Division of Informatics, University of Edinburgh

Institute of Perception, Action and Behaviour

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Keywords :

Towards an artificial pinna for a narrow-band biomimetic sonarhead

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Abstract. A genetic algorithm was used to evolve bat-like pinna shapes for a biomimetic sonarhead. Pinnae model consisted of small reflectors placed around the transducer. Experiments with ten reflectors showed the problem of phase cancellation in the received echoes. Analysis of phase cancellation suggests more realistic pinna models for future developments.

1 Introduction

Bats are very dynamic creatures; while flying they move their wings, head, pinnae and the nose or mouth whenever they emit. They can be divided into two broad non-taxonomic groups: broadband echolocators, or fm-bats, such as *Myotis lucifuqus*, whose cry consists of a frequency-swept from around 30-90 kHz; and narrowband echolocators, or cf-bats, who emit a call where about all the energy is in a single tone (for example 83 kHz for the *Rhinolophus ferrumequinum*).

Narrowband echolocators use pinna[1] motion to alter the directional sensitivity of their perceptual whereas broadband listening systems (*e.g.* humans and broadband emitting bats) rely on pinna *morphology* to alter acoustic directionality at different frequencies [9]. The importance of pinna motion along vertical arcs in the cf-bat for target localization in the vertical plane has been investigated with real bats [1, 2, 7]. The use of this motion might be the reason that the *Rhinolophus ferrumequinum* has unusually large pinnae compared to the size of its head as can be seen in figure 1.

The relationship between bats and robots arises because the sensor interpretation problems of bats while navigating in cluttered environments such as forests are very similar to those of mobile robots provided with ultrasonic sensors when navigating in laboratories. Moreover, the constant frequency pulse emitted by the cf-bat when echolocating is analogous to the one emitted by robotic ultrasonic sensors in terms of bandwidth. For their experiments, Walker *et al.* [9] used a robotic model composed of a 6 degree of freedom biomimetic sonarhead (figure

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[1] The complex convoluted external ear.

Fig. 1. *Rhinolophus ferrumequinum* (Photos from [3]).

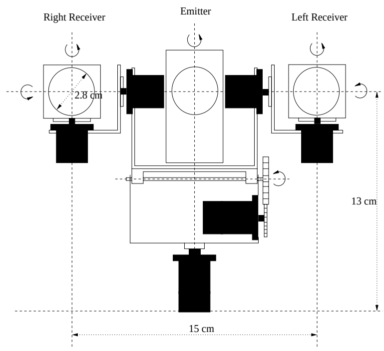


Fig. 2. Diagram of the biomimetic sonarhead.

2) mounted on a mobile robot [5]. In our work we are interested in integrating the cf-bat's sensorimotor system for obstacle avoidance in this robotic model (exploiting the physical capabilities of the sonarhead), as a biological approach to ultrasonic-based navigation in mobile robots.

Thus, as part of our working plan, we want to improve the directional sensitivity of the sonarhead's receivers (*i.e.* maximise the angular resolution of the receiving transducers) by adding artificial pinnae to them. Because of the difficulty of designing a pinna model by an analytical approach, an evolutionary approach consisting of a GA together with a software model of the sonarhead [8], in which to evaluate the evolved solutions, is used instead. Our work continues that of Papadopoulos, and of Peremans *et al.* [4, 6], who used genetic algorithms to evolve simple pinna shapes for broadband echolocators.

1.1 Narrow-band 3D target localisation

It is quite interesting to see the way in which echolocators with narrow-band call structures perform target localisation. In the case of the cf-bat, this localisation is performed mostly using the information contained in a single harmonic echo. In order to calculate the target's azimuth angle with a receiver placed on each side of the head (as in bats), interaural intensity differences (IIDs) as well as interaural time differences (ITDs) can be employed.

However, how can the elevation angle be estimated? Experiments with the biomimetic sonarhead [9] showed how, by sweeping a pair of receivers through opposite vertical arcs (figure 3), dynamic cues, in the form of amplitude modulations which vary systematically with target elevation, are created (figure 4). Thus, by this arc scanning, a delay-per-degree transformation is created.

