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Bachelor's thesis

NÁZEV PŘÍKLADNÉ ZÁVĚREČNÉ PRÁCE

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March 23, 2022

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Declaration

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Abstrakt

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Abstract

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Acronyms

DFA	Deterministic Finite Automaton
FA	Finite Automaton
LPS	Labelled Prüfer Sequence
NFA	Nondeterministic Finite Automaton
NPS	Numbered Prüfer Sequence
XML	Extensible Markup Language
XPath	XML Path Language
XSLT	eXtensible Stylesheet Language Transformations
W3C	World Wide Web Consortium

Chapter 1

Introduction

Imagine a party. You can hear a variety of sounds: music in the background, conversations between people, noises of somebody coughing, maybe even a dog barking outside... These sounds merge into a single stream that approaches your ears by vibrations in the air and then goes through different physical, biological and psychoacoustical processes to finally come in a form of electrical impulses to the brain. Despite all these sounds from different sources are mixed on the way to your ears, the brain can segregate one (or several) of them. You can focus your hearing on these "target" sounds and separate them from the complex mixture, leaving other sounds in the background. This phenomenon has been described as a "cocktail party effect", and the process of integrating separate sounds into meaningful streams, or "auditory objects" – auditory scene analysis, or ASA.

In machine perception — specifically in machine hearing — a related concept is referred to as Computational ASA (CASA) and is tightly connected to the fields of sound recognition and digital signal processing. CASA systems indeed aim to separate sounds from mixtures, but they differ from BSS (blind source separation) systems in that they try to do this in a way a human ear does. Being based on and trying to combine works from different fields of science, CASA systems can bring new solutions and insights to the complex problem of signal separation.

The main objective for this thesis is to describe the principles and goals of CASA, existing applications and approaches. Another objective is to practically apply the theoretical knowledge and implement a simple CASA system to separate monophonic music from noise. But before all of this, since this thesis is made for an IT-oriented audience, it is needed to make a brief introduction to the underlying physics and biology.

Thus, the thesis is structured as follows:

Firstly, physical background theory will be provided, including an introduction to what a sound is. Since the implemented system from the practical part aims to segregate music from noise, a special focus in this part will be made on describing harmonic sounds and pitch perception.

Secondly, having in mind that CASA tries to mimic the human auditory system, a brief introduction to the biological structure of the human ear will be made. Here, auditory scene analysis according to Bregman will be introduced too.

Next, to cover the math in the implementation part, the basics of digital sound processing will be described. The related mathematical principles and functions used during the implementation will also be given some attention.

In the following chapter, having all the related theory in mind, an introduction to the main principles and goals of CASA will be made, along with an overview of its applications and selected models.

Then, in the practical part, the focus will be made on describing the implementation of specific parts of the CASA system built for this thesis (see attached medium).

Finally, an overview of the experiments made to test the implemented system will be provided.

Chapter 2

Physical Background

Before starting to ponder the structures of the human ear, it is necessary to understand the basics of how sounds work in the real world. It is safe to say that many people don't ask this question – they just produce or react to them, unconsciously knowing the outcomes. Human mind has already developed a deep understanding of which sounds are produced under different circumstances – you can easily say which sounds to expect when somebody scratches a blackboard or rings a bell. Some could say that sounds are just "pressure waves that propagate through the air", but in reality, there is a lot of interesting and complex things beyond this definition to pay attention to. This chapter will introduce the reader to the underlying physics of sound and different types of them. A special focus will be made on describing harmonic sounds, which are essential to understand to be able to work with music and pitch.

2.1 What a Sound Is

The definition of sound above, saying that it is just vibrations in the air, is hard to be called incorrect. Of course, there are improvements to be made: for example, that the sound can propagate not only through the air, but through any medium that has inert mass and is "elastic", or stiff, meaning that it will respond to forces applied to it. It is also important to note that the definition above relates to sound as a physical phenomenon, but there is another definition used in psychology and physiology, saying that the sound is a perception in the brain, or auditory sensation of the concept described above. In this thesis, the term "sound" will be used primarily in the first (physical) sense, unless specified differently.

Now, the mass and elasticity of the air mentioned above play a very important role in the studies of sound. Mass-spring systems are a highly discussed topic, along with the type of oscillations they tend to have. Any object that can produce sounds can be considered a mass-spring system: a bell, a guitar string, or even air and water, which can be thought of as many small masses connected by invisible springs... If one imagines the simplest of such systems — any mass attached to an elastic spring — they can notice that when a particular force is applied to it, it tends to oscillate in a sinusoidal manner. In fact, this is true for all such systems: they naturally "want" to vibrate in a sinusoidal fashion with a preferred frequency, called resonance frequency.

