The Evolution of Bat Robots

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Introduction

The ability of bats to sense their surroundings with ultrasound has fascinated scientists ever since the discovery of the animals' biosonar system in the late 1930s (reviewed in Simmons, 2017). The riddle of how bats can extract so much information from a bunch of brief ultrasonic echoes has attracted researchers from varied backgrounds who have looked into the behavior, anatomy, and physiology of bats to unravel the mechanisms behind the animals' enviable acoustic capabilities.

Over the past 30 years, engineers have been drawn into the fray and have tried to mimic the bats' biosonar systems by designing a veritable zoo of "bat robots." Indeed, reproducing the biosonar abilities of bats in a man-made system would do far more than just satisfy a scientist's intellectual curiosity or an engineer's play instinct. Engineers working in the broad area of autonomous systems, in other words, machines that can act by themselves, have long dreamed of taking the capabilities of their creations to new levels, and bats could be just the right model system to accomplish this.

Up to now, the impact of man-made autonomy has been limited to environments that are carefully designed to support this, for example, robots working on manufacturing lines or in warehouses. Semiconstrained environments such as public roads have long been believed to be the logical next step for autonomous systems, with reliable self-driving cars lingering "just around the corner" for many years. However, the fact that the developers of self-driving cars continue to struggle with the lack of predictability in driving conditions speaks volumes as to how difficult advancing autonomous systems away from carefully constrained environments remains.

Being able to mimic the biosonar-based autonomous navigation skills of bats could leapfrog the semiconstrained road environments and open up the final frontier for autonomy: venturing out into complex natural environments that are completely free from any man-made constraints. Hence, autonomous bat robots could one day be used in areas such as precision agriculture and forestry or environmental surveillance and cleanup.

The creation of autonomous systems for the complex natural world is not just a matter of replicating the bats' biosonar; it requires an integration of multiple capabilities, namely for sensing, interpretation, mobility, and control. Two of these areas, mobility and interpretation, are currently being targeted by two powerful technical trends. Our ability to interpret complex signals is being taken to new levels by the ongoing deep-learning revolution that allows finding patterns and relationships in data that were previously completely inaccessible. With respect to mobility, the popularity of small drones ("micro air vehicles") has been driving the developments of new concepts for powered flight. Because the size of many of these drones puts them into a similar aerodynamic range as bats or birds, mimicking the flapping flight of these animals is an attractive proposition.

If the revolutions in deep learning and drone technology deliver on their respective promises, they will give us highly maneuverable and energy-efficient aerial platforms equipped with "brains" that can analyze even the most complicated inputs. In a future world with these technologies, robotic reproductions of the bats' biosonar system could fill a critical gap between these mobility and data analytics capabilities. However, a drone that has the mobility to master complex environments on the wing and the intelligence to make sense out of complex patterns still misses one important function, namely the ability to encode sensory information that can be processed by the deep-learning stage and then can be used to control the mobility of the system. Past and present work on bat robots is an almost perfect fit

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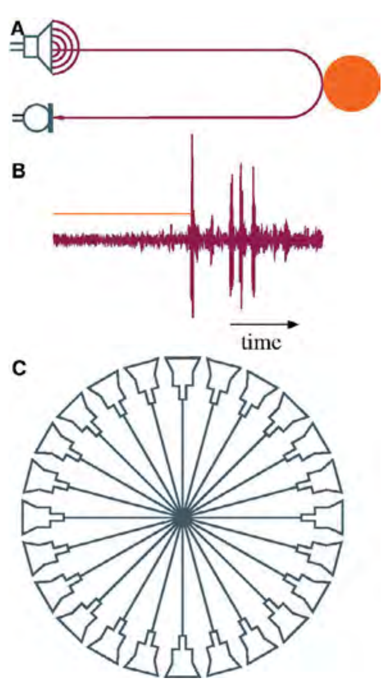
for this niche because the focus of these systems has been to encode useful sensory information about the outside world in the acoustic domain.

In fact, the entire evolution of the bat robots from its very beginnings to the present day can be understood as a sequence of attempts to extract more and more information from the ultrasonic echo wavefields that a (bio)sonar system elicits. In the process of designing ever more sophisticated bat robots, scientists and engineers have hence pushed the boundary of what can be learned from an ultrasonic echo by mimicking more and more sophisticated features found in bat biosonar. In this article, we attempt to trace this "parallel evolution" in robots and acoustic concepts.

