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Biosonar-inspired technology: goals, challenges and insights

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Abstract

Bioinspired engineering based on biosonar systems in nature is reviewed and discussed in terms of the merits of different approaches and their results: biosonar systems are attractive technological paragons because of their capabilities, built-in task-specific knowledge, intelligent system integration and diversity. Insights from the diverse set of sensing tasks solved by bats are relevant to a wide range of application areas such as sonar, biomedical ultrasound, non-destructive testing, sensors for autonomous systems and wireless communication. Challenges in the design of bioinspired sonar systems are posed by transducer performance, actuation for sensor mobility, design, actuation and integration of beamforming baffle shapes, echo encoding for signal processing, estimation algorithms and their implementations, as well as system integration and feedback control. The discussed examples of experimental systems have capabilities that include localization and tracking using binaural and multiple-band hearing as well as self-generated dynamic cues, classification of small deterministic and large random targets, beamforming with bioinspired baffle shapes, neuromorphic spike processing, artifact rejection in sonar maps and passing range estimation. In future research, bioinspired engineering could capitalize on some of its strengths to serve as a model system for basic automation methodologies for the bioinspired engineering process.

1. Introduction

Biosonar-inspired technology, i.e., the design of technical devices based on sonar systems found in nature, is neither a new field nor is its potential impact limited to niche applications. To the contrary, biosonar-inspired technology has a documented history of more than 90 years [1] and even predates the experimental discovery of fundamental biosonar function [2]. Since then, bioinspired sonar has yielded experimental systems with promising capabilities of wide applicability. However, at present, there are still some impediments that have played a significant role in preventing the field from realizing its full potential. A major factor is fragmented communities in biology as well as in engineering. Biological information about biosonar systems is distributed among different biological model systems (e.g., bats versus dolphins) and different subdisciplines (e.g., ecology, neuroscience). In engineering, different application areas such as sonar, biomedical ultrasound, robotics all have the potential to contribute to the development of biosonar-inspired technology, but typically have little interchange. Fragmentation is aggravated by the different backgrounds (e.g., acoustics, electrical engineering, computer science, robotics, biology) and goals of the researchers in the field. It should be noted, however, that the difficulty of transferring insights between biology and engineering is not solely an issue of scientific culture. There are objective difficulties in accommodating the differences in energy, locomotion, and information processing between biological and human-made systems. Biological systems tend to be nonlinear, special-purpose designs, i.e., they have evolved according to the constraints of a particular set of tasks. Nonlinear systems are more difficult to analyze and investigations using special-purpose designs require additional work to arrive at useful general principles. Maybe due to these difficulties, bio-inspired technology is still suffering from the lack of a highly

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visible 'killer application', which could prove the value of the approach to a wider scientific, engineering, and general audience.

Given this situation, the purpose of the present paper is to make a contribution to establishing biosonar-inspired engineering as a coherent field of research and raise its visibility. We take the following approach to meet these goals:

- Parallels between sensing problems in biosonar systems and technical applications are drawn to help researchers from various areas to see how they could contribute to and benefit from biosonar-inspired insights.
- Current design challenges are pointed out to provide researchers new to the field with information about possible opportunities and difficulties for making a contribution.
- Achievements of selected state-of-the-art experimental systems are summarized to demonstrate the power of the approach.
- Directions for future research are suggested that have the potential to advance biosonar-inspired technology and bioinspired engineering in general.

The present paper aims to provide the reader not only with information about past research results but also our perspective on how these results may be best turned into future research successes. The style of the paper is therefore that of an 'opinionated review' and it should be read more like a guidebook than like an encyclopedia. In particular, for reasons explained in the next section, the focus is on bats and the technical systems inspired by them. In the choice of the discussed examples, an emphasis is being placed on studies aimed at insights obtained from the specific function of biosonar at a system level. The use of general bioinspired techniques—such as standard artificial neural network classifiers—does not accomplish this by itself and hence no attempt is made to cover such work.

2. Biological context

The biological context in which biosonar systems evolved and in which they are presently used contains information about the kinds of sensing problems for which solutions may be found among biological systems and about the nature of these solutions. Sophisticated biosonar systems are found in two disparate groups of animals: bats use in-air biosonar whereas whales and dolphins use underwater biosonar. The biosonar systems of both groups have been recognized as sources for technological inspiration for several decades ago already. Dolphins in particular have been studied extensively with the goal of improving underwater sonar technology [3]. This is due to the importance of sonar as a sensing modality in water, where the propagation range of electromagnetic waves is severely limited and sonar cannot only see further, but can also penetrate many solid objects (as long as their acoustic impedances are similar enough to that of water). Although none of these factors applies in air, working with in-air sonar systems—biological as well as technical—has some significant advantages in terms of the effort required in setting up and maintaining the experimental systems proper as well as the basic experimental facilities. In underwater research, all used components must either be waterproof themselves or they must be sealed. This necessitates additional efforts to be made when building the initial setup as well as during each cycle of testing and modification, where the seals have to be broken and re-established constantly. In addition, laboratory work on underwater sonar or with marine mammals will often require large tanks and hence a considerable investment into the basic facilities. Probably for these reasons, most bioinspired sonar systems have been developed to operate in air and were more often inspired by bats than by dolphins.

Bats hold a much more prominent place among mammals than is reflected in public awareness. Bats, by themselves, are grouped as one of the top-level groupings (an 'order') within the mammals [4]. Compared to other mammals, bats rank highly on several measures of ecological and evolutionary success. First, they are distributed across almost the entire landmass of the earth, only leaving out the polar ice caps and some small remote islands [5]. Second, slightly more than 20% of all mammal species are bats, making bats the second most species-rich group of mammals with approximately 1000 species (second only to rodents with approximately 2000 to 3000 species). Finally, bats can also be very abundant, with some species being extremely common over large areas and forming large aggregations (colony sizes can reach up to 50 million individuals at times [6]).

Bats are further subdivided into the megabats with around 160 species found in tropical and subtropical regions of the old world and the much more species-rich and widespread microbats [4]. All microbats and some megabats use biosonar to some extent. The principal known uses of biosonar are related to the acquisition of food and navigation tasks such as obstacle avoidance and—possibly—the recognition of landmarks [7–9]. The diversity in terms of the number of bat species and their wide geographic distribution is probably related to the likewise considerable diversity in terms of the kinds of food bats can feed on and the habitats in which they live. To facilitate these diverse lifestyles, the biosonar systems of different bat species have been adapted to achieving a variety of sensing objectives under a variety of constraints. The diets of different bat species include aerial insects, arthropods gleaned from substrates, nectar and pollen from flowers, fruit, blood, fish, small terrestrial vertebrates, birds and even other bats. The large majority of bat species, however, eat insects. To find their food, bats hunt in various kinds of open vegetation and forests, over rocks and cliffs, water surfaces, as well as in the open air.

Although the use of *active sonar*, i.e., the analysis of echoes to self-emitted pulses, is universal to microbats, the animals resort to a broader set of senses. Unfortunately, the sensory basis for many tasks which bats perform has yet to be established. This limits the use of bats as an existence proof for sonar-based solutions to sensing problems. Finding a certain prey in the diet of a bat species, for example, cannot be taken as an existence proof for a way to catch this prey using sonar as the principal information source. Even if the latter has been established, the possible contribution of *a priori* knowledge has to be taken into account. Bats catching insect prey in the open air, for example, can safely assume that any small scatterer they encounter is a potential prey. Bats searching for insect prey flying close to vegetation cannot make this assumption, since the vegetation itself contributes to the echo signals with a multitude of reflecting facets. A prey-specific signal feature is needed to allow for classification of prey and non-prey in the absence of prior knowledge. The so-called cf-fm bats have availed themselves to such a feature by employing sonar pulses that contain a narrowband ('constant frequency' or cf) signal component along with frequency-modulated components. The narrowband component facilitates the detection of Doppler shifts caused by the rapid wingbeats of their prey [10]. Specific signal features that are good predictors of food are also known to be created by some flowering plants which rely on bats for pollination [11]. Bats catching small fish may use their sonar system to obtain information on reflections from perturbations of the water surface caused by fish swimming close to it [12], once again creating otherwise uncommon signal features with a high predictive value.