The knowledge that any source of sound can be thought of as a mass-spring system is quite staggering. In most cases, it is hard to imagine such a system, because there could be no obvious

mass nor elasticity, like in examples for resonant cavities: why a can of soda makes that clicking sound when it is being opened? The air is the answer. When you open the can, some parts of the air near its top act as a mass, and other parts near the bottom as a spring. The pressure in the can drops, and the "spring" at the bottom tries to suck the "mass" back in, producing the expected sound [Auditory Neuroscience citation].

Another essential topic to mention is why sounds fade in time. This is again connected to the concept of mass-spring systems and the amplitudes of their vibrations. Usually, the bigger these amplitudes are, the louder the resulting sound is, so if the amplitudes didn't become smaller, we would live in constant unbearable noise. In brief, the fading is caused by the resistance of the medium, in which the sound propagates, and the manner of this propagating. If you imagine air as above — as many masses connected by invisible springs — the mechanics of the propagation becomes clear: the sound source pushes the closest mass near it, which due to elasticity pushes its neighbors and returns to its starting location. Then its neighbors, in turn, push their neighbors and return, and so on, until these vibrations come to your ears. The air masses must be pushed again and again for the sound to spread, so it tends to lose its strength along the way, and the further from its source it travels, the smaller the amplitudes of the vibrations become.

2.2 Harmonicity and Pitch

Chapter 3

Biological Background

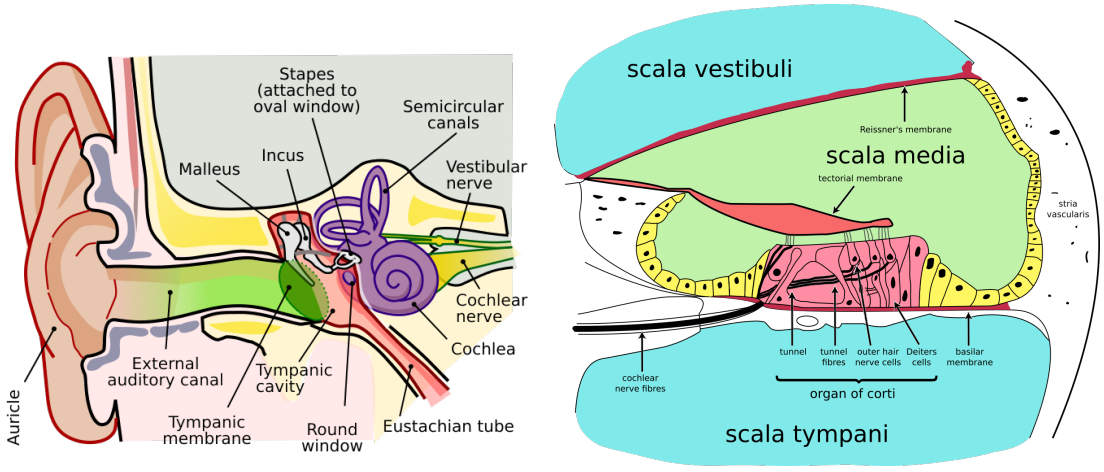
Sounds... For sure, they are one of the most important sources of information in our everyday life. By listening to them, one can describe what is happening around, understand how to react to occurring situations, or even tell if a danger is approaching, and it is time to take action. It is hard to imagine human perception without hearing, but as easy as this may sound (no pun intended), the biology behind it is quite complicated. This chapter will introduce the reader to how sound as a mechanical phenomenon is converted to sound as perception and provide a basic overview of the structures in the human ear, along with the mechanical and neurobiological processes happening inside of them.

3.1 Outer and Middle Ear

At the beginning, sound approaches the ear by vibrations in the air (or any other elastic medium) and enters the outer ear, which consists of the visible part (called the auricle, or the pinna) and the ear canal. The auricle is a thin plate of elastic cartilage, covered with integument, and connected to the surrounding parts by ligaments and muscles; and to the beginning of the ear canal by fibrous tissue [Wikipedia citation – Outer ear]. The ear canal is a tube leading from the bottom of the auricle to the middle ear, separated from it by the eardrum (or tympanic membrane). The main purpose of the ear canal is to focus the sound energy gathered by the auricle on the eardrum. It also amplifies frequencies between 3 kHz and 12 kHz.

Being gathered on the eardrum, the mechanical vibrations propagate through the middle ear. Three bones (called the ossicles) are located inside of it. The malleus (also called the hammer) is connected to the eardrum and transfers the vibrations from it to the incus (the anvil). These vibrations are quite chaotic, but the malleus is connected to the eardrum in a linear manner, also helping the ear to respond more linearly and smoothly. The incus, in turn, connects to the stapes (the stirrup). The footplate of the stapes introduces pressure waves in the inner ear, which starts with the oval window of the cochlea. The structures of the middle ear can be seen on Figure 3.1a

It may sound redundant to have additional structures in the ear which propagate the vibrations even further, when they could travel just one centimeter more in a way like before, in the ear canal, but in reality, the pressure of these mechanical vibrations is too small to cause the waves of the same velocity in the cochlear fluids. The ossicles help to amplify the pressure of these vibrations. They are positioned to form a lever, and, because the oval window is about 14 times smaller than the eardrum, the pressure gain becomes quite significant in the end –



(a) (b)

Figure 3.1 **(a)** Anatomy of the human ear. The ossicles of the middle ear are shown in white. The inner ear is shown in purple. **(b)** Cross-section of the cochlea showing the organ of Corti and three chambers filled with cochlear fluids. Both pictures were taken from `https://commons.wikimedia.org/`

at least 18.1 times [Wikipedia citation – Middle ear].