Evolutionary Origins: Autofocus Cameras

The oldest "evolutionary ancestor" of all bat robots actually came into being as part of a camera. In the early 1980s, Polaroid introduced an autofocus camera with an ultrasonic ranging module that was designed to determine the distance to a subject (Biber et al., 1980). To accomplish this, the ranging module emits a short burst of ultrasound and extracts a single rather simple feature from the returning echo, namely time of flight. This means that the module measures how long it took the ultrasonic pulse to travel out to the target and back (**Figure 1**). Such a time-of-flight measurement can be readily converted into an estimate of target distance by multiplying with sound velocity. In the Polaroid ranging module, the time of flight is determined by comparing the received echo amplitudes with a threshold value, which is simple but also susceptible to noise.

Figure 1. *Principle of sonar range finding.* ***A:*** *acoustic time of flight encodes the target distance because it can be used to estimate the distance traveled to the target and back.* ***B:*** *amplitude thresholding operation to estimate the time of flight. The received time waveform is compared with a threshold value (orange line).* ***C:*** *schematic representation of a sonar ring with 24 transducers (emitters/receivers).*



Because there are obvious shortcomings to using an ultrasonic range finder for a camera, for example, when taking a picture through a glass screen, camera makers soon moved on to optical systems such as active infrared and passive autofocus. But the ultrasonic range-finding modules they discarded did gain an unexpected second lease on life with mobile robots, where they soon became a standard feature of several commercially available systems.

Dinosaurs: Sonar Rings

Roboticists trying to perform useful tasks with the ranging modules quickly discovered that the readings from the ranging modules cannot only be imprecise but are also prone to grave errors; targets can be missed entirely, especially in cases where a flat surface forms an acoustic mirror that is angled in a way so that it reflects the echo away from the receiver. Narrow gaps between targets can be hard to find if their width is small compared with the sonar beam that is defined as the angle over which an above-threshold ultrasonic energy is emitted (about 30° for a Polaroid range finder).

Even if the targets are correctly detected and resolved and a precise enough distance measurement is obtained, all this is still not sufficient to pin down the location of a target. For any fixed distance, a target could be anywhere on a sphere around the ranging module, with a radius that equals the determined distance. To overcome this shortcoming, roboticists working with sonar range finders have come up with "sonar rings" that combine large numbers (up to 48) of ranging modules that are pointed radially outward to take range measurements in different directions (**Figure 1C**; Fazli and Kleeman, 2005). With their size, the sonar rings ushered in the dinosaur age in the evolution of bat robots.

The sonar rings were used to map out the environment of the robot by associating each reading of the target distance with the direction the respective ranging module was pointed in to fix the location of the target. This approach, however, did little to overcome the many fundamental shortcomings of the sonar range-finding approach outlined above. Because of these difficulties, most robotics engineers abandoned the ultrasonic rangefinders in favor of more powerful techniques such as stereo camera vision or laser range finding (i.e., "light radar" [LIDAR]) as the respective hardware became more widely available and the required computational capacities became more affordable.

Nevertheless, despite improvements to the costs of hardware and especially computing, autonomy solutions based on devices that collect large amounts of data such as laser scanners or stereo cameras remain too costly and too power hungry for applications such as small autonomous drones. If operated under the power and weight constraints of a drone, the processing latencies would be too large to allow for flying through a forest at speed, for example. In this respect, the modalities that replaced the ultrasonic range finders remain stuck in the same evolutionary dead-end road that has led to the extinction of the sonar-ring dinosaurs.

Seeing this situation, some engineers have returned to bats for more insight into how these sensing problems may be solved in a much more elegant and parsimonious fashion. If many millions of bats demonstrate every night that a few grams worth of sensors and computing are sufficient, how difficult could it be for engineers to catch up?

Less Is More: Back to Two Ears

The next step in the evolution of bat robots to lead forward from the ranging modules has focused on smarter ways to combine signals from two receivers. These efforts have been inspired by what bats do with their two ears. Such binaural sensing has been used to improve performance in target tracking as well as in target identification tasks.