This, combined with the azimuth angle estimation by means of IIDs and the target's range by the echo delay, provides a narrow-band echolocator with a 3D estimation of an insonified target's relative position.

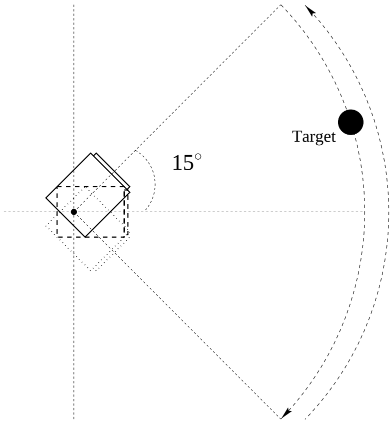


Fig. 3. Side view of sonarhead's receiver performing vertical arcs for elevation angle estimation.

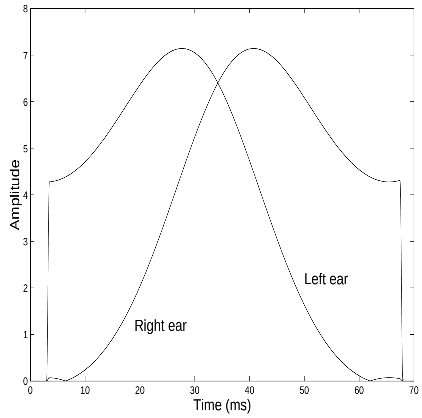


Fig. 4. Delay between amplitude peaks encodes target elevation (target elevation at 6 deg.).

2 Artificial pinnae

2.1 Previous work

Previous work in evolving pinna morphology [4, 6] focussed on broadband echolocators. The pinna was modelled by up to three disc reflectors whose position and orientation angle around the receiving transducer were determined by a genetic algorithm (GA), obtaining a chromosome with the following structure,

$$(x_1\ y_1\ z_1\ \alpha_1\ \beta_1 \quad x_2\ y_2\ z_2\ \alpha_2\ \beta_2 \quad \ldots \quad x_n\ y_n\ z_n\ \alpha_n\ \beta_n)$$

where x,y and z are cartesian position coordinates and α, β are azimuth and elevation angles. The GA comprised a population of candidate sets of reflector positions, whose fitness was determined by simulating their effect on the acoustic signals transduced by the receiver. *2-point* crossover and a mutation rate of 0.03 were used with a population of 100. A tournament selection scheme wherein a set of genomes is randomly selected from the population was used. The fittest genome was selected with a given probability; if it is not selected, then the second best is selected with the same probability, and so on. Experiments were run for 1000 generations [6].

The GA in [4, 6] was set for two tasks: first, to deploy reflectors in a monaural system so as to maximise the displacement between the axes of maximal sensitivity at 30 kHz and 90 kHz (thereby allowing target elevation to be most accurately inferred from the different amplitudes of the echo at these frequencies); and second, to deploy reflectors in a binaural system to produce a maximally steep IID curve with respect to target angular position (thereby maximising the angular resolution of the binaural system and allowing the target's position to be most accurately estimated from the IID). In the binaural case, the left ear was symmetrical with the right ear, i.e. the two pinna configurations were derived from the single disposition of reflectors indicated by the GA.

The results for the first experiment were reasonable, but for the second experiment no significant improvement of the IID performance could be obtained with up to three reflectors. We therefore began (see section 2.3) by repeating the IID experiment from [6], then changing the model to the narrowband (cf-bat) case, in each case allowing up to 10 reflectors to be used by the GA.

2.2 Model considerations

In this work we use similar model considerations as [6], that is: disc-shaped specular reflectors are used to modify the directionality characteristics of a dynamic binaural echolocation system. The differences with respect to [6] are the consideration of sound losses in the reflectors due to absorption, instead of considering perfect reflection, and the way in which we calculated the phase cancellation phenomena. We assumed an absorption rate of the reflectors of 20% of the incident sound. Phase cancellation among different echos from the reflectors when arriving at the transducer is also considered.

As in [6], the diffraction and diffusion phenomena around the edges of the reflector discs are considered insignificant. Also, no multiple reflections are taken into account, *i.e.* each reflector introduces one additional echo path. The reflectors' radii are constant and equal to that of the receiver. The reflector orientation angles vary between -90 and +90 degrees with a resolution of 2 degrees.

2.3 Results

The first step consisted of the repetition of the experiments reported in [6]. Figure 5 shows the directivity differences between a bare transducer and a transducer with 3 reflectors, and IID changes at various elevation angles. These results matched with the results reported in [6] so we decided to continue scaling up the model for more reflectors.

3 The evolutionary approach

Our goal is to evolve a reflector formation around the transducers for a desirable pinna shape for improving IID and arc scanning behaviours. The reason for taking this reflector approach instead of a more complex one, such as surface formation, is because of the extensive computational time the latter would take.

3.1 Methods

Two different methods were considered, a signal based method and a region coverage method, the latter being the chosen one because of its smaller processing time.

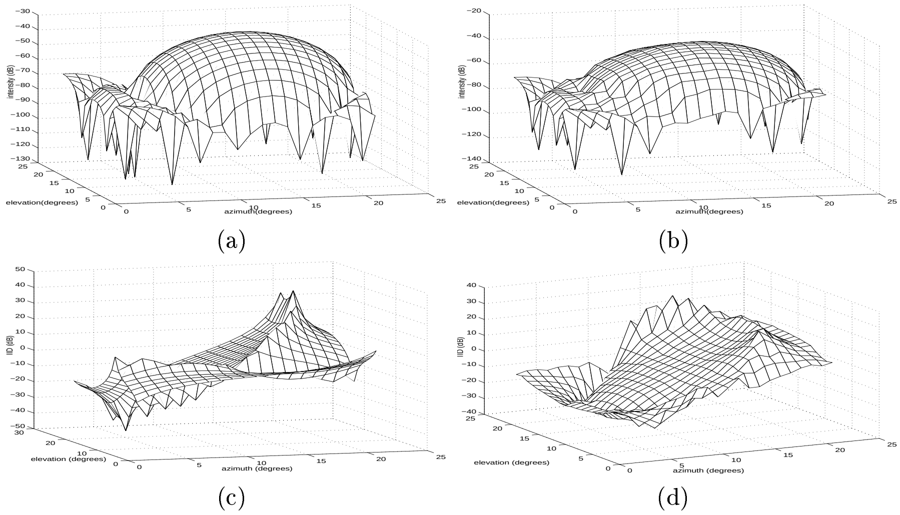


Fig. 5. Comparison between bare transducer and transducer with reflectors (a) directivity with bare transducer (b) directivity with reflectors (c) IID with bare transducer (d) IID with reflectors

Signal based method This method is based on the one used in [6] for IID behaviour. In our case, because of the arc scanning behaviour, we were seeking a high amplitude-modulated signal with sharp peaks for a better delay-per-degree estimation. For that purpose, a fitness function $F = A/\sigma$, where A is the maximum amplitude value during the arc scanning and σ is the standard deviation of the time-varying amplitude along time during the arc scanning, was used. This fitness function would possibly guarantee clarity of target position. The method was finally rejected because of the high amount of computational time required.

Region coverage method This is based on the following assumption: having an ear morphology whose left ear focuses on the left side of the target's position along azimuth angle and the right ear on the right side, a broader range of IIDs can be obtained. In this method we also sought to evolve a reflector formation for both a good IID range and arc scanning. For the IID case, targets at every azimuth and elevation angle were considered while for the arc scanning case we only considered *slices* of the vertical plane, *i.e.* all elevation positions for a fixed azimuth.

3.2 Fitness function

The fitness function aimed to combine the covered region method with the phase cancellation constraint, thus no reflector should be positioned in a location where, from any of the possible target positions, phase cancellation happens.

Based on this criterion, our fitness function was defined as

$$L = \alpha \mid \sum_{k=0}^{N} e^{-i(wt+\theta_k)} \mid + \beta(\sum_{i=1}^{N}\sum_{k=1}^{M} r_{ik})$$

where N is the number of reflectors, M is the target position, θ_k is the phase of the wave coming from reflector k and r_{ik} is set to 1 if the i-th reflector can reflect the left-sided target k on the left transducer (otherwise it is set to 0). This will allow the reflectors around one transducer to focus on the side of it. As a result, it should improve IID range by increasing the echo intensity of one ear with respect to the other.

