats on the wing, fruit, pollen and nectar, as well as blood [12].

Biosonar plays an important role in providing the sensory information that is needed to support the exploitation of these food sources as well as general navigation tasks in different habitats. To this end, bats employ *active* as well as *passive sonar* (s. Fig-

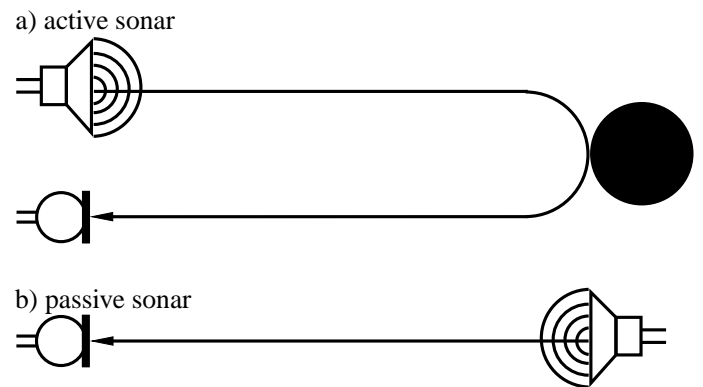


FIGURE 1. SCHEMATIC DEPICTIONS OF THE FUNCTIONAL PRINCIPLES OF A) ACTIVE AND B) PASSIVE SONAR.

ure 1). When operating in active mode (s. Figure 1a), the animals analyze echo returns triggered by their own sonar emissions. In passive mode (s. Figure 1b), the signals analyzed originate from external sources. An example for the latter would be the detection of a prey by virtue of sounds generated by the prey itself, as is the case in the frog-eating bat, *Trachops cirrhosus* [13]. In many cases, active and passive sonar appear to be sufficient far senses that can meet the informational needs of the animals' highly mobile and often predatory lifestyles [14]. While the basic principles of active and passive sonar are readily understood, technical reproduction of the same degree of autonomy that bats are able to achieve in natural, structure-rich environments have yet to be demonstrated.

A conspicuous feature of the bat biosonar system are the often intricate shapes of the baffles that frequently surround the sites of ultrasound emission and reception in the animals.

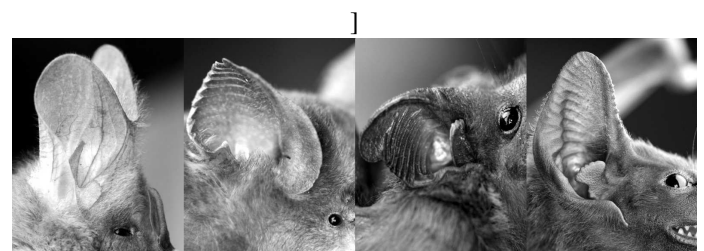


FIGURE 2. EXAMPLES OF BAT OUTER EAR SHAPES IN FOUR DIFFERENT BAT SPECIES FROM SOUTHERN INDIA (FROM LEFT TO RIGHT: MEGADERMA LYRA, HIPPOSIDEROS SPEORIS, RHINOPOMA HARDWICKEI, AND TAPHOZOUS NUDI-VENTRIS KACHENSIS).

The outer ears (pinnae) of many bat species are fairly large compared to the overall size of the animal and have many char-

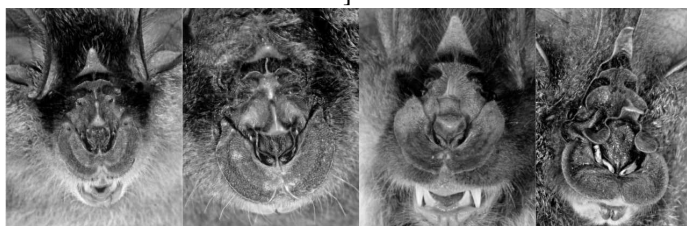


FIGURE 3. EXAMPLES OF BAT NOSELEAF SHAPES IN FOUR DIFFERENT HORSESHOE BAT SPECIES (FROM LEFT TO RIGHT: RHINOLOPHUS PUSILLUS, R. PEARSONII, R. AFFINIS, R. LUCIFUGUS).

acteristic shape features (s. Figure 2) such as flaps directly on – or in the vicinity of – the pinna rim or ridges and grooves on the pinna wall surface. In some species, ridges on the pinna wall can form regular washboard patterns that cover significant portions of the inner pinna surface. Bat species that emit their biosonar pulses through the nostrils (e.g., horseshoe bats, round leaf bats, New-World leaf-nosed bats, and false vampire bats), often carry elaborate “noseleaves” that diffract the emitted ultrasonic wavefields and hence can influence the emission beam pattern [15–18]. Some bat species that emit their biosonar pulses orally have visible specializations in the shape of their lips and surrounding facial appendages that could have similar functions (s. Figure 4).