Besides active sonar, the use of *passive sonar*, i.e., the analysis of direct or reflected sounds generated by a foreign source [13], also seems to be quite common among bats. Many species are known to listen to sounds generated by their prey for the detecting the presence of prey and finding its location. An example is the Fringe-lipped bat (*Trachops cirrhosus*), which hunts male frogs following their mating calls [6]. The use of passive sonar is particularly advantageous in situations where the prey is hiding among other objects such as in the foliage of a tree. In such a situation, the pulse emitted by an active sonar elicits a *clutter* echo which contains components not only due to the prey but also due to the other reflectors which surround it. Deciding whether one of the components in a clutter echo is due to prey can be very difficult. This difficulty is readily overcome by the use of passive sonar, if the prey emits specific sounds not associated with any other object. In this sense, the use of passive sonar can be regarded as an sensory strategy like the usage of cf-fm signals. Beyond the use of passive sonar, it has also been hypothesized that bats may use *bistatic sonar* by listening to echoes elicited by pulses which other bats have emitted nearby [13]. However, whereas bats can be found hunting in aggregation sizes sufficiently large to raise this possibility, the actual use of bistatic sonar has yet to be demonstrated.

The pulse designs employed in the active sonar of bats vary not only between species [14] but are also controlled by the individual bats. The changes seen in individual bats often correlate with behavioral context and habitat. Bats catching airborne insect prey—for instance—are known to shorten the duration of their pulses as they close in on their prey or move in more confined habitats [15, 16]. This behavior is interpreted as a strategy to avoid temporal overlap between the emitted pulse and the received echo as the echoes' time-of-flight decreases [15]. The basic structure of all biosonar pulses observed in microbats so far is a harmonic—to some extent—frequency-modulated signal. These signals are produced by the larynx (vocal cords) of the animals in a fashion similar to voiced human speech [17]. Because much of the frequency content of the signal is present sequentially rather than simultaneously in this basic *chirp* design, it allows the animals to achieve a comparatively large bandwidth and at the same time emit sufficient pulse energy over time. Doing so is a prerequisite for achieving a good signal-to-noise ratio when operating a sonar system with a peak-limited emission device in air. Otherwise, the large spreading losses which limit the range of air-sonar in three-dimensional, unconstrained propagation spaces would prohibit performing sensing tasks with any but the lowest demands on signal-to-noise ratio even at moderate distances. The fact that underwater sonar suffers much less from absorptive attenuation could serve as a hypothesis to explain why many species of whales and dolphins emit clicks instead of chirps. These clicks achieve a high signal bandwidth simply by virtue of their short duration which then also has to accommodate all the signal energy. Although bats can achieve very high output levels (up to 133 dB peSPL at 10 cm [18]), some bats living in dense forest environments are conspicuous for their low output levels (less than 75 dB SPL) and were hence called 'whispering bats' by early researchers [2].

The cf-fm bats mentioned above are a grouping of bat species that is based on pulse design rather than on phylogenetic relationship. This means that in the evolutionary family tree of bats, members of the cf-fm group have a closer relationship to species outside this group than they have to some other members of the group. The common signal design hence is an analogous signal structure, which implies that evolutionary optimization of biosonar function has converged on the same solution independently at least twice. The biosonar pulses of the cf-fm bats feature fairly long central portions during which the instantaneous frequency of the harmonics remains constant. Leading into this 'constant-frequency component' is an upward frequency-modulated chirp and leading out of it a—typically longer and more wideband—downward frequency-modulated chirp. In all the other microbats, which are referred to as 'fm-bats', the instantaneous frequency functions are either monotonically decreasing or—in rare cases—increasing. In fm-bats, genuine constant-frequency portions are limited to saddle points, but very shallow frequency sweeps may be found, for instance in trailing signal portions where a continuously decreasing frequency-modulation rate finally becomes negligible. Whereas the pulse design of the cf-fm bats has been demonstrated to serve the detection and classification of Doppler-shifted signal components [10], satisfactory functional explanations for the differences in the shapes of the instantaneous frequency functions seen among the chirps of the fm-bats still need to be found. It has been pointed out that linear-period-modulated signals allow Doppler-invariant range estimation [19]. However, flight speeds in bats are very small compared to the speed of sound and hence cause rather small Doppler shifts. Whether the associated range estimation errors can be of practical significance remains to be demonstrated.

The interspecific and individual variability in pulse design is just one example of the variation and adaptation, which exists in all stages of biosonar systems: besides their pulse shapes, bats change their behaviors which determine how their

Figure 1. Examples of noseleaf shapes in five horseshoe bat species, left to right: *Rhinolophus pusillus*, *R. pearsoni*, *R. affinis*, *R. macrotis*, *R. luctus*. Top row: frontal view; bottom row: side view.

sonar system is employed. Some cf-fm bats, for example, can hunt insect prey either while on the wing or scan their surroundings while hanging from a perch [20]. Bat species that emit their biosonar pulses through the nose often have elaborate protrusions—the so-called noseleaves—which act as beamforming baffles to direct the emitted sound energy as a function of frequency (see figure 1). Some of these species have muscular control over their noseleaves and could hence also control their emitted directivity dynamically. On the reception side, many species of bat can rotate their outer ears (pinnae) or even deform their pinna shapes. These behaviors can serve to orient [21] and possibly modify the directional sensitivity of the ear, although such a function still has to be established experimentally in most cases. Neurophysiological evidence shows that activation of the muscles in the middle ear can be tightly coupled with the muscular activity of the larynx [22]. This may serve to protect the hearing system from its own pulse and hence preserve sensitivity to the echoes. The inner ear and the auditory nerve play a major role as first-level feature extraction devices. The inner ear splits the signal into a bank of bandpass filters, the output of which is encoded in a sequence of nerve discharges known as 'spikes'. The inner ear of cf-fm bats is characterized by a set of specializations, which give rise to an 'acoustic fovea': the frequency band occupied by the constant-frequency portion of the biosonar pulse is represented by many bandpass channels with extremely high filter quality [23]. Since the inner ear is innervated in a feedback loop, which is made up by nerve fibers running up to the brain and others running back from the brain to the inner ear, it probably is also a site where system properties are controlled and adaptively adjusted.

We presently have identified only a subset of the sensory capabilities that bats must have in order to meet the informational needs of their varied lifestyles. In addition, satisfactory computational theories remain to be formulated for many of these established capabilities. Therefore, it is not clear at present whether a single operational principle would suffice for building technical sonar systems that are as powerful as biosonar. There is a possibility that such a unifying principle exists only at a level of abstraction that renders it of little use for the solution of specific technical sensing problems. Malleability and diversity seem to have been important factors in the evolutionary success of bats. This may be taken as an indication that customization and embedding of task-specific prior knowledge into each customized solution may be the direction to take in order to develop sensing technology to match the performance of biosonar. Comparative investigations of biological solutions hold the potential to inspire customization of technical solutions (see section 7). System integration also stands out as an important aspect of biosonar. Whereas technical sonar systems have relatively few parameters that can be varied, bats have many degrees of freedom on all levels of biological complexity and along the entire feedback loop, which leads from active sensing behaviors to perception and back. This layout opens many opportunities for system optimization but at the same time poses a major design challenge in finding the right set of parameters.