3.3 Results

When using the above fitness function, results for IID using 10 reflectors were very little improved from those in [6]. In figure 6, a reflector distribution around the transducer (a) and the region covered by these reflectors (b) is shown.

As can be seen, the middle part of the IID profiles, *i.e.* the part related to the main lobe of the transducer directivity, is quite similar to the bare transducer and to the 3 reflector case (figure 6(c)) in terms of steepness and linearity and therefore there is no improvement. However, there is a small improvement in the side lobe parts of the IID profile, for a target at 2 deg. elevation angle, in the form of smoothness of the peaks of such side lobes. A smoother performance along these lobes (*i.e.* removing the peaks) offers an improvement of the angular range along the horizontal plane. Arc scanning behaviour with this reflector configuration (d) performs fairly well, that is, there is some distortion in the wave peaks (continuous line) which is the significant part for arc scanning, but this could be resolved by a suitable curve-fitting process, *e.g.* using the bare transducer curve (dotted line).

When evolving a reflector configuration for arc scanning behaviour (figure 7), results are slightly more satisfactory than in figure 6(d)). In figure 7(b), there is an improvement in amplitude (continuous line), despite some distortion at the middle part of the scan, compared with bare transducer (dotted line).

From this results, it is clear that there are no big improvements in a 10 reflector configuration with respect to [6]. In order to investigate the reasons for this performance we analysed the simplest reflector case, as seen next.

4 Phase matters

The reason there is no big improvement in performance is the effect that phase cancellation produces in the final wave. Because of the difficulty of finding an optimal position for all the reflectors in all the target possible positions, final performance does not significantly improve with respect to a bare transducer configuration, as the analysis below suggests.

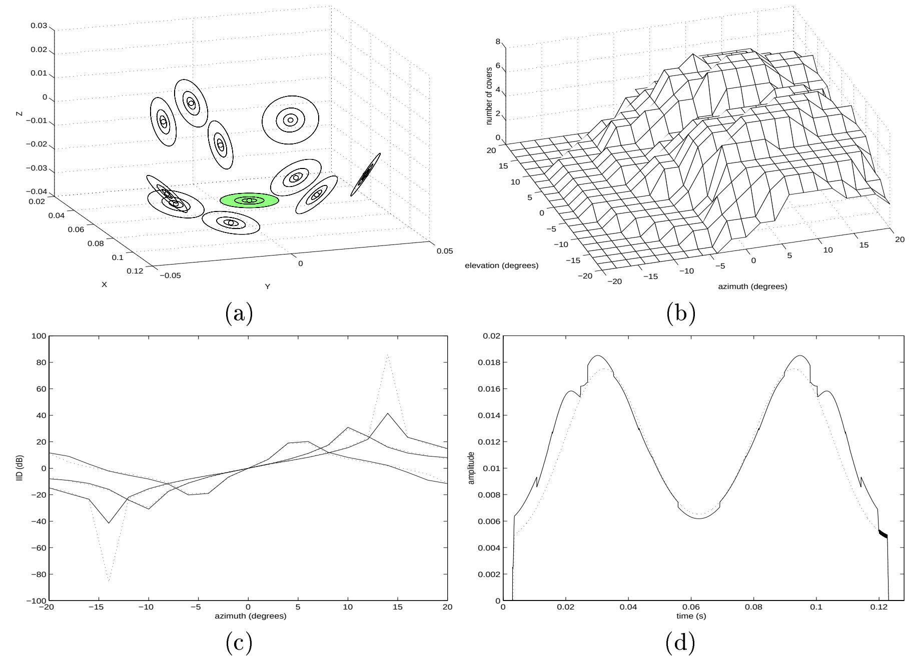


Fig. 6. IID results: (a) reflector formation (b) region covered by reflectors (c) IID at elevation 2, 13, and 18 degrees (d) arc scanning at azimuth 0 degree (dotted: bare transducer; solid: transducer with reflectors).