To regulate the middle ear and protect it from damage due to very loud sounds, two muscles are located inside of it: the stapedius muscle and the tensor tympani muscle. These muscles are controlled by unconscious reflexes and hold the ossicles when the vibrations become too intense.

To provide ventilation and drainage of the middle ear and to equalize pressures in this isolated environment, the middle ear is connected to the back of the throat by the eustachian tube [Auditory Neuroscience reference].

3.2 Inner Ear

The inner ear starts with the above-mentioned oval window, which is connected to the stapes of the middle ear. The oval window is a part of the cochlea — a structure of the inner ear dedicated to hearing. Along with the cochlea, the inner ear also contains the vestibular system, which is responsible for the sense of balance and spatial orientation and uses the same kinds of fluids and cells as the cochlea does. The vestibular system will not be covered in this thesis, but the fluids and cells will be described in more detail later in the section.

The cochlea itself is a spiral-shaped cavity made of bony tissue, which makes about 2.75 turns around its axis and is about 3 cm long [Wikipedia citation - Cochlea]. The core component of it is the basilar membrane, which runs along almost its entire length and separates two of the three chambers of the cochlea filled with different fluids: the tympanic duct filled with perilymph (scala tympani), and the cochlear duct filled with endolymph (scala media). The third chamber, the vestibular duct (scala vestibuli), is separated from the cochlear duct by the Reissner's membrane and is filled with perilymph (Figure 3.1b). When the footplate of the stapes of the middle ear introduces movements to the cochlear fluids, the basilar membrane is affected too, and the endolymph in the cochlear duct moves along.

The most interesting property of the basilar membrane is that its stiffness and width is different throughout its length – the membrane is narrow and stiff at the basal end of the cochlea, and

wide and floppy at the apical end [Auditory Neuroscience citation]. And here sound waves have two possible routes to take while propagating through the basilar membrane: a shorter path, which includes going through the stiffer parts of it, or a longer path, which means travelling along the membrane until it becomes easier to pass through, but pushing more fluid on the way. In fact, high-frequency waves tend to choose the shorter path, and low-frequency waves – the longer one.

Thus, the basilar membrane moves in different places depending on the frequencies of the vibrations. The organ of Corti, which sits on top of it and runs along its entire length, contains displacement cells able to respond to movements of the fluid nearby and send electrical impulses when this happens. Such cells are packed with a bunch of stereocilia (hair) that stick out of its top, and thus are called hair cells. These cells can be of two types: inner hair cells that are located closer to the center of the cochlea, and outer hair cells that sit closer to its outer side. Inner hair cells are less numerous than outer hair cells and form a single row along the organ of Corti, while outer hair cells usually form three rows [Auditory Neuroscience citation].

Now, it is important to mention that the endolymph in the cochlear duct contains high amounts of positively charged ions (primarily potassium and calcium). When it moves in response to the sound pressure, the stereocilia of the inner hair cells are deflected, and tiny ion channels open in them. This allows the charged ions from the endolymph to enter the stereocilia. The cell becomes depolarized, and a receptor potential is produced. This results in releasing the neurotransmitters at the basal end of the cell and then triggering action potentials in the nerve nearby [Wikipedia citation - Hair cells]. In this way, inner hair cells detect movements around them and convert mechanical sound waves to electrical nerve signals.

Outer hair cells, in turn, serve as amplifiers of the quiet sounds. Their receptor potentials are converted to cell body movements, thus increasing the sound pressure.

3.3 Auditory Scene Analysis

Chapter 4

Mathematical Background

Chapter 5

Computational ASA

Now, having described all the underlying concepts from different fields of science in previous chapters, it is time to finally focus on computational auditory scene analysis. CASA is said to be a field of study that groups practical, programmable solutions for auditory scene analysis problems, and thus can introduce new discoveries and insights to it. CASA systems are used primarily for source separation, meaning that they are machine listening systems that aim to separate sounds from different sources in mixtures. However, they are not the same as systems for blind signal separation – the core difference is that CASA systems try to mimic (at least to some extent) the mechanisms inside the human ear, which were described in chapter 3. In this chapter, main principles of CASA systems will be described, along with a typical structure, desired outputs and applications. In the second part, major works that use computational auditory scene analysis for source separation will be reviewed and compared.

5.1 Typical Structure of a CASA System

Chapter 6

Implementation

Chapter 7

Experiments