3. Applications

Since biosonar uses the same physical principles as technical sonar, any sensing strategy discovered in biosonar could be implemented in technical sonar systems immediately. However, such an immediate transfer is rarely feasible since biological and sonar-engineering tasks usually differ in their goals and in the constraints under which these goals are to be achieved. Different goals, for example, make it unlikely that a need will ever arise for a technical sonar system that can guide drinking nectar from a flower. Different constraints prohibit the application of sonar tracking as employed by insect-hunting bats to the tracking of aircraft, since the latter requires operation over much larger distances. To account for these differences, biosonar sensing strategies need to be generalized to an extent that they can be applied to technical applications.

Sonar is usually not the only available choice for a far-sense in a given application. Other options such as radar and computer vision can have significant advantages over sonar in terms of a wider operating range (radar, in particular) and an easier-to-interpret representation of three-dimensional geometry in the output signal (computer vision). However, sonar may still be the best choice depending on the circumstances: in certain media, sound propagates further than electromagnetic waves. Examples include water (especially turbid water), smoke-filled environments as may be encountered by firefighters, and fog. Besides better propagation in certain media, sonar may also offer an opportunity to look inside, around or through objects, when visible light or radar waves do not allow this. Looking around an object is possible if its size is not much larger than the wavelength so that the waves are able to diffract around it. This is for instance the case for ultrasound and foliages consisting of small leaves (e.g., a yew hedge [7]), which hence can be impenetrable to vision but may be seen through with sonar. Looking at the inside of objects is possible whenever the difference in the acoustic impedance between the object's material and the medium in which the sonar waves propagate toward it is not too large. This is not uncommon in water, which has an acoustic impedance close enough to that of many solids for this purpose. Impedances are actively matched to achieve penetration of an object by ultrasound in non-destructive testing of manufactured parts as well as in biomedical diagnostic and therapeutic applications of ultrasound. In these applications, a layer of a liquid or solid couplant is placed between the ultrasonic transducer and the surface of the test object. Further important practical advantages of sonar result from its comparatively small input and output data rates. Since an individual ultrasonic echo signal is a function of a single independent variable (amplitude as a function of time), it will—in general—be representable by a much smaller number of amplitude samples than a two-dimensional image from a camera. Smaller data rates impose less demanding specifications on the system's hardware for acquiring, processing and storing the input data. This is particularly important for applications that are constrained by cost, size and weight, power consumption or heat dissipation.

Such constraints frequently apply to sensing systems to be integrated into autonomous robots. As a consequence, many commercially available experimental platforms used in autonomous robotics are equipped with a set of sonar sensors by their manufacturers. The intended use of these sensors is path planning and obstacle avoidance via the generation of range maps [24, 25]. The pre-installed sonar units [26] are designed to act exclusively as simple ranging devices with very few optimizations: the emitter (loudspeaker) is limited to producing an invariant narrowband signal. Likewise, the processing of the received signal is a fixed operation in which the signal amplitude is compared to a time-variant threshold. As a consequence of their simple design, these devices lack most of the capabilities biosonar systems have for multi-level optimization, adaptiveness and inclusion of embedded knowledge about information-bearing parameters in the signal. Given these shortcomings, sonar sensing in autonomous robotics could potentially benefit significantly from the introduction of bioinspired functional principles. However, use of a bioinspired approach has been limited to experimental systems custom-build for this purpose and mainstream robotic platforms have failed to adopt it so far. One possible reason for this could be that in the past most autonomous robots have been developed for conditions (office environments) in which many of the capabilities sonar systems are not readily applied. Another probable reason is the availability of alternative, more intuitive sensors, such as camera vision and laser ranging. Both factors may be overcome by looking at biological systems: a move into richer environments (such as outdoor environments where bats live) is likely to make the advantages of sonar more obvious. Insights from biosonar could help to foster an understanding of how sonar signals can be interpreted. Through suitable generalization, this could lead to the adoption of more capable sonar systems for autonomous robots in any environment. Once the gap between what a state-of-the-art bioinspired sonar system can deliver and what widely used autonomous robotic platforms offer has been closed, autonomous robotics could become a major application area for biosonar-inspired technology. Such a breakthrough could in turn lead to a more widespread use in products into which autonomous robots could be 'embedded' such as cars with aids for automated parking or intelligent wheelchairs which aid their users in maneuvering and avoiding collisions.

The advantages of sonar suit its use as a sensory system in mobility aids for the blind. A simple sonar system can be carried conveniently in a cane (see figure 2) or as a wearable device and users can learn to make judgments about objects in the environment based on sonar output signals turned into audible sounds or into vibrations [27–31]. Typically, sensing intelligence—bioinspired or otherwise—is limited to transforming the raw sonar returns into an informative yet unobtrusive signal representation. The user is left in charge of sensor mobility (i.e., aiming the device) as well as signal processing and evaluation. Some of these tasks could be performed partially or completely by bioinspired processing built into the device. Biosonar could serve as an inspiration for better signal processing algorithms, the embedding of prior knowledge and feedback control over system parameters such as the pointing direction. If successful, this would improve the quality of the information provided lower the burden on the user's attention.

The potential application areas for insights inspired by biosonar go well beyond technical sonar. Sonar is part of a large class of wave-based contact-free sensing applications. All such applications share common properties derived from the general laws governing waves and wave propagation (e.g., spreading losses, scattering). Once bioinspired insights have been abstracted to this level, they should become applicable to a wide set of engineering applications.

An additional route to achieve generalization of bioinspired sonar exists through the abstract estimation problems solved: the most basic of these problems is *detection*, i.e., deciding whether the input contains only noise or a signal of interest in noise. The goal of all other tasks is to learn more

Figure 2. Example of a biosonar-inspired mobility aid for the blind, the 'Ultracane' [27]; the handle includes two ultrasonic transducers—one forward-looking, one upward-looking—and a tactile display consisting of four transducers. Photograph by Dean Waters, reproduced with permission by the copyright owner.

about the source of the signal or the channel through which it has traveled. A common next step is the *localization* of the source at a given time. Although source *tracking* is related to localization, obtaining a sequence of three-dimensional target locations is not the most parsimonious implementation. Simpler sensing and control strategies suffice [32]. All remaining estimation tasks can be considered a form of source or channel *classification*, in which properties of the source or the channel are determined to a certain precision or specificity. If the estimated properties are specific enough to classify the source or the channel into a class with only one member, this is the special case of a source or channel *identification*. Classification may not only be an end in itself. If class-specific properties of the source or the channel are confounding factors in another estimation task, class knowledge can be used to eliminate them. Finally, when performing any estimation tasks in a two- or three-dimensional space, a choice has to made—either deliberately or implicitly—as to how the emitted energy and the receiver sensitivity should be distributed in this space to optimize performance. This is the *beamforming* problem.

Optimal solutions for the tasks above, where known at all, are restricted to a set of assumptions that often impose severe limitations on the practical usefulness of these results. This leaves the possibility that from the study of biosonar good solutions—if not solutions of proven optimality—can be found that are general enough to apply to a wide range of technical problems with no obvious link to (bio)sonar. For instance, beamforming frequently has an impact on system performance and power economy in wireless communication devices. Fast estimation of channel properties is used to adjust the signal processing strategy to improve the quality of the link. Thus, a bat may estimate properties of a random sound propagation channel in a forest to tell what type of habitat it is in and a wireless communication device could employ a fundamentally similar method to estimate the propagation channel for its current link and mitigate its adverse effects on the transmitted signal. Tasks in the related fields of non-destructive testing and biomedical diagnosis can also be phrased as channel estimation problems. Statistical properties of the channel can—for example—allow diagnosis of diseased tissue [33]. In these cases, localizing the source, e.g., a defect in a work piece, can also be of importance. The generalized tasks of source localization and source tracking are of obvious importance to 'surveillance' applications in a wide sense. This includes not only applications in which knowledge of the position of a source is the ultimate goal but also—for instance—smart rooms which try to understand where their inhabitants are and what they would like to do as an intermediate step to adjusting to the inhabitants' needs.

