Binaural Sound Localization Systems Based on Neural Approaches

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Introduction

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Motivation:

- sound localization plays an important role for mobile robots
- binaural localization systems are common in nature

Reference: **Biologically Inspired Binaural Sound Source Localization and Tracking for Mobile Robots**, Calmes 2009

- uses barn owl as biological example
- implements system using artificial barn owl ruff
- also uses statistical tracking and visual sensor aids

Barn Owl as Biological Example

Barn Owl

Tyto Alba by Peter Trimming, Creative Commons 2.0

- one of natures most precise example of sound localization
- can hunt only by hearing
- special structure of head makes 110 degree hearing possible
- asymmetric ears to distinguish the elevation of sounds
- first research on acoustic hunting was performed by Roger S. Payne in 1971

Neural Audio Processing

Neural Network Basics (Biological)

- neurons:
    - create a charge
    - release the charge when triggered/excited
    - stronger impulse - higher frequency of charges
- synapses:
    - transfer charges from one neuron to another
    - can increase or reduce the excitation of the target node
    - exhibitory connections:
        - connections increasing the excitation
    - inhibitory connections
        - connections decreasing the excitation

Neural Network Basics (Technical)

- first attempt of mathematical description by McCulloch and Pitts in 1943
- linear combination of weighted inputs
  - $\Rightarrow$ equivalent of synapses
- apply activation function on the combination
  - $\Rightarrow$ equivalent of neurons

$$y = f(w_1 x_1 + w_2 x_2 + ... + w_n x_n)$$

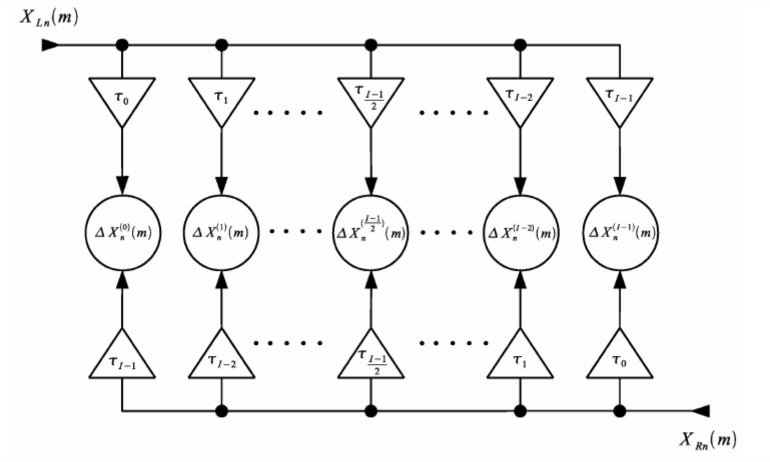
- activation function e.g. sigmoid function

$$f(x) = \frac{1}{1+e^{-x}}$$

Jeffress Model

- presented by Lloyd A. Jeffress in 1948
- implemented as delay-line algorithm by Liu et. al in 2000
- a model for the ITD part of the brain
- uses I neurons with delayed inputs from left and right ear for each timestep n
- includes delay lines to match phase shifts
- phase shift is computed for each frequency band (m) by using fast fourier transformation
- the azimuth spectrum is divided into I parts

Jeffress Model Structure



Dual Line structure (Calmes, 2009)

Jeffress Model Notation

- for each node, the signal is delayed by:

$$\boxed{\tau_i = \frac{\mathrm{ITD}_{\mathrm{max}}}{2} \sin\left(\frac{i}{I-1}\pi - \frac{\pi}{2}\right)}$$