It may thus be hypothesized that some of the natural, interspecific variability that can be seen in these shapes (s. Figure 5) is indicative of adaptations to specific sensing tasks or constraints that result from the animals’ varied use of biosonar sonar.

The effects of these baffle shapes in the far-field, where most bat biosonars operate, can be described by a *directivity pattern* or *beam pattern* (s. Figure 6). The term “beam pattern” is used for both emission and reception. For emission, it describes the distribution of emitted power or energy as a function $D(\theta, \phi, f)$ of direction (specified by two angles, θ and ϕ and frequency f). For reception, the power is replaced by receiver sensitivity (gain), but apart from this, the pattern remains unchanged. For emitters and receivers operating under far-field conditions, the beam pattern provides a complete characterization of the space-frequency characteristics of the device [19], since all waves propagating under far-field conditions behave as spherical waves. The distribution of emitted power and receiver sensitivity is critical for the operation of a wave-based sensing system. The beam pattern superimposes a spatial sensitivity filter on the environment and hence determines which region of space contribute how much to the echo. Furthermore, the shape of the beam pattern as a function of direction and frequency determines the encoding of features pertinent to the spatial distribution of sound sources and sonar targets into the received signal [20–22].

Like for the pinna and noseleaf shapes themselves, the



FIGURE 4. EXAMPLE OF SPECIALIZED LIPS AND OTHER FACIAL APPENDAGES IN A MOUTH-EMITTING BAT SPECIES (ANTILLEAN GHOST-FACED BAT, MORMOOPS BLAINVILLEI, PHOTO: M. BROCK FENTON - REPRODUCED WITH THE AUTHOR’S PERMISSION).

beam patterns that are produced by these structures also vary widely between species (as well as within a species and between the left and right ear [23]). In many cases (s. Figure 6), the distribution of hearing sensitivity over direction depends strongly on frequency. Beam patterns may or may not contain prominent sidelobes or be split into multiple lobes of approximately even strength. The direction a lobe is pointing in could either remain approximately constant over frequency or the lobe could carry out a frequency driven scan over direction. Lobes can also change their shape along with their orientation with frequency, in some cases resulting in an intricate beam pattern dynamics as a function of frequency [24].

Engineering Analysis of Biodiversity Shape Space Approach

Transferring biodiversity-level insights from the natural variability in the biosonar systems of bats to engineering research requires a quantitative analysis of form, function, and the connection between the two. Specifically, for the beamforming operation carried out by the noseleaves and outer ears, this calls for an analysis of the variability in these shapes, their beam patterns, along with the links between the physical shapes and beam patterns.

The acoustic properties of the noseleaves and pinnae are

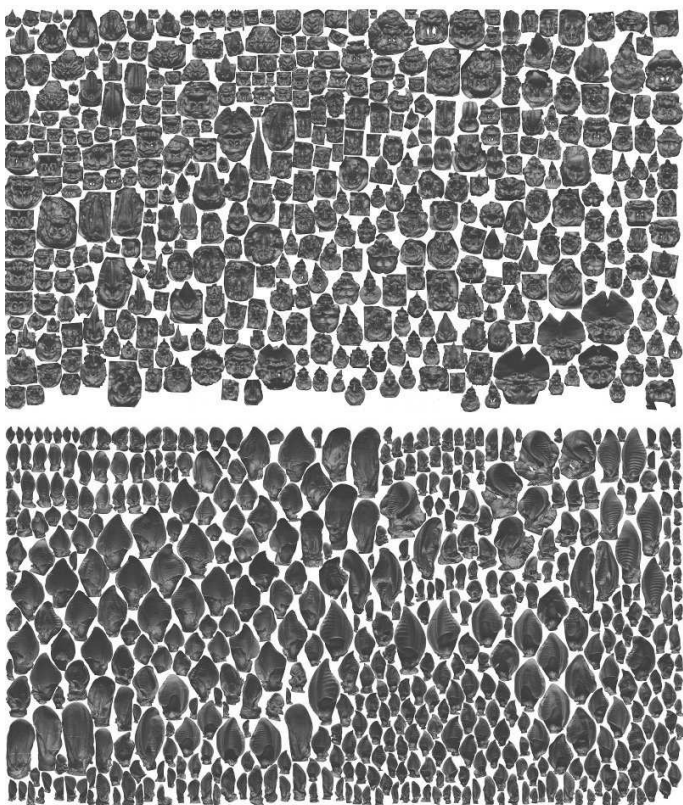


FIGURE 5. BIODIVERSITY IN THE PHYSICAL BAFFLE SHAPES OF THE BAT BIOSONAR SYSTEM. TOP: NOSELEAF SHAPES; BOTTOM: OUTER EAR (PINNA) SHAPES. EACH IMAGE SHOWN IS A RENDERING OF A DIGITAL 3D SHAPE MODEL OBTAINED USING COMPUTER MICRO TOMOGRAPHY.

linked to the physical shapes of these structures through an acoustic diffraction or scattering process. Due to the large differences in the characteristic acoustic impedances of air and any biological tissue [25], the acoustic effects of noseleaves and pinnae are to a very good approximation determined by the geometries of the diffracting surface alone. In principle, this relationship can be stated in an analytic form by an integral equation such as the surface Helmholtz integral formulation for exterior scattering problems [26],

$$p(x) = \iint_S \left[p(\zeta) \frac{\partial G(x, \zeta)}{\partial n_\zeta} - \frac{\partial p(\zeta)}{\partial n_\zeta} G(x, \zeta) \right] dS(\zeta) \quad (1)$$

where ζ denotes the points on the scattering surface S and n_ζ its local surface normal, $p(x)$ and $p(\zeta)$ are the pressures at an exterior point x and a surface point ζ respectively, and $G(x, \zeta)$ is the free-space Green's function (s. Figure 7). Eq. 1 shows that

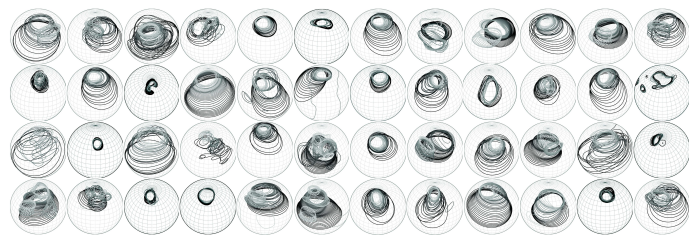


FIGURE 6. BIODIVERSITY IN THE FUNCTION OF BIOSONAR: NUMERICAL BEAMPATTERN ESTIMATES (-3DB CONTOUR MAPS) FOR PINNA SHAPE SAMPLES FROM 48 DIFFERENT BAT SPECIES. DIFFERENT GRAY LEVELS ENCODE FREQUENCY (LIGHT GRAY: HIGH FREQUENCIES, DARK GRAY: LOW FREQUENCIES)

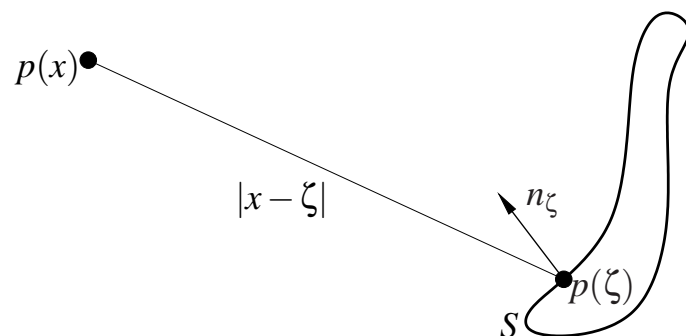


FIGURE 7. GEOMETRIC DEFINITIONS FOR THE GENERAL RELATIONSHIP BETWEEN PHYSICAL BAFFLE SHAPE AND ACOUSTIC FUNCTION (S. EQ. 1).

each point on the surface of a bat biosonar baffle could – at least in principle – contribute to the acoustic function of the baffle.