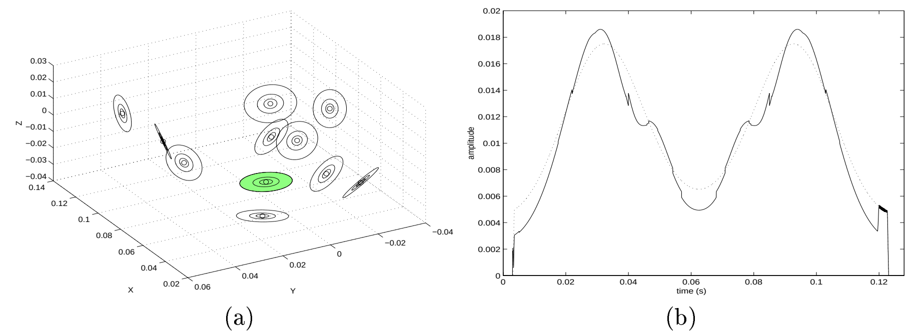


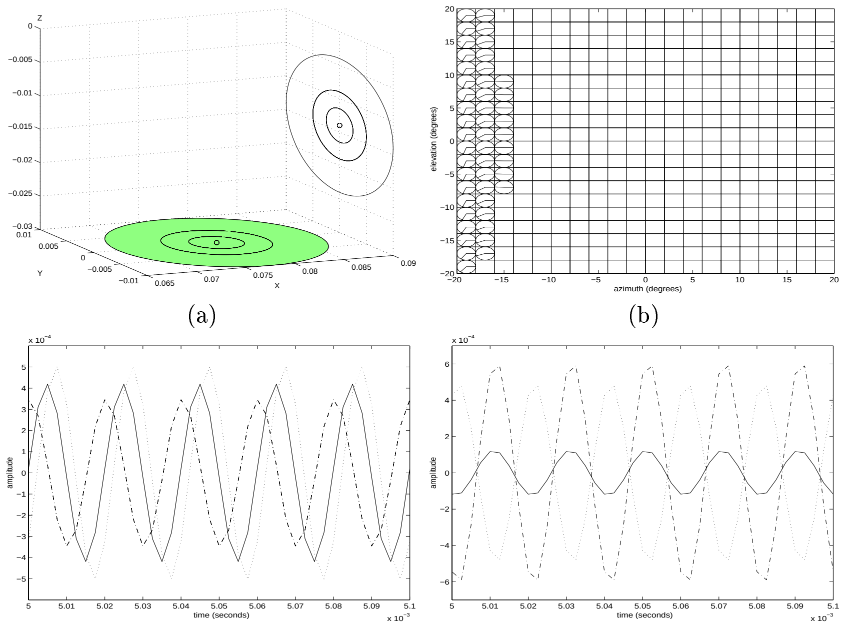
Fig. 7. Arc scanning results: (a) reflector formation (b) arc scanning at azimuth 0 degree (dotted: bare transducer; solid: transducer with reflectors).

For investigating the effect of phase cancellation, we used a single reflector configuration and then we scaled it up to three reflectors. In both cases, the transducers were considered static, *i.e.* no arc scanning behaviour was considered.

4.1 Simplest case: one reflector

A static transducer with a fixed reflector was evaluated for all the possible target positions, that is, an array of 21×21 positions representing a range of -20 to $+20$ degrees in both horizontal and vertical planes (the sonarhead's resolution is 2 deg.).

As seen in figure 8(a), the reflector is positioned beside the transducer on the right ear. The reflector can be effective only in target positions at azimuth angle ranging from -20 to -14. Figure 8(b) shows the region covered by this reflector; each cell shows a phase diagram of how much signal of the reflector's echo is phase-shifted from the transducers's direct echo signal. The reflected signal is about 235 degree phase-shifted at -20 degrees in azimuth and -18 degrees in elevation (c), and about 180 degrees at -16 degrees in azimuth and -6 degrees in elevation (d). The net effect of the signals into the transducer is the superposition of all the incoming signals and we can see the result of echo interference.



(a) (b) (c) (d)

Fig. 8. Phase effects for 1 reflector: (a) reflector formation (b) cover region and phase shift (c) echo signals at azimuth -20, elevation -18 (d) echo signals at azimuth -16, elevation -6 (dotted: transducer; dashed: reflector; solid: superposition of signals).