The most straightforward way to combine signals from two receivers is to check which receiver detects the input first. This is similar to the use of binaural time differences in many mammals, including humans, — for telling the direction of a sound source on the horizontal plane. A biomimetic sonar system that used this principle in the horizontal as well as in the vertical employed four transducers implemented in horizontal and vertical pairs to track a target in these dimensions (**Figure 2**). This bat robot was not only extremely parsimonious in its layout but also with respect to the computations that were required for its operation. All that was necessary was to determine which sensor in the pair detects an echo first (Kuc, 1993). This nonlinear system operated with minimum delay, which is important for optimal sensorimotor operation because the later echo arriving at the contralateral ear was not used.

Bats and humans have two ears instead of four and hence can use time-of-arrival differences only to determine the direction of a sound source in one direction, typically the horizontal plane. In the vertical plane, comparisons of sound amplitude across different frequencies are typically made to determine the direction from which a sound is coming. Such frequency- and direction-dependent effects are particularly easy to model based on the harmonic structure of bat biosonar pulses where each harmonic produces its own beam with a width that decreases with each harmonic. A binaural tracking simulation (Kuc,

Figure 2. *Bat robot with two pairs of ultrasonic receivers (circular object on each branch of the cross; "ears") that are arranged horizontally and vertically. The transducer in the center is the emitter. Pneumatic tubes (with red caps seen only in the horizontal branches) allow the system to track a target in both of these directions based on the sensory inputs.*

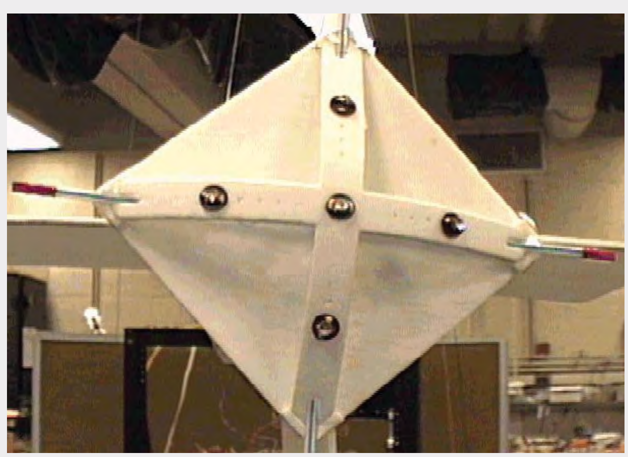


Figure 3. *Gallery of noseleaves and pinnae in different bat species:* ***A:*** *Hildebrandt's horseshoe bat (*Rhinolophus hildebrandtii*).* ***B*** *and* ***C:*** *Schneider's roundleaf bat (*Hipposideros speoris*).* ***D:*** *Trident bat (*Asellia tridens*). All photos courtesy of M. Brock Fenton.*

1994), which can be seen as a virtual bat robot, has shown that two such beams were sufficient for a sensorimotor system to track and capture a flying prey. In this case, one harmonic beam is used to determine the target direction in the horizontal plane and the other in the vertical plane.

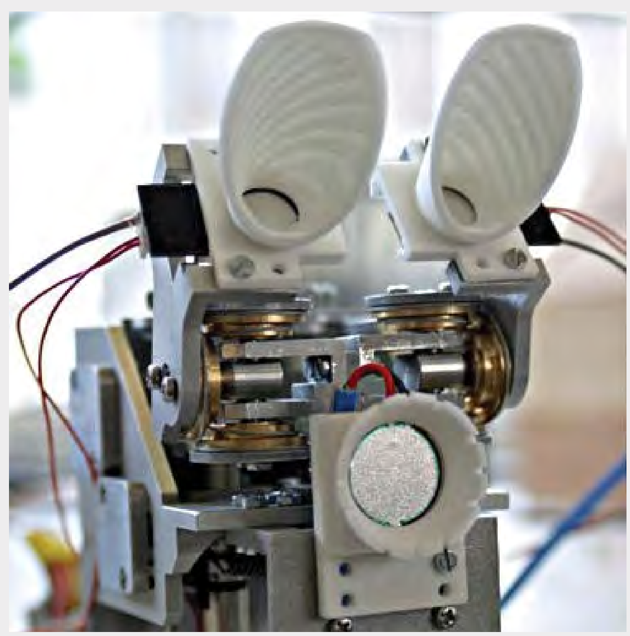
Evolving Beautiful Acoustics from Ugly Faces

When looking at portrait photos from virtually any bat species, it hard to miss that the facial features of the animals are reminiscent of gargoyles and other imaginary creatures from the Gothic period (**Figure 3**). To begin with, the outer ears (pinnae) of almost all bat species are, by human standards, very large compared with the size of the head. Besides their conspicuous size, bat pinnae often feature striking shape details such as combinations of different curvatures, washboard patterns, and flaps along the rim.

