Binaural Hearing for Robots

Introduction to Robot Hearing
Binaural Hearing for Robots

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2. Human-robot interaction
3. Auditory scene analysis
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Robots in Industry

Researchers and engineers have developed sophisticated robots that can work efficiently in well-structured and predictable environments.

Examples: manufacturing industries (cars, ships, planes, electric appliances, etc.),

The emphasis has been on studying **physical interactions** between robots and objects/environment, for example:

- perform complex articulated movements,
- grasp/ungrasp and assemble/disassemble objects,
- move safely among obstacles,
- perform specific tasks: painting, welding, etc.
Robots and People

Robots are expected to gradually move from factory floors to populated spaces, therefore there is a paradigm shift from **robot-object interactions** to **human-robot interactions** (HRI).

HRI has the ambition to enable unconstrained communication between robots and people.

Robot hearing is a fundamental ability because it allows interaction via highly rich content, e.g., **speech**.

The challenge: Extract content from complex acoustic signals.
Acoustic Signals Are Very Rich

Robot hearing should not be limited to speech recognition.

There is a large number of acoustic events, other than speech, that are of interest to a robot:

- laughing, crying, whistling, singing, hand clapping, etc.
- animal sounds, musical instruments, environmental sounds,
- falling objects/people, warnings, electronic appliances, hazards, etc.
Session Summary

- Robots in industry
- Robots and people
- What can be done with hearing?
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Constrained (Tethered) HRI

Inspired from human-computer interaction (HCI).
Advantage: clean acoustic signals available for automatic speech recognition (95% recognition rate).

Disadvantages:
- restricted to speech communication with a single user that must wear a microphone,
- sound localization and recognition of other types of acoustic events not possible.
- audio perception cannot be combined with other sensorial modalities (vision).
Unconstrained (Untethered) HRI

- The microphones are embedded into the robot head.
- The relevant auditory signals are at some distance from the robot.
- These signals are mixed with signals from other sound sources, affected by reverberations, noise, etc.
- Auditory processing is more difficult in this case.
- This setup allows auditory scene analysis.
- It is possible to combine audio and vision.
Automatic Speech Recognition
People-Robot Interaction
Session Summary

- Human-computer interaction
- Human-robot interaction
- Speech recognition
- Other hearing tasks
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Auditory Scene Analysis

With two or more microphones it is possible to address several problems:

- detect the presence/absence of the sound sources,
- extract the signal emitted by each emitting source,
- localize the sounds and track them over time,
- identify each source (voice, musical instrument, etc.)
- enhance the signals for subsequent ASR.
Robot Hearing Challenges

A robot hearing system must solve several problems:

Analysis:
- **Who** are the speakers in front of the robot?
- **Where** are the speakers?
- **When** do they speak?
- **What** are they saying?

Interaction:
- Is the robot able to pop into the conversation?
- Is the robot able to synthesize appropriate behavior?
Constrained Audio Interaction

$s(t)$: the signal emitted by a speaker is a function of time $t$,
$m(t)$: the signal recorded with a microphone,
$n(t)$: additive noise.

We have:

$$m(t) = s(t) + n(t)$$

The emitted and recorded signals differ by additive noise (for example, microphone noise).

Extracting a **clean speech signal**, for subsequent automatic speech recognition (ASR), is straightforward in this case.
Unconstrained Audio Interaction

The relationship between the emitted and received signals is more complex

\[ m(t) = h_1(t) \ast s_1(t) + h_2(t) \ast s_2(t) + \ldots + h_K(t) \ast s_K(t) + n(t) \]

- Indeed, the microphone records not a single signal but several signals: \( s_1(t), s_2(t), \ldots, s_K(t) \).
- When waves travel from their positions to the microphone, they are modified.
- These modifications can be modeled by convolution (the symbol \( \ast \)) between an unknown transfer function, \( h_k(t) \), and the emitted signal, \( s_k(t) \).

Extracting clean signals is more difficult!
Session Summary

- Auditory scene analysis
- Robot hearing challenges
- Constrained interaction
- Unconstrained interaction
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Using Several Microphones

For each microphone $j = 1 \ldots J$ we have a different equation:

\[
m_j(t) = h_{1j}(t) \ast s_1(t) + h_{2j}(t) \ast s_2(t) + \ldots + h_{Kj}(t) \ast s_K(t) + n_j(t)
\]

\[
\vdots
\]

\[
m_J(t) = h_{1J}(t) \ast s_1(t) + h_{2J}(t) \ast s_2(t) + \ldots + h_{KJ}(t) \ast s_K(t) + n_J(t)
\]
Binaural Hearing

The microphones are plugged into the left and right “ears” of a dummy head. In the absence of reverberations, there is a head-related transfer function (HRTF) for each ear:

\[ m_L(t) = h_L(t) \ast s_1(t) + h_L(t) \ast s_2(t) + \ldots + h_L(t) \ast s_K(t) + n_L(t) \]
\[ m_R(t) = h_R(t) \ast s_1(t) + h_R(t) \ast s_2(t) + \ldots + h_R(t) \ast s_K(t) + n_L(t) \]