4.2 Three reflectors case

In this case a three reflection configuration was used (figure 9(a)). The regions coverage of each reflector (b), are located on the right side as expected. The echo interference becomes more complex when we have more reflectors. As a matter of fact, echo interference occurs with a large number of signals from any surface around the transducer position. In some cases the net echo signal is overwhelmed by the direct signal to the transducer (d), and in other cases the reflected signals greatly influence the net echo becoming unpredictable for a target position. Thus, it is not possible to focus on all target positions with a good reflector formation. Even a slight movement of target position makes a phase shift signal for one reflector as in 8(b). This results in our objective being a very difficult problem to solve with a genetic algorithm.

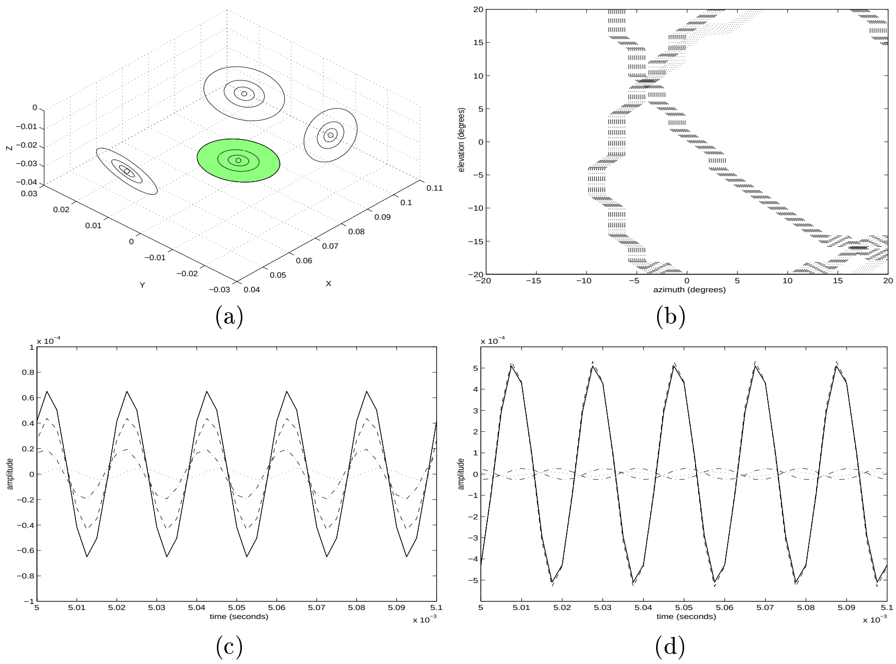


Fig. 9. Phase effects for 3 reflectors (a) reflector formation (b) contour of cover region (c) echo signals at azimuth -2, elevation -20 (d) echo signals at azimuth 20, elevation 14 (dash: transducer; dashdot: reflector 1 and 3; dot: reflector 2; solid: superposition of signals).

5 Discussion and further work

This work aimed to improve the results obtained in [6] in which artificial pinnae in the form of three reflectors were attached to a biomimetic sonarhead. The goal was to improve on that work for IID behaviour and arc scanning. Using a GA similar to [6], a region coverage method was used to evolve pinna shapes of up to ten reflectors. From the results obtained, we realised that increasing the number of reflectors from three to ten does not improve performance enough, because of the adverse effect of multipath *phase cancellation* phenomena. Experiments with one and three reflector models showed how the effect of phase cancellation for a fixed reflector configuration varies for different target positions. Our conclusion from these results is that we were using too simple a model of the pinnae, *i.e.* using small reflectors instead of surfaces. Hence, to evolve an optimal reflector configuration which will improve performance for every target position using this simple model seems to be a very difficult task.

This suggests that a more realistic model of the bat's pinna would be a fruitful avenue to explore. However, the problem with a more realistic surface-based model is the substantial increase in parameters required and hence in the space to be searched by the GA.

At this point, we propose as further work to investigate good compromises for the tradeoff mentioned above. As an example, we propose to use parabolic surfaces in which many small reflectors would be placed around the focus point. Because of the inherent properties of the parabola equation, all the reflections will direct to the focus, *i.e.* the transducer. Also, from the intersection of different parabolic surfaces we might obtain better results.

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