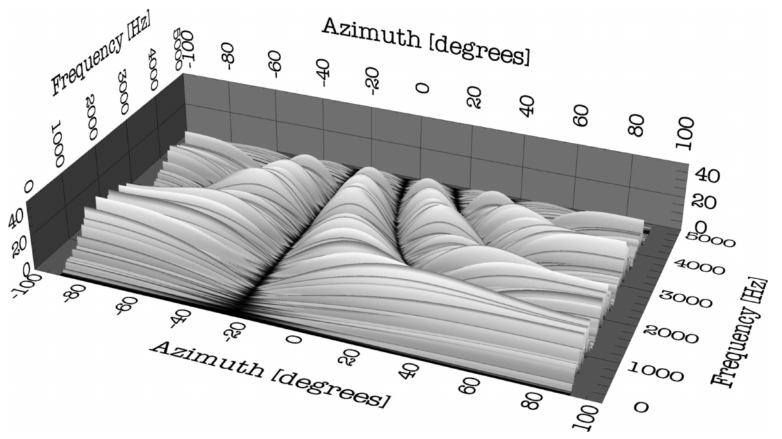
- to shift a signal in the frequency domain, the complex vector is rotated:

$$\boxed{X_{L,n}^{(i)}(m) = X_{L,n}(m) e^{-j2\pi f_m \tau_i}}$$

- the azimuth sector is selected by the minimal distance of the complex values:

$$\boxed{i_n(m) = \arg\min_i [\Delta X_n^{(i)}(m)]}$$

Jeffress Model Diagram



3D coincidence map (Calmes, 2009)

Spence & Pearson

- a model for the ILD part of the brain
  (Spence & Pearson, 1989)
- simulates different parts of the barn owl brain
  - NA - frequency filtered signal intensity
    (nucleus angularis)
  - VLVp - sigmoidal shaping of the intensity
    (nucleus ventralis lemnisci lateralis, pars anterior)
  - ICc - peaked response curves determining the ILD sector
    (central nucleus of the inferior colliculus)
- parameters tuned in a way to achieve similar results as the barn owl

Spence & Pearson - Nodes

- each neural node has a predefined activation function
  - equal for every node
  - values determined by research on the barn owl
- voltage v and activity a determined by inputs g:

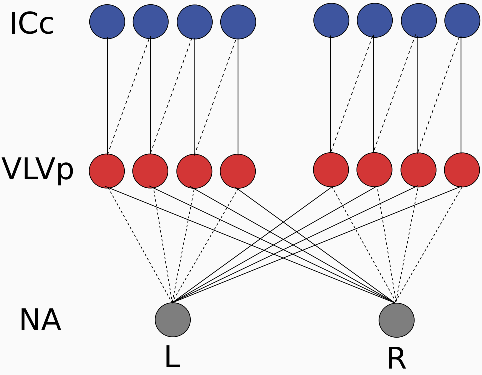
$$v = \frac{g_e \cdot v_e + g_i \cdot v_i + g_l \cdot v_l}{g_e + g_i + g_l}$$

with $e =$ excitatory, $i =$ inhibitory and $l =$ leakage

$$a = \frac{1}{1 + e^{ln(s)\cdot(v - v_t)}}$$

with s determining the steepness of the sigmoidal slope

Spence & Pearson - Structure



neural network structure of the implemented Spence & Pearson model

- $+w^{icc}_{j,k} = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{\frac{-(k-j)^2}{2 \cdot \sigma^2}}$
  if $j - \sigma \leq k \leq j + \sigma$
- $-w^{icc}_{j,k} = \frac{k-j}{\sigma}$
  if $j < k \leq j + \sigma$

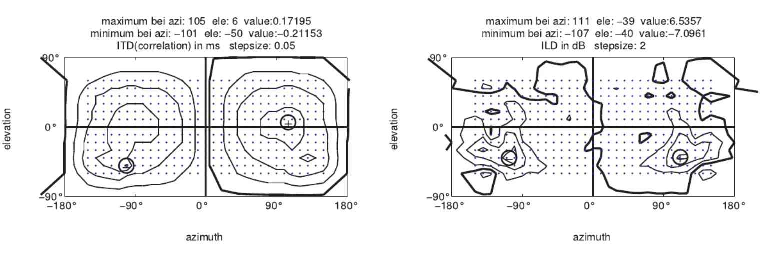
- $-w^{vlvp}_{k} = 1 - \frac{k}{|VLVp|}$
- $+w^{vlvp}_{k} = \frac{1}{max_{input}}$

Spence & Pearson - Parameters

- setting $v_e = 0$, $v_i = -90$, $v_l = -65$ and $g_l = 1$
- achieves similar peak responses as the internal brain structure of the barn owl
- activation function parameters may be randomized
- most active ICc node determines the sound direction

Sound Localization Setup

- combine Dual-Line/Jeffress model with Spence & Pearson model
- select most active nodes from both models
- assign nodes to sectors regarding azimuth and elevation by testing



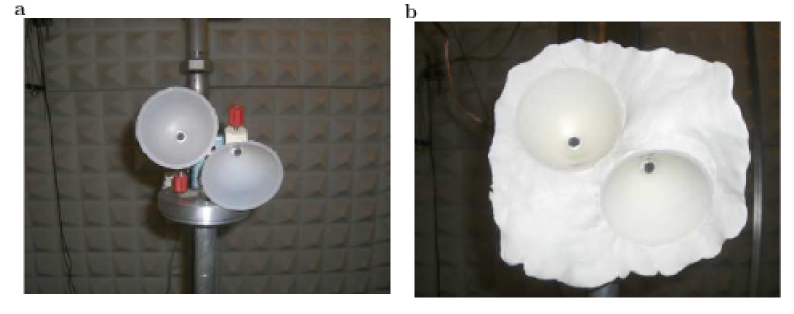
ITD/ILD contour lines of simple two-microphone setup (Calmes, 2009)

Artifical Owl Ruff Localization System

Artificial Owl Ruff

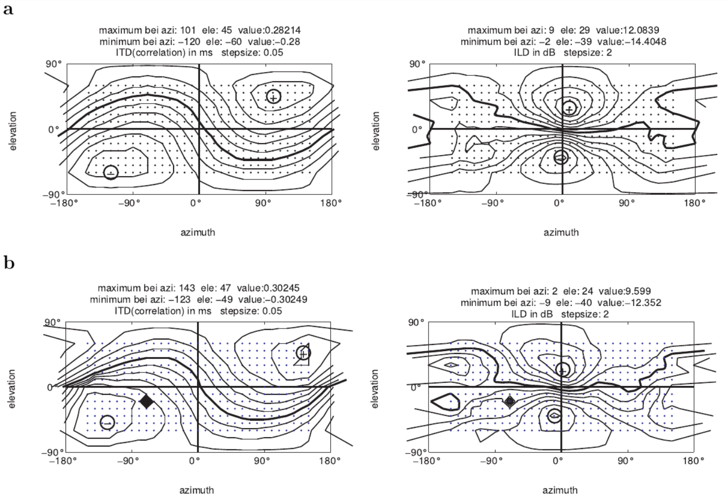
Aim:

- expand the azimuth spectrum above 90 degrees
- make the left ear more sensitive for higher elevated sounds
- make the right ear more sensitive for lower elevated sounds
- achieve frequency distortion with a custom HRTF



artificial owl ruff setups (Calmes, 2009)

ITD / ILD Analysis



ITD/ILD contour lines of artificial owl ruff setup (Calmes, 2009)

Effects of the Artificial Owl Ruff

- achieved to expand the azimuth range above 90 degree
- achieved to focus the ILD part on measuring elevation
- did not achieve to benefit from a custom HRTF...
- ...but:
    - azimuth range further increased
    - ILD sensitivity increased in regards to elevation
- possibly the improvement was too noisy to improve the localization

Effect of an Artificial Head to Human Acoustic Perception

Demo

- binaural listening demonstration

Conclusion

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- biological inspired neural methods enhance sound localization systems:
  - ITD part: Jeffress model
  - ILD part: Spence & Pearson model
- artificial microphone setups inspired by the barn owl enhance sound localization
- artificial structures have an important effect on acoustic perception

  $\Rightarrow$ for localization systems as well as humans thank you for your attention!

References

Biologically Inspired Binaural Sound Source Localization and Tracking for Mobile Robots , *Lauent Calmes* PhD thesis at I5 chair of the RWTH, 2009

Biologically Inspired Binaural Sound Localization using Interaural Level Differences , *Daniel Peger* diploma thesis at I5 chair of the RWTH, 2005

The Computation of Sound Source Elevation in the Barn Owl, *Clay D. Spence & John C. Pearson* , Advances in Neural Information Processing Systems 2, NIPS Conference, Denver, Colorado, USA, November 27-30, 1989