This general setting is difficult to solve in practice.
Spectral Representation

- In signal processing, it is common to perform spectral analysis, namely to apply the Fourier Transform (FT) to the microphone signals.
- In practice, one should use the discrete Fourier transform (DFT).
- The DFT applied over a short period of time is called the short-time Fourier transform (STFT).
- By applying the STFT to a signal at discrete time steps, one obtains a spectrogram (see next slide).
- Each spectrogram point indicates the amount of oscillation contained in the signal at time $t$ and at frequency $f$. 
Spectrogram

A Spectrogram is an example of a time-frequency representation of a signal.
Binaural Cues for Sound Localization

Suppose that there is a single emitting sound source. The signals received by the two ears are different. Their difference is mainly characterized by two cues:

- They reach each ear at different times: interaural time difference, or ITD.
- They have different intensities (or levels): interaural intensity (or level) difference, or IID (ILD).
ITD and ILD

- ITD: interaural time difference (also TDOA or time difference of arrival)
- ILD: interaural level difference

From these two features it is possible to localize the sound source.
Session Summary

- Audio signal processing
- Emitted and perceived signals
- Spectrograms
- Binaural localization cues
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The Auditory Pathways: the Ears and the Brain

All the living species, from fish to primates (monkeys, humans) have binaural hearing.

There is considerable variability in the sub-cortical and cortical organization across species.

Roughly speaking, the auditory pathway can be divided into two parts:

- transformation of sound waves (air pressure) into spike trains (neural activity), and
- representation and extraction of auditory information (localization, speech, etc.) in different brain areas.
From Air Pressure to Neural Activity

- **Outer ear**: composed of the *pinna* and *ear canal*, transmits air to the *eardrum*.
- **Middle ear**: it is air filled, contains a chain of little bones, or *ossicles* that collect sound pressure on the *eardrum* and concentrates it onto the *cochlea*;
- **Cochlea**: Acts as a mechanical bank of bandwidth filters that transform the air/liquid vibrations into electric currents and then into spike trains.
The Cochlea
The Main Components of the Cochlea

- A coiled tube enclosed in a hard bony shell,
- It is filled with a liquid (salted water),
- The *basilar membrane* splits the spaces inside the cochlea into two canals, vestibular and tympanic,
- The basilar membrane is stiff at its base and flexible at its apex,
- all along the basilar membrane there is a structure called *organ of Corti* that contains the *hair cells*,
- Hair cells are the hearing receptor cells, or the equivalent of photo-receptor cells on the retina.
The Cochlea: From Air Pressure to Electrical Signals

The cochlea is equipped with two types of mechanical resistance:

- the stiffness of the basilar membrane, and
- the inertia of the liquid

Both are graded along the cochlea: the stiffness gradient decreases while the inertial gradient increases.

Altogether the cochlea operates as some kind of mechanical frequency analyzer, modeled as a *gamma tone filter bank*
The Organ of Corti

- There are 15000 hair cells all along the basilar membrane, inner and outer hair cells.
- The outer cells play the role of amplification.
- The inner hair cells transform mechanical vibrations into electric signals that are transmitted to the auditory nerve.
- Mathematically, the information passed to the brain can be represented as a cochleagram (see next slide) which is somehow equivalent to a spectrogram (see slide ??)
Cochleargram
• The ear is a very complex organ
• Air pressure is transformed into electric spikes
• Detailed ear anatomy
• Brief description of ear’s functions
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Auditory Processing in the Brain

- The brain has the difficult task of transforming the acoustic-wave input into auditory object perception.
- The data flow travels from the ear to the auditory cortex via the midbrain that is composed of several nuclei.
- The auditory cortex is divided into several areas, both its anatomy and organization varies considerably between the species.
The Ascending Auditory Pathway
Sound Localization in the Midbrain

- The superior olivary complex (SOC) is the first *station* that receives input from both ears
- The SOC is subdivided into two nuclei, the lateral superior olive (LSO) and the medial superior olive (MSO)
- These nuclei seem to be well suited to represent and measure time differences (MSO) and intensity differences (LSO)
Session Summary

- The midbrain is composed of nuclei
- These nuclei preprocess the audio information before it is passed to the cortex
- Several nuclei receive input from both ears.
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Auditory Cortex

The auditory cortex is largely understood today, there are two main hypotheses:

- There are two pathways, with a division of labor between spatial and non-spatial processing
- Dynamically organized processing networks are likely to support auditory perception.

The first hypothesis is supported by functional imaging (humans) and single-neuron physiological studies (non-human animals)
Auditory Streams in the Cortex

- Dorsal stream (red) analyze space and motion.
- Ventral stream (green) involved in auditory-object perception.
- Core regions (blue) of the auditory cortex for different species.
Session Summary

- Division of labor: where and what pathways
- Dorsal and ventral streams
- The auditory cortex varies from species to species
Week Summary (I)

- It is necessary to augment physical interactions between robots and their environment with cognitive interactions between robots and people.
- Human-robot interaction (HRI) is more general and more difficult than human-computer interaction.
- HRI goes well beyond speech processing/recognition, it needs auditory scene analysis.
- Binaural hearing allows rich interactions based on acoustic wave processing and understanding.
Week Summary (II)

- All animals (fish, frogs, reptiles, owls, bats, cats, monkeys, humans) have two ears...
- The anatomy/physiology of the ear is well understood... more than just a *microphone*.
- The midbrain plays a crucial role in spatial hearing, a simple physiological model for ITD/ILD processing is available.
- The auditory cortex processes in parallel two flow of information: where and what
- Biological models for the analysis of complex auditory information are not yet available.