While equations such as the one given in Eq. 1 can be evaluated with suitable numerical approaches [27], the general relationship that they describe is not readily comprehensible to a human observer for all but the most simple geometries of S . It can be expected that through evolutionary adaptation, the diffracting baffle shapes of bats have come to exploit a limited set of physical effects that can enhance biosonar performance. Hence, there is hope that the relationship between form and function may be more readily understood in an intuitive fashion for these specific effects than is the case for the general relationship described in Eq. 1.

If such specific and more simple relationships exist, it should be possible to reduce the complexity of the different shapes (s. Figure 5) and the beampatterns (s. Figure 6) to reflect these relationships in a straightforward, ready accessible manner. A promising approach to find such a reduced representation could be to represent each *physical shape* and each *functional shape*

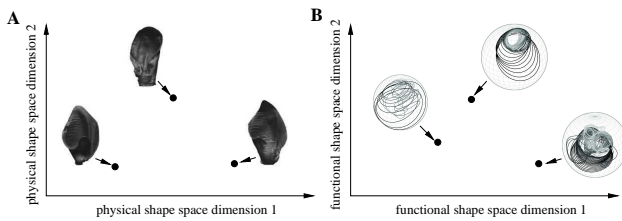


FIGURE 8. SKETCH ILLUSTRATING THE VIEW OF BIOLOGICAL FORM (A, PINNA SHAPES) AND FUNCTION (B, BEAMPATTERNS) IN BIOSONAR IN A HYPOTHETICAL SHAPE SPACE.

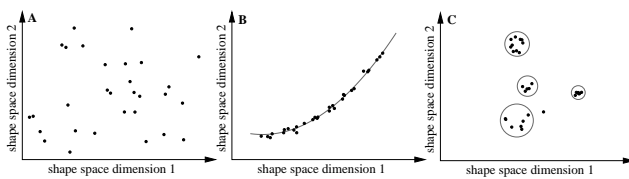


FIGURE 9. SKETCH ILLUSTRATING POSSIBLE INSIGHTS FROM SHAPE SPACE ANALYSIS: (A) UNIFORM DISTRIBUTION OF SHAPES, (B) FUNCTIONAL RELATIONSHIP BETWEEN SHAPE SPACE DIMENSIONS, (C) CLUSTER FORMATION IN SHAPE SPACE.

(i.e., beam pattern) as a point in a derived *shape space* (s. Figure 8) that has considerably less dimensions than would be required to describe the original objects.

Such lower-dimensional shape spaces could reveal properties of the variability in shape more clearly and in a more readily quantifiable fashion than would be possible from the raw shape data. Insights to be gained from shape space analysis could include functional relationships between shape space dimensions (s. Figure 9B) or the existence of clusters (s. Figure 9C). Functional relationships between shape space variables could provide access to physical principles that are either exploited by biosonar function or impose significant limits on it. The occurrence of clusters could indicate the utilization of distinct physical effects or ways to realize them by different groups of bats.

Interspecific Registration

In order to analyze the variability in the diversity of biological shapes, it is necessary to align physical and functional shapes so that corresponding parts can be compared. Shape registration can already pose significant problems between individuals of the same species, e.g., when aligning brains from different patients [28]. But aligning the diverse noseleaf and pinna shapes found across different bat species has to deal with even greater differences that are often qualitative in nature (s. Figure 10). For example, the outer ears of some bat species have a prominent

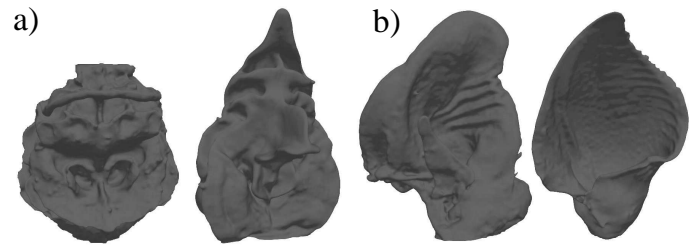


FIGURE 10. EXAMPLES OF ALIGNMENT/FEATURE MATCHING PROBLEMS POSED BY A) NOSELEAF AND B) PINNA SHAPES FROM DIFFERENT BAT SPECIES.

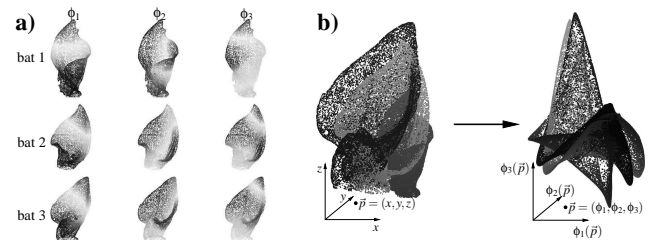


FIGURE 11. EXAMPLE OF BAT PINNA ALIGNMENT OF USING SPECTRAL EMBEDDING.

tragus (s. Figure 10b), whereas in other species the antitragus is more prominent. In yet other bat species, neither the tragus nor the antitragus are prominent features of the outer ear and hence a match for either of these features is difficult to establish.

Across different taxonomic bat groups, the noseleaves show a particularly large degree of variability that often manifests itself in the occurrence of shape features that are not readily matched across groups. For example, round leaf bats (*Hipposideridae*) and horseshoe bats (*Rhinolophidae*) are sister groups [29], but their noseleaf shapes differ considerably in several conspicuous shape features some of which appear to be exclusive to a single group (s. Figure 10a).

From an engineering perspective, it is more desirable to establish interspecific matches that capture similar acoustic functions than common evolutionary origins. Since acoustic function is entirely determined by geometry, it should be possible – at least in principle – to establish such matches from the analysis of shape alone. Information on evolutionary relationships, while insightful in general and useful for identifying candidates for key functional features in particular, is not a necessity for this purpose.

In order to perform the interspecific shape alignment, it is necessary to identify shape characteristics that change little between species. Features which are not dominated by high spatial frequencies are likely to offer a more stable alignment that is robust to small changes in the position and shape of local features.

Spectral embedding [30, 31] is an example of a method that is currently under investigation for this purpose. The underlying spectral analysis is related to modal analysis and uses a generalized description of the vibrational eigenmodes of the structure (eigenfunctions of the Laplace-Beltrami operator). Since the eigenmodes that are obtained in this fashion are naturally ordered by their spatial frequencies, the lowest eigenmodes do not contain high-frequency geometrical detail and are hence candidates for robust alignments of shape. For a small test data set of bat pinnae, it was found that the first three eigenmodes (ϕ_1, ϕ_2, ϕ_3) were very similar, although the pinnae differed quite considerably in a number of shape details (s. Figure 11a). Spectral embedding (s. Figure 11b) is accomplished through a transform in which the Cartesian coordinates for each point of the original shape are replaced by the amplitudes of the first three modes. In these new coordinates of eigenmode amplitudes (s. Figure 11b), the shapes are a lot more similar than in their original coordinates. This increased similarity can be exploited to establish correspondences between points that can then be used for analysis of the original shapes.

Principal Component Analysis

Principal component analysis (PCA, [32]) is a method commonly used to describe the variability in a sample. It is designed to find the linear dimensions along which the sample exhibits the most variability. It does so by virtue of rotating the sample coordinate system so that the first axis is aligned with the direction of maximum variability. The other – orthogonal – axes are oriented so that each captures as much as possible of the remaining variability.

For research on non-human species (including bats), it has been common practice to define a set of discrete parameters to be measured on the specimens as input to the PCA [33, 34]. The major drawback of this approach is that it requires a-priori decisions on what the relevant shape features should be. This strategy could hence miss unanticipated functional features of the original shapes.