Additional Gothic facial features can be found in association with sound emission. Different bat species emit their ultrasonic pulses either through the mouth, like human speech, or through the nostrils. In species with nasal ultrasound emission, the nostrils are surrounded by elaborate emission baffles, so-called noseleaves. Like the pinnae, the noseleaves usually come with a fair amount of geometric complexity. In bats, these features have been shown to result in likewise complex distributions of the pinna's sensitivity over direction and frequency (i.e., beam pattern). Attempts to replicate some of this complexity have been made either using highly simplified versions of the biological shapes (**Figure 4**; Müller and Hallam, 2004; Pannala et al. 2013) or by creating physical replicas of actual bat noseleaves or pinnae based on digitized specimens (Caspers and Müller, 2018).

These developments have not only led to systems that can be readily recognized as bat robots but have also demonstrated that shape detail in the noseleaves (Gupta et al., 2015) and pinnae (Müller et al., 2008) create useful acoustic properties. For example, a ridge on the inner pinna surface of a certain bat species was found to create a fan of frequency-dependent sidelobes of the biosonar

Figure 4. *Early attempt at fitting a bat robot with a biomimetic noseleaf and pinnae. All shapes were highly simplified and placed around large transducers, which failed to yield effects because the diffracting surfaces did not receive much sound energy.*



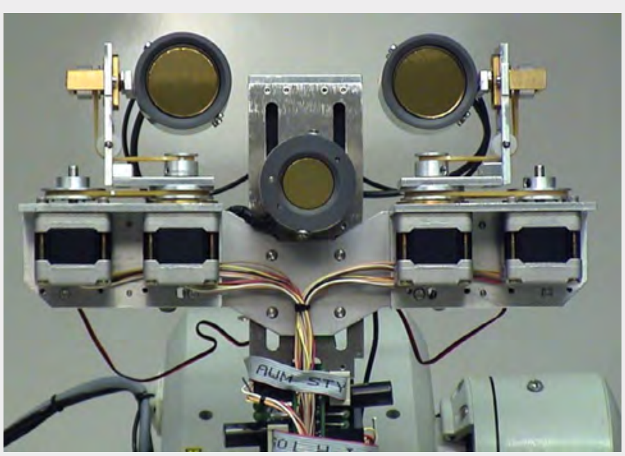
beam that are well suited for encoding the direction of a target by virtue of simple dependence between target direction and the signal frequency with the most signal energy (Müller et al., 2008).

Evolution Setting Ears in Motion

As if the shapes of the noseleaves and pinnae of bats were not complicated enough already, many bat species also have the ability to move these structures under muscular actuation. This insight from the biology of bats has triggered a next stage in the evolution of bat robots where the robots started to not only look like bats but also to have some of the animals' noseleaf and pinna mobility.

The first bat robots with this kind of dynamics were able to carry out rigid pinnae rotations where the robots could change the orientation of their pinnae (**Figure 5**). The geometries and hence also the acoustic properties of the pinnae did not change during the reorientation; they were just orientated in a different way in the surrounding space. Such rigid rotations of the pinna can be used to determine the direction of a target. For example, by monitoring the received echo amplitudes across a rotational sweep, it is possible to determine which direction a target is in. One just needs to take note of the pinna orientation at which the maximum echo amplitude occurs, which should coincide with the direction of the target (Walker et al., 1998).

Figure 5. *Bat robot with two rotational degrees of freedom for each receiver (ears;* ***top****). Rotation torques are transmitted to each receiver via a belt-and-pulley system to keep the rotating mass low. The stepper motors driving the ear motions are mounted below.*



Rigid motions of a biomimetic sonar can consist of rotations as well as translations (**Figure 6A**), and their use is not limited to determining the direction of a target. Another important application is identification of a target. If the echoes returned from different targets differ only in very subtle ways, a special effort is necessary to bring these small distinguishing features to the fore. This can be expected to be true in the sensory worlds of bats that hunt their prey amid dense vegetation.

An example from the sensory world of bat robots can be found in the classification of the head and tail sides of a coin (Kuc, 1997). The relief of a coin is just a fraction of a millimeter thick, whereas the ultrasonic wavelengths typically used by bat robots are several millimeters long. Hence telling heads and tails of a coin poses a daunting task to any bat robot. Mobility of a bat robot mounted on the end of a robot arm with five degrees of freedom that included ear rotations (**Figure 6B**) has been used to enhance the signal-to-noise ratio by positioning the target coin in the center of the beam. Furthermore, positional errors could be taken into account by virtue of a set of echo templates that were formed by scanning a target in elevation.

The Rise of the Soft Robots

The things that real bats can do with their noseleaves and pinnae go far beyond the rigid rotations that have been mimicked by the bat robots of the 1990s and early 2000s. Bat species with sophisticated biosonar systems such as the horseshoe bats (family Rhinolophidae) and the closely related Old World roundleaf bats (family Hipposideridae) also have elaborate musculatures on their noseleaves and pinna.

For example, a single pinna in a horseshoe bat contains slightly more than 20 muscles (Schneider and Möhres, 1960). Furthermore, many of these muscles are arranged in a way such that muscular contraction causes a change in the pinna shape. It should also be noted that these shape changes happen very fast. For example, the pinna of a greater horseshoe bat (*Rhinolophus ferrumequinum*) has been found to transition from one extreme shape configuration to the other in about one-tenth of a second. A human blink of an eye takes three times as long.

What has driven the evolution of bat pinnae to such extremes in intricacy and speed? Because the pinna is in charge of diffracting incoming sound toward the entrance

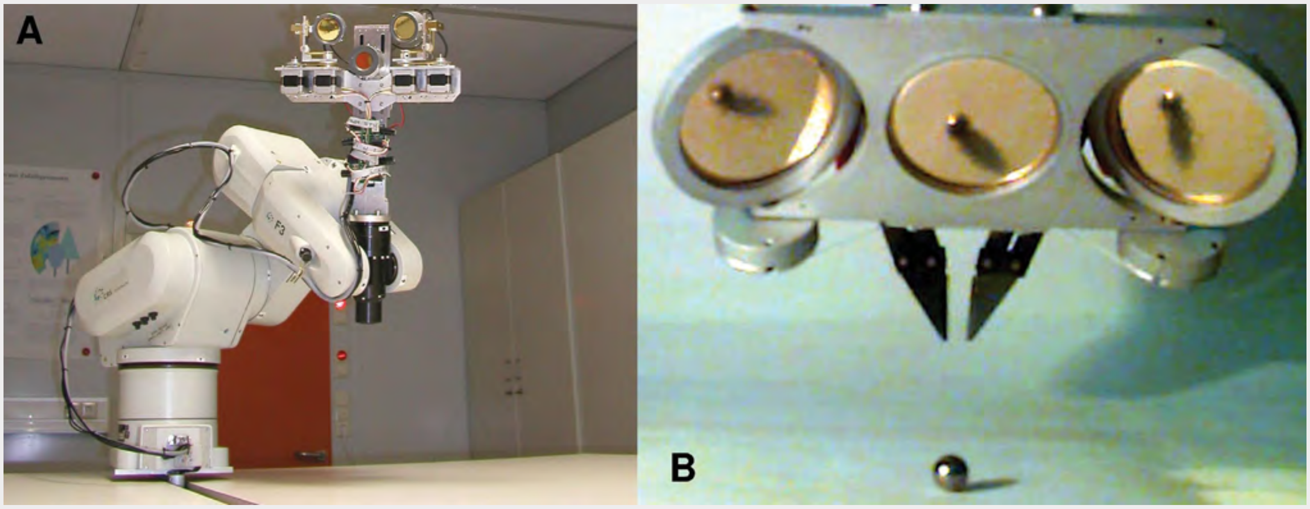


Figure 6. *Different forms of mobility in bat robots:* ***A:*** *bat robot mounted on a six degree of freedom humanoid robot arm that is capable of translating and rotating the entire bat robot;* ***B:*** *bat robot that can track targets by comparing inputs received from a pair of microphones and can rotate the ears as well as translate the entire head. The target (ball bearing) can be seen in reflections by the emitter (****center****) and the two receivers (on the side).*

of the ear canal, its geometry is of critical importance in determining some of the ear's acoustic properties. In general, sound diffraction by a surface is determined by the geometry of the surface, its size relative to the sound wavelength involved, and the material. Hence changing the shape will change the properties of the diffraction process. The diffraction process at the pinna determines how sensitive the bat is for sound from any given direction at any given frequency.