4. Design goals

The previous discussion of bat biosonar (see section 2) and possible applications of insights derived from it (see section 3) suggest that design of bioinspired sonar systems should be directed toward one or several of six basic goals in order to maximize their technological impact. In particular, they should:

- be capable of performing unique tasks for which there is no alternative solution or at least outperform insufficient alternative solutions. By doing so, they can bring forth sonar's unique capabilities and make it available for new contactless sensing applications.
- operate under constraints that alternative methods cannot meet (e.g., size, power consumption and heat dissipation, data rates, computing power and computer memory, manufacturing cost and manufacturing tolerances). Performing under sets of constraints that could not be met previously can enable new applications and can hence be as beneficial for technology development as performing entirely new tasks.
- employ adaptive, active sensing strategies in the integration of different components and levels of

complexity. In this way, the bioinspired systems are most likely to tap into the probable foundation of the superior performance of bat biosonar.

- incorporate advanced implicit knowledge about all relevant stages of the sensing process. Like adaptive sensing, built-in knowledge is a likely candidate for explaining the performance advantage of biological systems.
- implement sensing strategies based on robust physical principles, which will insure high reliability even in the presence of interfering factors inside and outside the system.
- serve as a testbed for general sensing strategies. This maximizes number of technology fields in which the result could be applied.

5. Design challenges

Meeting the design goals outlined in the previous section poses challenges for all components of a biosonar-inspired systems as well as for integrating them into a whole.

Achieving a good signal-to-noise ratio [34] is simplified by emitting transducers (loudspeakers) capable of generating a high-power acoustic output. Likewise, the detection threshold of the system benefits from sensitive receivers (microphones) as long as the noise power is still sufficiently low for this. However, maximizing output power and receiver sensitivity is not suitable for all sensing situations: For example, target strength permitting, spreading losses and directivity gain can be used to ensonify a small spatial region selectively and exclude clutter-producing targets outside this region from contributing to the detected echo. This kind of clutter rejection may be a factor in the low output power seen in ‘whispering bats’ (see section 2). Emitter output power and receiver sensitivity both increase with the surface area of the transducer for all commonly used transduction mechanisms (e.g., capacitive and piezoelectric transducers). This gives large transducers a clear advantage in terms of the signal quality they are able to deliver. But there are also significant disadvantages to large transducers: they are not so readily integrated into a sonar head because of their larger mass and size, particularly when small moving masses are required for head designs that include mobility (e.g., rotation—see below). In addition, large transducers constrain the design of beamforming baffles as all possible baffle shapes must contain an opening fitting the transducer. Typical requirements on loudspeakers and microphones used in acoustic measurement and audio applications are a flat transfer function and a linear system behavior. There is probably no benefit to meeting either of these two when mimicking biosonar systems. All bats are known to produce harmonics to some extent, so transducer linearity is certainly not a requirement for what they achieve with their sonars. To the contrary, bats may make use of the harmonics to accomplish their sensing goals [32]. Likewise, the frequency content in the sonar pulse of the bat is heavily weighted upon emission and by the sound channel, so a flat transfer function on the emission side can hardly be a requirement for performing like a bat. On the receiver side, it is also unlikely that any bat species has a flat transfer function, but it is not clear in which way the transfer functions at different stages of the hearing system may affect sonar performance by a weighting of different frequency bands. Optimum detection of signals in noise implies that the transfer function should emphasize the signal components that have a favorable signal-to-noise ratio to implement a matched filter.

Through rotating their outer ears and deforming their shapes, bats have the opportunity to dynamically control the shape of their directivity pattern and the direction it is pointing in. Reproducing these capabilities in a bioinspired system could follow one of two different approaches or use a combination of the two: the transducers could be actuated mechanically or the effect of mechanical actuation could be emulated by means of array signal processing techniques. In the latter case, the surface of the transducer is split into elements which can be driven individually to steer the beam by a pattern of phase shifts between the element signals.

Rotation of the directivity pattern is readily accomplished with either technique in principle. However, if the overall size of the sonar head is to be kept small, this poses a challenge for either method. For mechanical actuation, the actuators (motors) and the linkage cannot be miniaturized without also reducing the actuator’s power and the strength of the mechanical linkage to the transducer. For phased arrays, a complete driver circuit is required for each element. On the emitter side in particular, miniaturization of this circuitry is limited by the heat dissipation of the power amplifiers.

Performing a physical deformation of the shape of transducer baffle poses a challenge that has not been addressed experimentally so far. Achieving the goal of a malleable baffle shape which can be deformed like a bat pinna requires solutions for at least two key components: an actuation scheme through which the desired deformation is brought about and a material for the baffle surface which shows the desired behavior when actuated. Custom actuation schemes and suitable materials still need to be found for overall deformations of pinna shape. Bioinspired solutions could be considered to devise such a novel actuation scheme. A more tractable alternative is to change the directivity pattern of the outer ear not by an overall deformation of the shape but by actuating a single part of the outer ear relative to the rest. A more conventional actuation scheme (e.g., a rotation) could be used to accomplish this objective.

The incoming echo signal needs to be processed in order to arrive at estimates for the parameters of interest, which requires a suitable representation for the input signal as the first step. This representation must conserve the information content of the relevant signal features and should enhance their accessibility. In addition, it may be desirable to perform a lossy data compression by discarding information about signal features not relevant to any of the sensing tasks at hand. This allows downstream signal processing stages to operate at lower data rates and hence makes their operation less demanding. The peripheral hearing system of bats is known to perform two basic transformations in converting the incoming echo waveform into a neural representation: in the first step, the input signal is split into a bank of bandpass filters and for each bandpass filter output only the amplitude-demodulated envelope is transmitted [35]. This transformation is similar to early analog vocoder systems. In the second step, the envelope-detected output of the bandpass filters is encoded into a neural spike code, i.e., it is represented by a sequence of nerve pulses ('spikes'), where all information about the input is conveyed by the timing of the individual spikes or some time-variant statistics of the spike times (e.g., a rate). Although the basics of these transformations are straightforward, it is the choice of parameters that poses the major challenge. This is particularly true for the spike-encoding step. For the bandpass filtering step, the general transformation (filtering plus some nonlinear additions such as adaptive gain control) is well known for mammals in general and several parameters such as the number of filters, their center frequencies and their bandwidths, can be inferred from neurophysiological and neuro-anatomical data on bats [36]. This is not true for the spike-encoding step. Neurons (nerve cells) fire spikes as a result of a nonlinear dynamic behavior which is governed by the electrical properties of the cell membrane, in particular by its capacitance and the conductance due to ion channels. The result is the triggering of a spike discharge when the input signal(s) to the neuron reach a certain threshold. The value of the threshold depends on the discharge history of the cell, in particular, there is a refractory period after a spike during which a new spike cannot be triggered or can only be triggered if a very high firing threshold is crossed. A specific quantitative model for the firing behavior of the neurons in the auditory nerve of bats remains to be formulated. The challenge for bioinspired technology development is hence to understand how a spike code can be used effectively in lossy data compression and feature extraction without relying on detailed knowledge of the transformation performed in bats.

A further, interrelated challenge is posed by the development of estimation algorithms operating on a lossy compressed representation of the echo data. The first challenge in devising any biosonar-inspired estimation algorithm is to identify correctly the sensing problem that underlies the task performed by the bats. For example, it is important to distinguish between the detection of a target echo in independent noise and classifying echoes according to their origin from a target of interest or from clutter targets. Once the sensing problem is properly characterized, the next step is to identify suitable information-bearing signal parameters for solving it. Although methods for automated identification of information-bearing parameters, such as classification features, are available, none of them is guaranteed to deliver optimal or even useful results. There two main reasons for failure: first, the method used may have been based on inadequate assumptions. Second, the dimensionality of the data may be too high and its structure too complicated to give a search for a good feature set a reasonable chance of success. An alternative to automated methods is to rely on physical insight into the problem. The advantage of this approach is not that it is immune against the problems described above. To the contrary, the search for physical insights faces similar obstacles as automated feature extraction. However, unlike in automated feature extraction, these problems do not carry over into the identification of the features themselves since the latter is based on an understood physical mechanism and not immediately on the data. As a result, such solutions will often be of superior quality. In addition, it may be possible to adapt the physical analysis and hence the features derived from it to related scenarios. Features obtained from an automated method without physical insight are not readily generalized in this way. For all these reasons, features based on physical insight are preferable whenever they can be obtained with reasonable effort. Irrespective of the feature extraction method to be chosen, bioinspiration can be used to deal with high-dimensional data: the biological representation of an echo waveform by a spike code is a sparse, lossy compression, searching for features at the level of the spike code to deal with fewer possible feature dimensions than that of the original data. Working with a spike code can hence facilitate both physical insight and automated feature extraction. However, since only approximate models for the spiking behavior of auditory nerve fibers in bats exist [37], such an analysis is for practical purposes limited to features that are robust with respect to these parameters. While this may be a crippling restriction at times, it can also be regarded as a useful filter which will only pass effects strong enough so that they can also be exploited in a technical system without requiring too many specific system properties.

Not only the design of each individual component in a bioinspired sonar system poses a challenge, but also the integration of all the parts into a whole. The latter challenge goes well beyond issues associated with ensuring the compatibility of mechanical, electrical and data interfaces. This is because knowledge about the tasks that the system is designed to perform can and should be embedded on the component as well as on the system level. System-level knowledge can be implemented into a feedback scheme where the results from the analysis of the input data are used to make adjustments to the system parameters. Such feedback systems implement adaptive sensing strategies which generate a sequence of signals to contain the information required to solve the estimation problem at hand. In principle, all signal analysis stages can serve as information sources for the feedback loop and the generated control signal can be based on readily accessible properties of the input signal (e.g., its energy) or on the results of a far-reaching analysis which may itself incorporate prior knowledge. All parameters of the sonar system, e.g., generation of the pulse waveform, transducer sensitivity and actuation (rotation, etc), as well as signal processing stages are potential targets for feedback control; some of these feedback mechanisms have been implemented in experimental systems already and will be discussed in the next section.

6. Biosonar-inspired systems

Biosonar has inspired designers of realized experimental sonar systems in terms of the implemented sonar morphology, the strategy in acquiring echo information, and the processing of this information for localization and classification. The implemented functional principles include the following:

- Binaural sensing for localization and tracking.

- Fundamental and harmonics for localization.
- Receiver rotation for localization.
- Binaural processing for object classification.
- Sequential echo processing for classification.
- Adaptive sensor positioning.
- Beamforming via baffle shapes surrounding the transduction sites,
- Adaptive configuration for acquiring additional echoes
- Neuromorphic processing.

6.1. *Binaural sensing for localization and tracking*

Bats use a sonar configuration with a central emitter flanked by two ears for binaural detection to track moving aerial prey. The task solved by one of the early bioinspired systems replicating this behavior [38] was to use an equivalent transducer configuration in intercepting a target moving along a linear trajectory based only on echo information. The binaural difference in observed echo arrival times estimated the bearing and range to a target moving along a linear path. Different strategies for intercept path planning were examined based upon the information describing the target trajectory, specifically should the robot move toward the last sensed location or toward a predicted location. The results indicated that when sampling often enough, at a rate typical for bats, moving toward the last sensed location was a reasonable strategy. Sonar-guided motion is not ballistic, that is, based upon only a single reading, but rather sequential, reacting to a series of echoes. The echo quality, as measured by the signal-to-noise ratio, typically improves in the pursuit because the echoes get stronger as the pursuer gets closer to the prey.

Tracking an isolated target moving in two dimensions can be performed easily with a bioinspired sonar by rotating the sonar so that the echo arrival times detected at each ear are equal. A system implementing this strategy was able to track a swinging ball in real time [39].

6.2. *Fundamental and harmonics for localization*

Spectrograms of bat calls indicate the presence of harmonics (see section 2). The utility of the fundamental and harmonics was investigated in a simulation of a sensori-motor model of a bat-like sonar pursuing randomly moving prey [32]. Physical beam patterns were computed for a transmitted beam produced by a circular aperture and the receiver sensitivity patterns formed by a pair of outward-oriented ear apertures. It was found that three-dimensional localization was possible with binaural hearing using the following approach: the target bearing can be determined by detecting an echo with both ears, either from the interaural time difference or the interaural intensity difference. The echo from a target off to the side arrives sooner and is stronger at the ipsilateral ear. If integrated-intensity threshold detection is employed, then increased echo strength also shifts the detection time downward [40]. The target elevation was determined from the relative strength of the fundamental and harmonic components in the echo. The harmonic component, being higher frequency, produced a narrower beam, while the fundamental produced a wider beam. This can be seen as the simplest version of the head-related transfer functions studied in spatial hearing [41]. When the pursuer is approaching the prey, the bearing is typically close to zero and the ratio of the harmonic to fundamental echo intensities provides a control law which directs the bat to the prey.

6.3. *Receiver rotation for localization*

Stereotypic ear movements are a conspicuous behavioral feature of many bat species. They are seen—for example—in the horseshoe bats, which belong into the group of cf-fm bats and show a pattern of the two pinnae rotating antiphasically in elevation. It is known that these movements are essential to localizing targets in elevation [21]. Broadband sonar pulses allow it to estimate target elevation from spectral profiles caused by frequency-dependent directivity patterns for emission or reception which impose a spectral weighting according to the target's elevation. This principle cannot be applied to obtaining elevation information from narrowband signal portions. Instead, the behavior seen in bats presumably translates the changing relative orientation of the receiver with respect to the target into an amplitude modulation. This computational theory has been investigated in a robotic model [42–44]. It was found that the ambiguity inherent in the interaural intensity differences obtained for an individual position of two piston receivers could be resolved by considering multiple positions along an antiphasic scan in which two receivers were rotated in opposite directions.

6.4. *Classifying small deterministic targets*

Echo waveforms are repeatable in deterministic targets, whereas in random targets repeatability applies only to the waveform statistics. Small targets are those that fit completely within the sonar beam, so that all the scattering features produce echoes. In contrast, large objects do not fit into the beam and hence echoes from the entire object must be obtained by scanning, either by rotating the sonar to form a sector scan or by translating the sonar to form a linear scan. In both scans the echo information must be stored and integrated to classify a target. All four target types (small deterministic to large random) are encountered by biosonar as well as technical sonar systems and require separate strategies, which are still open research questions.

For example, classifying small deterministic targets is problematic because diffraction effects in the transmitted and detected signals cause the echo waveforms to vary as the target location changes in the beam pattern. With the swept-frequency transmissions and multiple-band hearing systems seen in bats, the sonar beam can be broken up into its frequency components, with beam widths decreasing as the frequency component increases as mandated by basic physical principles. A target lying off to the side will lie within some of the lower frequency beams but be outside some of the higher frequency beams.

To accommodate this bothersome effect, a sonar was implemented at the end of a robot arm to position a small target at a repeatable location [45]. Figure 3 shows the transducer configuration used by this system: a center transmitter is

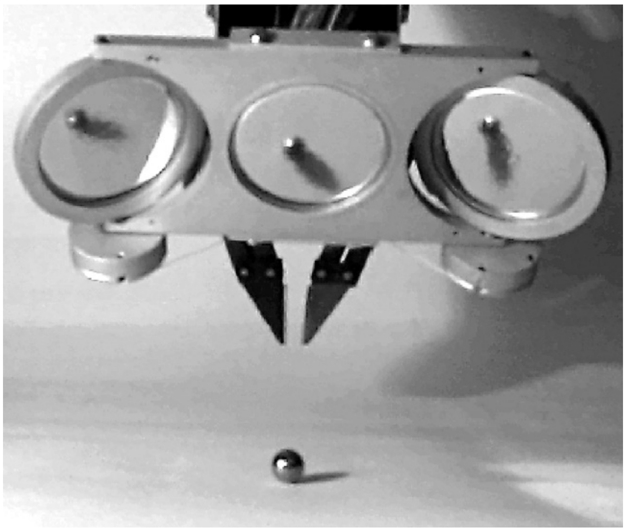

Figure 3. Bioinspired sonar system [45] situated at the end of a robot arm. The sonar is configured as a center transmitter flanked by two receivers that can rotate to focus on an echo-producing object (shown here is a sphere, a mirror image of which is produced on each transducer surface).

flanked by two receivers. The receivers rotated to place the target on their respective transducer axis, thereby maximizing the echo bandwidth since the sensitivity main lobe of the employed piston-transducer is aligned with the transducer axis for all frequencies. The system learned the object by initially scanning it and storing samples of the echo waveforms. Although the two side receivers accurately positioned the object in bearing along the sonar axis, the object elevation was less accurately determined. The system mimicked observed dolphin behavior when foraging for food to accommodate this lack of accuracy: the dolphins appear to nod up-and-down as if performing a scan over elevation. The same strategy was implemented in the bioinspired sonar by storing multiple learned templates for the same target by scanning in elevation. The target could then be classified by virtue of these templates over any one of these elevations. This system was able to classify the heads and tails sides of a coin from the echoes, which differed only because of their relief patterns. This demonstrates the power of the approach since the relief depth is much smaller than any of the employed wavelengths.

6.5. Classification of large random targets

Natural landmarks, such as foliage, rock or water surfaces, represent large random targets that do not fit into a single sonar beam. Like in deterministic targets, direction-dependent scattering and weighting of individual reflecting features by the beam pattern result in echo waveforms that depend on the position and orientation of the sonar head with respect to the foliage. Unlike in small deterministic targets, the search space for all possible echoes is enlarged because of the size of the target to an extent which makes searching for templates impractical when, e.g., identifying a landmark in a forest. In an experimental investigation [46], the correlation distances for four different foliage types were found to be below four centimeters for translation of the sonar head. Furthermore, the waveforms are unstable in time as—for example—a gust of wind rustling through the forest will thoroughly change the entire set of echo waveforms. This instability is particularly evident in the case of turbulent water surfaces for which no stable echo waveform can be obtained on any practical time scale.

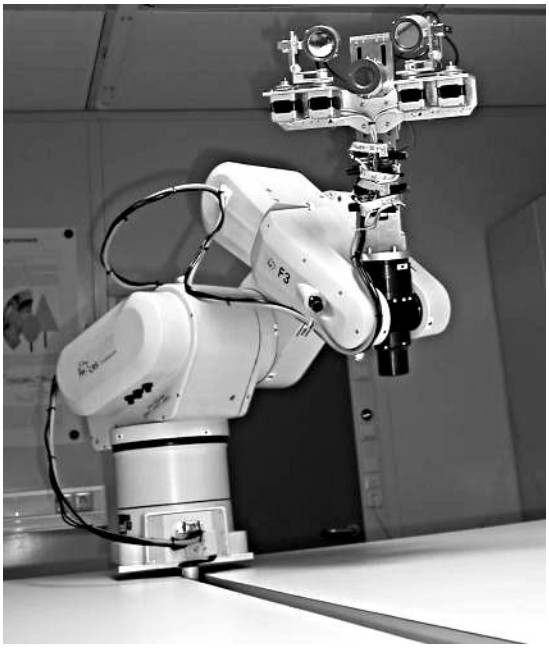

Figure 4. Bioinspired sonar head mounted on a 6-degree-of-freedom industrial robot arm and a linear track for expansion of work envelope [52].

Several studies have examined potted foliage of different plant species with continuous-wave frequency-modulated (CWFM) [47–50] or wideband sonar [7, 51]. All these studies found class-specific differences in echo properties which demonstrated that echo classification was possible and formulated hypotheses as to how these properties relate to foliage structure. Work by Müller [46] used a bioinspired sonar system mounted on a six degree of freedom industrial robot arm (see figure 4) with a large work envelope ($116 \times 64 \times 96$ cm^3) to compile a corpus of echo data (84 800 echoes in total) obtained from four large natural foliages re-assembled in the laboratory. Using a sequential classification paradigm for multihypothesis testing [53], highly accurate classification (0.06% classification error on an expected number of less than ten echoes) could be obtained on just a small expected number of echoes based on features from a parsimonious spike code (see section 6.7). Important spike code features underlying classification were linked to the presence of large sudden upward steps in the echo amplitude and the gaps between them. These signal features correspond to the presence and spacing of strong specular echo components which result from favorably oriented single reflectors (such as large planar leaves). Using these features foliages can be classified based on where they fall between sparse collections of large specular reflectors (foliages with few large leaves) to dense collections of reflectors with more uniform target strength (dense foliages with many small leaves).

Sequential classification provides a good match to the way sonar systems operate: because emission is organized in pulse trains, an individual echo is an inexpensive commodity and even moderately sized echo samples can be collected within short time spans. Although sequential testing is usually geared toward independent samples, the dependencies between echoes obtained along a scan can also be used for classification: *in situ* foliage classification was examined by using the conventional robot sonar to obtain echo envelope information from sector scans of tree trunks and plants [54]. A mobile sonar converted echoes into biologically similar temporal point processes, termed pseudo-action potentials (PAPs), whose inter-PAP interval relates to echo amplitude. The sonar forms a sector scan of an object to produce a spatial-temporal PAP field. Specular facets were sought out by orienting sonar to be normally incident to leaf surfaces. Classifier neurons apply delays and coincidence detection to the PAP field to identify three distinct echo types, glints, blobs and fuzz, which characterize plant features. Glints are large amplitude echoes exhibiting coherence over successive echoes in the sector scan, typically produced by favorably oriented isolated specular reflectors. Blobs are large echoes lacking coherence, typically bordering glints or formed by collections of interfering reflectors. Fuzz represents weak echoes, typically produced by collections of weak scatterers or by reflectors on the beam periphery. The narrowband sonar modeled the activity of a single frequency bin in the frequency-modulated (FM) sweep emitted by bats.

6.6. Beamforming

Technical sonar systems rely on array signal processing to accomplish all but the most basic beamforming operations. Often fairly large numbers of transducers arranged in one-, two- or even three-dimensional arrays are used for this purpose. In contrast to this, bats have only one or two sites for sound emission (the mouth or the two nostrils) and two sites for sound reception (the two eardrums). Their capabilities for array-based beamforming are hence limited and—on the emission side [55]—still hypothetical. The conspicuous shapes of the noseleaves and pinnae in bats suggest that diffraction by baffle shapes surrounding the sites of sonar pulse emission (nostrils) and reception (eardrum) is the prevailing beamforming principle in bat biosonar instead. The set of beamforming goals accomplished by technical sonar systems is rather narrow and commonly limited to beam steering and focusing (including side-lobe suppression). This may also not be true for bat biosonar, where the large diversity seen in the noseleaf and pinna shapes is evidence for a greater richness in beamforming mechanisms and goals. In order to study the beamforming properties and mechanisms in bats across a sufficient sample of different shapes, numerical methods for representing the biological shapes and predicting their acoustic properties have been optimized for all work steps involved [56, 57]. This work has identified the following functional properties and principles:

- The pinna directivity patterns of all bat species included in this study showed progressive, frequency-driven, motion-free scanning to some degree. This means that the direction of the main-lobe or the overall highest sensitivity shifts systematically as a function of frequency. Motion-free scanning is an advantageous system property since it can be used to eliminate the shortcomings in terms of speed and reliability associated with mechanical actuation [58]. Since phased-array techniques for motion-free beam steering can solve these problems only at the cost of implementation complexity, alternative methods such as antennas with optically controlled refraction have been investigated [59]. The diffraction mechanisms in bat pinna offer similar advantages and could hence enrich the inventory of available technical methods.
- Prominent asymmetric (i.e., one-sided) side lobes are present in the directivity patterns and their sensitivity is controlled through diffraction around flaps on the pinna rim (e.g., the tragus or a thickened ledge). The frequency-dependent side lobes and the sensitivity minima which separate them from the main lobe (or multiple side lobes from each other) translate into direction-dependent transfer functions. Based on this, direction finding by means of spectral estimation can be carried out by biosonars [60, 61]. There may be additional uses to the capability of extending or retracting side lobes in a directivity pattern, for instance in distributing attention in two directions at once.
- The shape of the directivity pattern changes as a function of frequency. Such changes in beam shape can implement a scanning pattern, for example a helical scan as was seen in a noctule bat [62]. In this scan, a single dominating main lobe alternated with a conical sleeve of side lobes with a frequency-dependent sensitivity maximum along its rim. The effect is a 'center-surround' pattern similar in appearance—and maybe in function—to center-surround antagonisms in vision [63].
- The width of sonar beam can be controlled in a frequency-specific manner through open-cavity resonators in the baffle surface. This effect was observed and characterized by numerical experiments on the noseleaf shape of a species of horseshoe bat (*Rhinolophus rouxi*) [64]. The frequency selectivity of the resonance allows the animals to modify the directivities only for a narrow band of frequencies. This operational principle also has the advantages of very low implementation complexity and high reliability, because open-cavity resonance can be produced easily by a grooved surface (as in horseshoe bats, see figure 1).

Pinna shape properties identified as likely candidates for functionally relevant features have been incorporated into a simplified parametric shape model for a bat pinna [65]. In this model, the basic shape of the pinna is represented by an obliquely truncated horn which has been proposed previously as an idealized model for mammalian pinnae [66, 67]. This basic shape is augmented by a tragus-like flap and surface

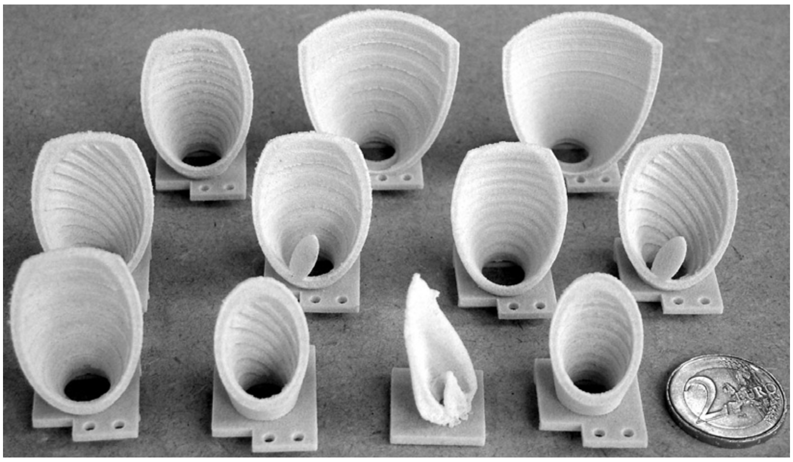

Figure 5. Prototypes of shapes realizations from an idealized pinna model [65] with the shape of a biological bat ear (Plecotus auritus—second from the right in the first row).

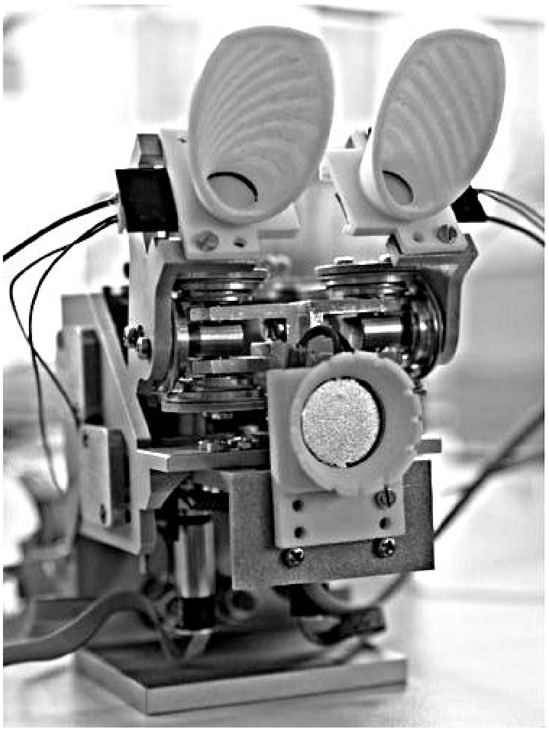

Figure 6. CIRCE robotic bat head [68–70] with bioinspired transducer baffles—photograph by Herbert Peremans, reproduced with permission by the copyright owner.

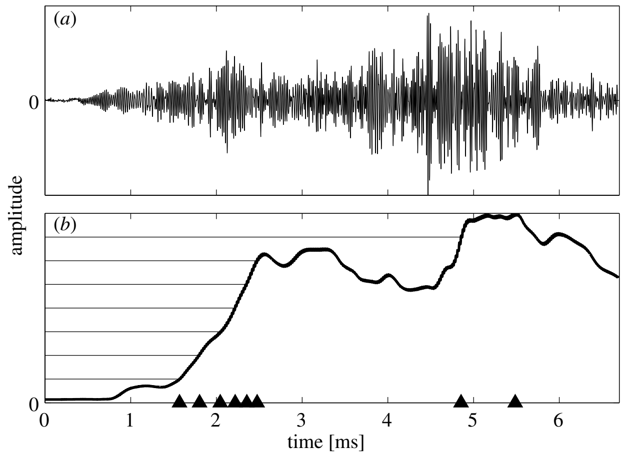

Figure 7. Spike encoding used for classification of large random targets [46, 51]. (a) Example of an unprocessed echo waveform from a Sycamore foliage; the duration of the echo shown corresponds to a range of about 1.1 m. (b) Signal envelope after bandpass filtering (center frequency 50 kHz, filter quality, the ratio of center frequency to −3 dB-bandwidth, 20) and demodulation (half-wave rectification and first-order recursive low-pass filter with time constant 1 ms); horizontal lines indicate spike-firing thresholds, the corresponding spike times are marked by the triangles (▲).

ripple on the inner wall of the horn. The shape model has 22 parameters to represent these biological features along with some variability in their shapes (e.g., tragus angle, ripple amplitude and spatial frequency). At the same time, the dimensionality of the optimization problem posed by finding at least a local optimum for a performance metric is within the reach of stochastic optimization methods such as genetic algorithms.

In order to test some of the shapes generated by this model under the conditions of actual sensing tasks, the prototypes of the model pinna were produced with snap-on connectors, which allow them to be mounted onto the CIRCE robotic bat head [68–70], a platform for experiments in bioinspired sonar which implements many other important functional features of biosonar such as sensor mobility and neuromorphic signal processing.

6.7. Neuromorphic spike processing

A parsimonious model proposed for spike encoding in the auditory nerve of bats transforms a half-wave rectified, low-pass-filtered input signal into a vector of spike times through a simple thresholding operation [46, 51]. As quantitative descriptions of the refractory behavior of auditory neurons in bat neurons are not available (see section 5), only the first spike generated by a neuron in response to an input is considered (see figure 7). The spike is triggered when the signal passes the threshold of the respective neuron for the first time. This approach facilitates analysis and minimizes the risk of making incorrect assumptions about biological function at the cost of discarding additional information that the brain of the bat may have. Another important feature of this model is to consider individual neurons with different firing thresholds instead of a statistical ensemble of neurons in different excitation. This view is motivated by the sparsity of the spike code for ultrasonic signals, which are rather short compared to the rate with which neurons can fire spikes. Spike times relative to the emission of the pulse are informative about the echo's time-of-flight and hence target distance [71]. Spike timing differences within the spikes triggered at different firing thresholds by one echo can be used to characterize the target. Since the signal amplitude of the rising signal flank passes all thresholds in order of their amplitude value, all information about the spike times in the code is contained in the time differences between subsequent spikes. Simple, first-order statistics of these timing differences and threshold amplitudes have been used to classify natural random targets successfully as described in section 6.5 [46].

A similar parsimonious spike code was also used in investigating linear scans during which echoes from *in situ* tree trunks were acquired in a similar fashion as by flying bats [72]. A moving sonar converted echoes into spike sequences and applies neural-computational methods to classify objects and estimate passing range. Two classes of tree trunks acted as retro-reflectors that generate strong echoes (SEs), identified by a locally dense spike pattern. Linear drive-by sonar trajectories cause SEs to follow hyperbolic curves specified by passing range. A glint is a collection of consecutive range readings matching expected values on a specific hyperbolic curve. Passing-range detectors compare successive SE data with expected values in a table and tally coincidences. A glint terminates after tallying a sufficient number of coincidences and coincidence failure occurs in the maximum-count detector. Reflector roughness, deviations in sonar trajectory and echo jitter necessitate a variable-width coincidence window to define matches. Short windows identify small glints over piecewise linear sonar trajectories, while long windows accommodate deviations in sonar speed and trajectory and associate multiple glints observed with shorter windows. The minimum coincidence window size yielding glints classify smooth and rough retro-reflectors.

While many investigations of computational theories for neural signal processing by bats have been performed only in software, hardware implementations have been produced using both analog (VLSI [73, 74]) and digital hardware (field programmable gate arrays [75, 76]). In the latter implementations, it was possible to replicate the number of neural channels in the auditory nerve of some bat species by time-multiplexing the necessary operations on devices with a sufficiently large clock rate.

6.8. Artifact rejection

Physical reasoning in the context of bioinspired receiver orientation and spike-based processing were able to eliminate troublesome artifacts in sonar maps [77]. The artifacts considered here are points in the map that do not relate to actual objects. A bioinspired sonar consisting of two conventional sensors generated random point processes related to echo waveform intensity. The sensors pointed slightly outward from the sonar axis, similar to pinnae in some bats, to acquire slightly different views of the environment during a rotational scan. Physical criteria identified artifacts by applying echo strength, azimuthal extent and binaural coincidence criteria. Neuromorphic processing implemented these criteria with thresholding, delays and short-term memories. Hence it was possible to eliminate the artifacts and to produce robust sonar maps. Multiple resolution maps, generated by using two thresholds, illustrated improvements over conventional sonar maps and tradeoffs between resolution and stability.

6.9. Passing-range estimation

Ranging sensors typically estimate range in order to register object locations with respect to a floor plan. Bats perform target ranging while moving on the wing. To mimic this, range readings from a moving sonar estimated the passing range, equal to the minimum range as the sonar passes by the object [78]. Estimating passing range not only indicates if a collision will occur, but can also lead to artifact rejection and object classification. A conventional sonar was controlled to generate a bioinspired spike process whose density relates to echo waveform intensity. The sonar extracted strong echoes and stored their range measurements in memory as it moved along a linear trajectory. Neuromorphic processing applied delays and coincidence detection to passing-range estimates for localizing and classifying objects. Physical principles governing echo production motivated a multi-resolution coincidence detector that accomplished five important sensing tasks (object classification, collision avoidance, trajectory alignment, artifact rejection and sonar data fusion). Objects were classified by their hyperbolic range readings that exhibit passing-range estimate coincidence at a resolution related to surface roughness. Distributed objects parallel to the sonar trajectory, such as rough surfaces, exhibited coincidence in range readings, which could facilitate flight parallel to a rough surface, such as the ground or a cave wall.

7. Outlook

Bioinspiration comes from systems that are usually highly complex. The search for technical solutions in the high-dimensional space spanned by their properties has to be random until the space is better understood. This is—at present—rarely the case. Therefore, the search for technical inspiration typically leads to many promising, yet false, results and a few amazing insights obtained through serendipity. The yield is further reduced since not all genuine insights also have a significant technological impact. Currently, there is no methodology available to address these issues in a systematic way. It is therefore worthwhile to consider not only how biosonar-inspired technology could be developed as a specific field of bioinspired engineering but also how it could serve as a model system in creating general methodology for the entire field. Such methods could be directed toward achieving the following three intermediate goals:

(i) extract information from biology more efficiently,
(ii) address general technological needs better,
(iii) target wider mainstream application areas.

The first and second strategies can both capitalize on the diversity in biosonar systems: the biosonar systems of the different bat species represent an ensemble of variations of common principles which have been adapted to suit the needs arising from different sets of sensory tasks. Like the variability in any dataset, it should be possible to subject the dataset of biosonar system features to lossy compression. This could be achieved by methods derived from—or similar in spirit to—principal component analysis. Looking at the principal components of the natural variability should provide insights into how the functional features of the system were modified to achieve adaptation. Principal components could be extracted for system features of likely functional significance as well as for descriptions of the effects they are likely to be responsible for. A comparison of the results from both analyses has the potential for unraveling relationships between form and function which would be too difficult to unravel in the far less constrained original feature and function space.

The principal components can be regarded as 'design rules' which can be used to execute the second strategy, i.e., addressing general technological needs better. Once the design space spanned by biosonar systems and the rules which govern it are understood, the rules can be used to generate solutions to specific sensing tasks anywhere in the space they span. The new solutions can fall in between or even outside the biological solutions. Used in this way, the rules could address the general need for customized technology by allowing for the automated (rule-based) design of solutions to specific problems.

The signal processing performed by bats in the acoustic domain, i.e., by virtue of the diffraction on the surface of the noseleaves and outer ears is particularly well suited for the automated extraction of design rules: the determining system feature is the geometry of the tissue–air boundary. A quantitative description of this geometry can be obtained in an automated fashion using tomography [79]. Once the shape is known, it suffices for estimating a complete description of the system behavior in the far-field (the two-dimensional directivity function) by virtue of efficient numerical methods [56]. These techniques are able to produce the input data for a systematic analysis of natural variability. The result of such an analysis could be 'eigen-noseleaves', 'eigenears' and 'eigenbeams' in analogy to the eigenfaces used to describe the variability in human faces [80]. However, it is still necessary to develop or at least adapt suitable techniques for the special features of these data sets. Even though general methods—such as principal component analysis—could be used at the core of the analysis, the input data must be preprocessed to insure informative and intuitive results.

Because beamforming is a likely issue whenever the operation of a device is based on waves propagating in two- or three-dimensional media, novel beamforming principles can be considered for a large set of potential applications. The necessary generalization is trivial at the level of directivity functions, but needs to consider the physics of the particular problem at hand when it comes to realizing a directivity function by a given device. Likewise, generalization of signal processing principles to applicable tasks is straightforward. It should be noted, however, that signal processing is most powerful if it exploits some robust physical principles and these principles may need to be adapted for different sensing tasks or wave phenomena. Advances in computational and experimental research, along with the synergy of interested research groups, are likely to produce numerous physical principles of this kind and hence promise to probe biosonar sensing at a deeper level.

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