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Modelling simultaneous echo waveform reconstruction and localization in bats

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ABSTRACT

Echolocating bats perceive the world through sound signals reflecting from the objects around them. In these signals, information is contained about reflector location and reflector identity. Bats are able to extract and separate the cues for location from those that carry identification information. We propose a model based on Wiener deconvolution that also performs this separation for a virtual system mimicking the echolocation system of the lesser spearnosed bat, *Phyllostomus discolor*. In particular, the model simultaneously reconstructs the reflected echo signal and localizes the reflector from which the echo originates. The proposed technique is based on a model that performs a similar task based on information from the frog's lateral line system. We show that direct application of the frog model to the bat sonar system is not feasible. However, we suggest a technique that does apply to the bat biosonar and indicate its performance in the presence of noise.

1. Introduction

Bats of the suborder *Microchiroptera*, which are small and often insectivorous, use echolocation to navigate their environment and to localize and identify prey (Nowak, 1994; Griffin, 1974). These tasks are accomplished by classifying incoming echoes using information gained from the way the call is filtered.

On one hand, the call is filtered by the reflector. Several delayed and possibly attenuated versions of the call are likely to be superimposed in this filter step. As a consequence spectral peaks and notches are introduced. Such a peak and notch pattern is related to the object that brings it about, and Habersetzer and Vogler (1983) showed that those spectral cues are used by bats to classify targets. On the other hand, the sound is transformed by the head related transfer function (HRTF). This function describes the directional properties of the bat's hearing system. Due to reflections and diffractions of the sound on the bat's head and its external ears, interference patterns emerge. These patterns introduce spectral peaks and notches into the spectrum of the incoming sound as well. For mammals in general (Butler and Belendiuk, 1977; Asano et al., 1990; Huang and May, 1996), and bats in particular (Wotton and Simmons, 2000; Aytekin et al., 2004), these cues have been shown to be essential in the localization of sound origin.

As cues need to be extracted from the incoming sound for both filtering processes, it is important that the peaks and notches introduced by the reflector do not obscure the ones introduced by the HRTF, and vice versa.

In essence, the spectral features appearing in the echo characterize the impulse responses of the reflector and the external ear. As of yet, it is not known whether the impulse response of the reflector is reconstructed in the bat's brain for identification, or if bats only extract specific cues from the echo. In this paper, however, we do try to reconstruct the impulse response. The rationale behind this is that we want to assess whether or not directional cues can be separated from the cues used for identification. By assuring that signal reconstruction is possible, all information about target identity is maintained, including all possible cues for classification.

In sum, the objective of this paper is to construct a model that can estimate and localize a signal simultaneously. This involves three tasks: ranging, direction estimation, and signal reconstruction. Extracting range information can be done in echolocation by measuring the delay between the call and the arriving echo. Getting a direction estimate for the object is by far less trivial, as is having to estimate the impulse response of the reflector. These two tasks are tackled by the model presented in this paper.

Several publications solely model the localization capability of the bat's echolocation system. They do not consider reflector identification or signal reconstruction. The theoretical analysis by Altes (1978) is a standard work covering localization with biosonar. Practical implementations that localize reflectors can be found in Matsuo et al. (2001); Abdalla and Horiuchi (2008); Walker et al. (1998); Reijniers and Peremans (2007). Few publications exist on implementations of bat models that simultaneously localize and estimate the incoming signal, and hence, the impulse response of the reflector. Fontaine and Peremans (2009) used a sparse encoding technique, and obtained reliable localization and estimation results if the sparsity constraint is valid.

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In signal processing, extracting a signal from a filtered version that is subject to noise is generally known as deconvolution. A deconvolution technique often used is Wiener deconvolution (Kay, 1993). This technique ensures optimal signal reconstruction in a minimum mean squares sense, given that the original signal and the noise are independent from each other and that their spectral properties are approximately known, and provided that the impulse response of the forward filter is known too. When a signal needs to be reconstructed after unknown filtering is applied, blind deconvolution techniques, such as expectation maximization, can be applied. A probabilistic model of the environment is essential, however, for successful application of blind deconvolution.

In our problem we would know the impulse response of the forward filters, if the location of the reflector were known. In that case, applying Wiener deconvolution would be straightforward. The location, however, is not known, so we need to estimate both the location and the original signal. In Franosch et al. (2003), however, Wiener deconvolution was shown to be useful for blind deconvolution based on array beamforming. In this paper, we investigate whether the model as put forward in that publication can be used for localization with a two element array having the directional properties of a bat.

The paper is organized as follows. First, we elaborate on the characteristics of the echolocation process and the bat's echolocation system. Then, we show how direct application of the model outlined in Franosch et al. (2003) to bat biosonar fails. Next, we show that a modified version of binaural Wiener deconvolution can be used for localization and identification and explore the limits of this approach. We conclude with a brief discussion.

2. The Bat Echolocation System

Microchiropterae can make use of two localization modes: active echolocation and passive sound localization. In active echolocation, bats vocalize and listen to reflections from prey, predators and obstacles. In passive sound localization, the bats do not produce any sound themselves, but localize using prey-generated sounds. Since active echolocation is predominant in most microchiropterae's daily life, in this paper we restrict ourselves to analysing this mode. Nevertheless, most of the arguments we put forward are sufficiently general to be extended to the passive sound localization mode.