The task of reproducing the deformations seen in bat noseleaves or pinnae poses a worthy challenge for the emerging field of soft robotics, where researchers try to build robots using materials that mimic the compliant nature of biological tissues. It is pretty straightforward to create a flexible noseleaf or pinna shape modeled on the geometry of bats from a silicone material, for example.

The tricky parts are getting the shape to deform like a bat ear and controlling the motion. Packing the equivalent of more than 20 muscles onto a small pinna shape is not an easy task given the state of the art in soft robotics. In particular, fitting 20 tiny motors on a structure the size of a bat noseleaf (typically 1 to 2 cm tall) or pinna (typically 1 to 5 cm tall) remains a daunting task. It is possible to provide a bit relief by increasing the size of the noseleaves and pinnae somewhat over what is found in bats as long as the used frequencies are scaled down simultaneously so that the ratio of structure size and wavelength stays the same. However, this approach has its limits because the environment/sonar targets would also have to be scaled to replicate the context of bat biosonar and hence retain the opportunity to discover or leverage functional principles from the bats.

Early attempts to reproduce the deformations in bat noseleaves and pinnae with a soft robot (**Figure 7**; Pannala et al., 2013; Caspers and Müller, 2018) have avoided the problem of integrating actuators altogether. Instead, an external motor was connected to the noseleaf or pinna with a lever to insert a point force into the structure. In this approach, the deformation pattern is determined by the geometry and material of the structure as well as by the insertion point for the force. Once the system design covering these parameters is in place, the noseleaf or pinna can only carry out a single deformation pattern that can only be varied in terms of speed and amplitude. Nevertheless, the research carried out with these (severely limited) systems has been able to demonstrate that changes in the geometry of noseleaves and pinnae that occur during the sound diffraction process can encode additional sensory information that is useful to standard sonar tasks such as estimating the direction of a target (Müller et al., 2017).

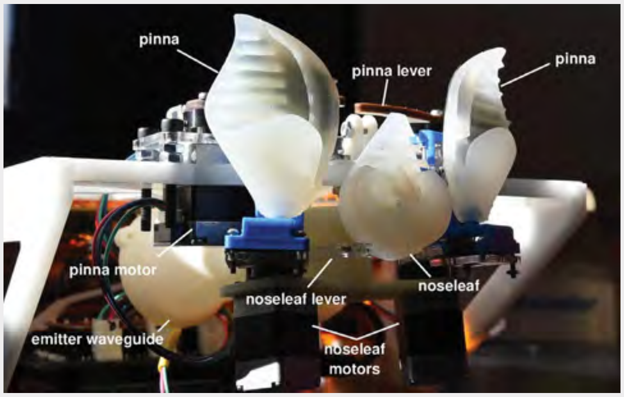


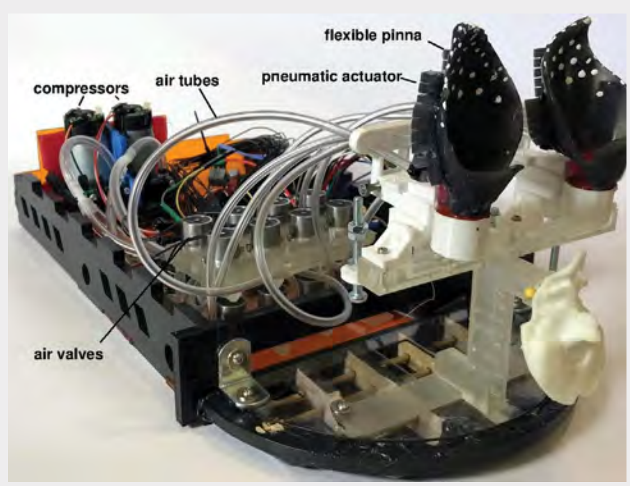
Figure 7. *Early soft-robotic bat robot with single-point lever actuation for flexible (silicone) noseleaf and pinnae.*

Behavioral studies in horseshoe and hipposiderid bats (Yin et al., 2017; Qiu and Müller, 2020) have demonstrated that these animals have far greater variability in their ear motions than what could be accomplished with single-point actuation. Hence, the next generation of soft-robotic bats has been designed to integrate actuators into its noseleaves and pinnae (**Figure 8**; Eckman et al., 2019). One way to accomplish this is to use small pneumatic actuators in the shape of small "sausages" that can made from the same flexible materials as the ears (e.g., silicone) and can be filled with pressured air (Sullivan et al., 2019). If one side of the actuator is attached to the surface of the pinna while the other is left unattached, the result will be an asymmetrical stiffness. For example, the side of the actuator that is attached to the pinna is stiffer than the unattached side. With this arrangement, filling the actuator with air will produce a bending motion to deform the attached pinna. In systems designed this way, two actuators have been attached to the noseleaf, one to actuate the tip ("lancet") and the other to actuate a semicircular baffle around the nostrils ("anterior leaf"). Flexible biomimetic pinnae have been outfitted with up to four pneumatic actuators to support different deformation patterns (Eckman et al., 2019).

Evolving Beyond Linear Systems

Describing the acoustical effects of static noseleaves and pinna shapes on the spatial sensitivity of the bats' biosonar systems as outlined in **Evolving Beautiful Acoustics from Ugly Faces** can be accomplished by simple linear systems theory, for example, by virtue of a set of transfer functions (i.e., amplitude as a function of frequency) that also depend on direction. If the noseleaf or pinna deforms, the transfer functions describing the system become time variant. This means that these functions become dependent not only on frequency but also on time, with the latter dependence reflecting the deformation of the physical structure (Meymand et al., 2013). As if this time-variant nature of the bat's biosonar periphery was not complicated enough already, there are also nonlinear effects to consider. Some bat species have been shown to move their pinnae so fast that the incoming echoes are subject to a Doppler shift on diffraction by the surface of the moving pinna (Yin and Müller, 2019). Bat robots with fast moving pinnae have since been able to create Doppler shifts as well (Yin and Müller, 2019). Whereas research on whether bats actually perceive and use the Doppler shifts created by their own pinnae has yet to be carried out, the bat robots are already ahead of their flesh-and-blood cousins. Thus, using a robotic replica of a fast-moving bat pinna, it has been possible to demonstrate that these motions create Doppler signatures that enter the ear canal and carry useful information on the direction of an incoming sound (Yin and Müller, 2019). Through these findings, observation of the bats' behavior has advanced technological evolution to a novel, nonlinear principle for telling the direction of a sound source. In return, the evolution of bat robots has generated a new hypothesis for how bats may use the Doppler shifts created by their pinna motions.

Figure 8. *Soft-robotic bat robot with pneumatic actuation consisting of air compressors, control valves, soft actuators ("pneu-nets"), and flexible pinnae.*



Future Challenges

Despite decades of hard work, it still appears as if research on the biosonar system of bats has only scratched the surface. Many critical aspects of how bat biosonar functions in the animal's complex natural environments remain, literally, shrouded in darkness. However, ever-improving recording and data-analytics technologies are likely to not only keep the flow of new insights from bat biosonar going but also to accelerate it. Based on this increasing flow of information, the future evolution of bat robots is likely to make a multitude of improvements to all aspects of biomimetic sonar function.

In the course of bat robot evolution so far, the encoding of sensory information has received the most attention. With the ongoing deep-learning revolution, there is hope that the information extraction stages of the bat robots will be able to undergo a rapid evolution in coming years.

However, neglecting the encoding stage in this endeavor could quickly lead down an evolutionary dead-end road. This is because encoding of sensory information is a necessary precondition for being able to extract it. If this is taken into account, the future evolution of bat robots could lead to more sophisticated approaches to tackle the problems of encoding and extracting sensory information jointly instead of one at a time. This would be just one example of system-level integration where approaches designed to make a bat robot be more than the sum of its parts. Other examples for this can be found in the coordination of noseleaf and pinna motions where bats are known to have a tight coupling between the dynamics of the emission and reception interfaces (Zhang et al., 2019). With regard to all of these and many other aspects, research on bat biosonar continues to produce new and unexpected insights that are likely to fuel the evolution of bat robots for decades to come. If the insights from bat biosonar can be transitioned to engineering successfully, the pinnacle of the evolution of bat robots could be an autonomous drone that flies effortlessly through a dense forest just like many millions of bats have done every night for the many millions of years in their evolution.

Acknowledgments

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