In the study of human morphology, PCA has been employed extensively in the area of biometrics to harness its data compression and sample identification capabilities. In these applications, images of faces [35, 36], palms [37], fingers [38], and ears [39] have been used as input data. The input data for PCA of human faces, for example, are typically digital gray-scale portrait images that can be represented as vectors of gray-level pixel values. This is a viable approach, because human faces, ears, as well as finger and palm prints are approximately planar structures that permit capturing a sufficient number of identifying features from a single canonical viewing direction. This is not the case for bat pinnae, which are cone-shaped structures that can carry shape elements of potential acoustic relevance, such as flaps or ridges, in a variety of positions. It is hence highly un-

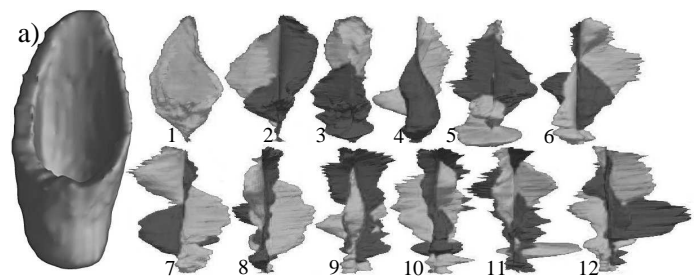


FIGURE 12. PRINCIPAL COMPONENTS OF BAT PINNA SHAPES: A) AVERAGE EAR, 1-12) FIRST TWELVE EIGENEAR. DIFFERENT SHADES OF GRAY REPRESENT PARTS OF THE EIGENEAR SURFACES WITH DIFFERENT SIGNS.

likely that a two-dimensional image projection could be found to capture all potentially relevant pinna shapes. Analysis of the natural variability in pinna shapes therefore needs to preserve the three-dimensional, concave nature of these structures.

This has been accomplished by virtue of a customized solution in which points on the inner and outer pinna surfaces were transformed into cylindrical coordinates [40]. In this case, the PCA was performed on vectors containing pinna radius values obtained for a set of discrete direction and height values. As for the eigenfaces used in human biometrics, the result of the PCA (eigenvectors of the covariance matrix) were transformed back into the coordinate space of the original ear data to yield “eigenears” (s. Figure 12, 1-12). At the origin of the shape space spanned by the eigenears, is the average pinna shape (s. Figure 12a). It was found to resemble a symmetrical obliquely truncated cone [40], a shape that has been previously proposed as an idealized model of the mammalian pinna [41, 42]. Unlike the original bat pinnae, the eigenear surfaces have regions that differ in the sign of their radii. Negative radii correspond to a narrowing of the resulting pinna when different points in the shape space are reached by adding one or multiple eigenears to the average ear at the origin.

From the average ear and the eigenears (s. Figure 12), a “recipe” can be formulated for the generation of biomimetic baffle shapes inspired by the pinna of bats from additive components. Following this recipe, the design of a baffle shape would start with an obliquely truncated cone inspired by the average bat pinna. Next, the first eigenear (Figure 12)-1) would be added. The first eigenear is very similar in shape to the average ear in that it is also cone-shaped with no change in the sign of the radius between any (significant) regions of the surface. Hence, adding the first eigenear to the average ear amounts to an addition of two cones, where the radius of the one of the cones (the first eigenear) is controlled by a scalar weighting factor. This weighting factor can hence be used to control the opening angle of the result. In the vicinity of the shape space origin, this opening angle can be

used to control the width of the beam pattern [40]. All eigenears beyond the first have significant surface portions with opposing signs. Since the eigenears are ordered with respect to the spatial frequencies of their features, including the sign changes, higher eigenears can have differential effects on different regions of the baffle. For example, adding the second eigenear breaks the left-right symmetry of the pinna as the left and right sides of this eigenear have opposite sign. The same effect has also been seen in the corresponding beam patterns [40]. The third eigenear affects the top and bottom portion of the pinna differentially, adding the eigenear with one sign will result in a shape that is widened at the top and narrowed at the bottom, whereas using the opposite sign would result in a shape with a narrow top and a wide bottom. With their increasing spatial frequencies, the following eigenears are more and more responsible for molding out local shape features such as grooves and ridges.

The cylindrical transform used to obtain these eigenear results (s. Figure 12) included an implicit shape registration in the vertical direction through the choice of the cylinder axis (accomplished through the minimization of a potential function defined by forces exerted by elements of the pinna wall [40]) as well as an explicit alignment along the angular dimension of the cylindrical coordinates. The cylindrical coordinate transform and the attached shape registration methods do not generalize readily to biological shapes of a different nature, such as the noseleaves used in the biosonar system of bats. Methods such as the spectral embedding described above or approaches based on local features (s. below) will be evaluated for this purpose in future work.

PCA is not the only method available to describe the natural variability in biological shapes and other approaches also have the potential to reveal evolutionary trends in form and function that could inspire engineering design rules. Non-negative matrix factorization [43] is a candidate approach with properties that make it interesting for the analysis of biological structures with an acoustic (sound scattering) function. Whereas PCA results in additive eigenshape components which each contribute to every part of the original shapes, non-negative matrix factorization decomposes the shapes into local features. This could be of interest to the design of bioinspired diffracting baffles, where local features can play a significant role in bringing about salient functional properties (s. below).

Local Shape Features

The active biosonar systems of bats employ frequencies that range from approximately 15 to 200kHz [44]. In air, this corresponds to wavelengths from below 2 millimeters to above 2 centimeters. In particular for the wavelengths in the lower half of this range, comparatively small local features (e.g., on the scale of a few millimeters) of the noseleaves and outer ears could still have profound effects on acoustic function.

Evidence from numerical and behavioral experiments indi-

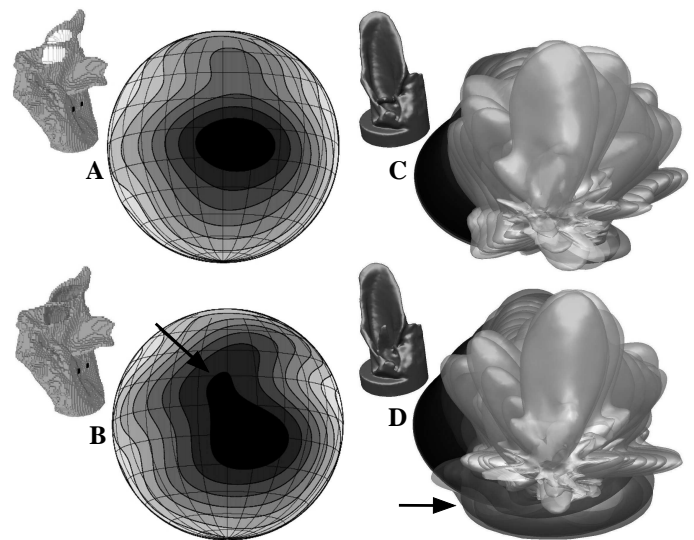


FIGURE 13. EXAMPLES OF LOCAL SHAPE FEATURES HAVING AN EFFECT ON ACOUSTIC PROPERTIES: A-B) FURROWS IN THE NOSELEAF OF THE RUFOUS HORSESHOE BAT (*RHINOLOPHUS ROUXII*) WIDEN THE BEAM SELECTIVELY AT LOWER FREQUENCIES [15], SHOWN ARE THE SHAPE RENDERINGS AND THE CORRESPONDING BEAMPATTERNS FOR A FREQUENCY OF 60 KHZ WITH A) FURROWS FILLED DIGITALLY AND B) FURROWS OPEN, C-D) THE TRAGUS IN THE BIG BROWN BAT (*EPTESICUS FUSCUS*) CAUSES A SET OF FREQUENCY-SWEPT SIDELOBES, SHOWN ARE THE PINNA SHAPES AND THE 3D SENSITIVITY CONTOURS FOR C) A DIGITALLY REMOVED TRAGUS AND D) AN UPRIGHT UNALTERED TRAGUS [45].

cates that this is indeed the case: The performance of big brown bats (*Eptesicus fuscus*) in estimating the elevation of a sound was found to be degraded when the animals' tragus was tied away from its natural position [46,47]. A similar effect was observed in the biosonar capability of free-flying bats, but the animals were able adjust and recover their performance [48]. Matching these behavioral observations, the tragus was found to be responsible for acoustic functional features, i.e., an elevation-dependent spectral notch [49] and a – probably corresponding – set of frequency-swept sidelobes [45] (s. Figure 13 c and d). A small ridge in the pinna of the brown long-eared bat (*Plecotus auritus*) was found to have a similar effect on the beam pattern as the tragus in the big brown bat [20]. In the latter case, it could also be demonstrated that the set of sidelobes caused by the ridge significantly improved the encoding of information on target direction into the received signals.

Local shape features are not readily captured by methods that perform a global shape analysis. In PCA, for example, local flaps and ridges, are represented in the high spatial frequencies of

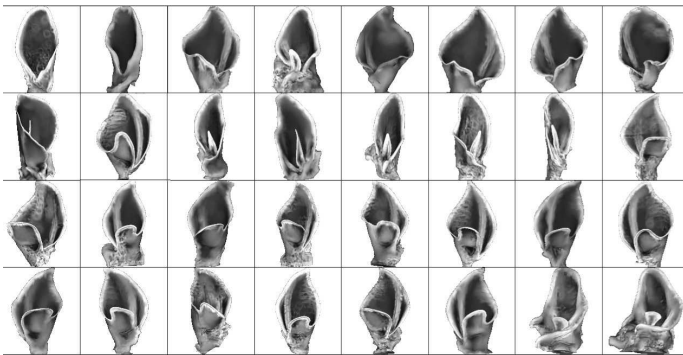


FIGURE 14. LOCAL SHAPE FEATURES OF DIFFERENT BAT OUTER EARS: MEAN CURVATURE VALUES AVERAGED OVER A LOCAL NEIGHBORHOOD CODED BY GRAY SCALE VALUES.

the numerous higher eigenvalues, that are difficult to estimate accurately, even from comparatively large data sets, and also hard to interpret. To address this issue, methods are needed that are designed to identify and characterize local shape features specifically. This can, for example, be accomplished through local metrics such as average curvature (s. Figure 14), measures of the distribution of surface normals, the shape diameter function (SDF, [50]), or distance of surface points to a plane [51]. By computing an entire set of these metrics for points or local neighborhoods on the surface of a biosonar baffle, regions of similar local shape properties can be identified. These similarities in shape can then be used as hypotheses for existing similarities in acoustic function as well as for tasks such as shape registration and segmentation based on – hypothetical – function.

Conclusions

Analysis of biological function across many different species promises to yield engineering design rules that could guide the customization of technology. In terms of sensing technology, the biosonar systems of different bat species are a prime example of how a simple set of common sensing principles can be adjusted to deliver an unmatched performance in many different sensing tasks and under many different constraints.

Exploiting such outcomes of adaptive radiations from biological evolution for engineering research still requires significant developments with respect to the available data sources as well as the approaches and tools that are required to analyze them.

Data sources need to be established that can produce large amounts of quantitative data on biological form and function across different species. Again, the beamforming portions of the biosonar systems of bats could be an advantageous model system for research address this issue, because their acoustic function can be inferred from their external geometries alone. Individ-

ual case studies have already demonstrated that shape features such as noseleaf furrows or pinna rim folds and flaps can have potentially useful acoustic effects. However, shape space representations for form and function that reduce the dimensionality of the data and provide insight into evolutionary trends useful to engineering still need to be developed.

Principal component analysis (PCA) has been adapted successfully to non-parametric representations of the shapes of the outer ears of bats. The results can be cast as design rules that could be used in the design of beamforming baffles for engineering applications. However, this was achieved using an individually approach based on cylindrical coordinate transform, that may not generalize well to other biological structures of engineering interests, such as the noseleaves of bats. More general methods that can solve registration problems in these shapes still need to be developed. Furthermore, the results of the principal component analysis are most readily interpreted in terms of global shape properties such as the overall opening angle of the pinnae, than in terms of local features that could play a crucial role with respect to acoustic function.

Methods equivalent to the ones used for the physical shapes also still need to be developed to establish functional shape spaces for the acoustic beampatterns. Once low-dimensional shape spaces have been established for both the physical shapes (i.e., the beamforming baffles) and their functional shapes (i.e., the acoustic beampatterns), links between the two shape spaces have to be established. Under fortunate circumstances, the low dimensionality of the two shape spaces may already reveal some relationships between form and function. Under less fortunate circumstances, additional methods will have to be developed to accomplish this. Such method could either operate on given shape space representations or could simultaneously transform the shape spaces in order to facilitate the discovery of relationships, as is the case in methods related to canonical correlation analysis (CCA).

Once suitable, general methods have been developed for all these steps, biodiversity could become a natural resource for engineering knowledge that could be mined and moved into the engineering design process in an automated fashion.

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