Another bifurcation exists when only considering active echolocation. Some bats, the so-called CF/FM-bats, use a long constant frequency call, with possibly short frequency modulated sweeps at the beginning and end of the call. FM-bats, on the other hand, use a broadband chirp as their call. As a broadband signal is essential to localize and identify objects using spectral cues, this paper only applies to the FM-bats.

In order to facilitate the introduction of the model later, we first formalize the echolocation process. The call of the bat, $call(t)$, that reflects from an object, obj, is transformed by a linear combination of filters before arriving at the bat's tympana (see Eq. (1)).

$$echo_u^{(r,\vec{p})}(t) = call(t) * h_{send}^{\vec{p}}(t) * h_{air}^{r}(t) * h_{obj}(t) * h_{air}^{r}(t) * h_{HRTF\,u}^{\vec{p}}(t) \quad (1)$$

$echo_u^{(r,\vec{p})}(t)$ is the transformed call, and $u \in \{L, R\}$ respectively indicates left or right. $(r, \vec{p})$ represents the location of obj relative to the bat's head, with r being the distance and $\vec{p}$ being (θ, ϕ). θ (azimuth) and ϕ (elevation) are defined according to Fig. 1. $h_{send}^{\vec{p}}(t)$ is the impulse response of the call-site (the bat's nostrils or mouth) for sound leaving in direction $\vec{p}$, $h_{air}^{r}(t)$ is the impulse response of the filtering done in air (spherical spreading loss and absorption), dependent on the distance of the reflector to the bat, $h_{obj}(t)$ is the impulse response of the reflector dependent filtering of obj, and $h_{HRTF\,u}^{\vec{p}}(t)$ is the impulse response of the HRTF of one of the bat's ears, as indicated by u, for a sound coming from direction $\vec{p}$, and $*$ is the convolution operator.

This theoretical deconstruction of the echolocation process ignores the fact that in practice, the mammalian hearing system does not directly obtain a time signal. Instead, the envelope magnitudes of bandpass-filtered versions of the incoming sound as obtained by the cochlear inner hair cells (a cochleagram) are available. However, algorithms exist for extraction of a time signal from the short-time Fourier transform magnitude (see Griffin and Lim, 1984). These can be applied to the envelope data at different frequencies present in the cochleagram of the mammal. So for our modelling purposes, considering the time signals is a viable assumption.

Taking into account noise introduced by the reconstruction techniques, Eq. (1) can be rewritten as

$$y_u^{(r,\vec{p})}(t) = x^r(t) * h_u^{\vec{p}}(t) + n(t) \quad (2)$$

in which $y_u^{(r,\vec{p})}(t) = echo_u^{(r,\vec{p})}(t)$, $x^r(t) = call(t) * h_{obj}(t) * h_{air}^{2r}(t)$, and $h_u^{\vec{p}}(t) = h_{send}^{\vec{p}}(t) * h_{HRTF\,u}^{\vec{p}}(t)$. We model $n(t)$ as zero mean white Gaussian noise ($n(t) \sim N(0, \sigma_n)$), but the proposed method also works with other noise models, as long as the spectral properties of the noise are known. $x^r(t)$ is direction independent, $h_u^{\vec{p}}(t)$ direction dependent. Clearly, the direction dependent component is not only determined by the HRTF, as mentioned in the introduction. It consists of the combination of the directional sending pattern and the HRTF. Moreover, spectral cues tend to be enhanced under the influence of this combination (Wotton et al., 1997). Therefore, we use the term echolocation-related transfer function (ERTF) throughout the paper, designating this directional echolocation sensitivity.

The echo's time of arrival relative to the call time enables the bat to estimate r, and hence, $h_{air}^{2r}(t)$. Additionally, it knows which call it has sent. Consequently, if the bat can determine $x^r(t)$ from $y_u^{(r,\vec{p})}(t)$, it can estimate $h_{obj}(t)$. This is one of the arguments presented which are not generalizable to the passive sound localization mode: range detection should be performed with another strategy, as in passive localization no relative timing is available. Without knowing the position of obj, however, the bat cannot determine $x^r(t)$ from the incoming signal $y_u^{(r,\vec{p})}(t)$. The simultaneous signal reconstruction and localization model we propose, envisages to reconstruct $x^r(t)$ without knowing the exact location beforehand.

Note that, as explained earlier, the bat does not necessarily reconstruct the reflected signal. From the perceived signals, it could extract the relevant features for localization and identification. By assuring reconstruction, we guarantee, however, that the necessary information is still available in spite of filtering the reflected signal with the ERTF.

3. Binaural Wiener Filtering

We propose a binaural model that is inspired by a signal estimation and localization approach for biological arrays elaborated in Franosch et al. (2003). In that publication, the lateral line system of the frog is modelled. We investigate whether the bat's echolocation system consisting of an emitter and the two-element array made up from the ears of a bat is suited equally well as the frog's array for localization and reconstruction with the model in question.

The directional properties of the echolocation system we consider originate from a specimen of the lesser spearnosed bat, *Phyllostomus discolor*. Its ERTFs have been obtained according to the following procedure: