Detecting Structural Deformation in Ear using Earables

Thesis Part-I (CS570003) report submitted to

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in

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by

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Under the supervision of

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Autumn Semester, 2021-22

November 26, 2021

DECLARATION

I certify that

(a) The work contained in this report has been done by me under the guidance of my supervisor.

(b) The work has not been submitted to any other Institute for any degree or diploma.

(c) I have conformed to the norms and guidelines given in the Ethical Code of Conduct of the Institute.

(d) Whenever I have used materials (data, theoretical analysis, figures, and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references. Further, I have taken permission from the copyright owners of the sources, whenever necessary.

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DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR

KHARAGPUR - 721302, INDIA

CERTIFICATE

This is to certify that the project report entitled "**Detecting Structural Deformation in Ear using Earables**" submitted by **Deepank Agrawal** (Roll No. 17CS30011) to Indian Institute of Technology Kharagpur towards partial fulfilment of requirements for the award of degree of Master of Technology in Computer Science and Engineering is a record of bona fide work carried out by him under my supervision and guidance during Autumn Semester, 2021-22.

Date: November 26, 2021

Place: Kharagpur

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Abstract

Name of the student: **Deepank Agrawal** Roll No: **17CS30011**

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Rapid advancement in the semiconductor industry and fast technological development in earable computing have made these earphone devices an indispensable part of one's life. Earable devices have the potential to disrupt the wearable mobile computing paradigm, and the industry has already started reaping some of its benefits. Earphones or earables can be used to track our motion or health using vibrations in face muscles or by producing and capturing high-frequency sound in the ear canal. In this work, we attempt to solve one of the problems in the healthcare industry. Detecting structural deformation of the ear canal is challenging without the right equipment. Early detection of such deformations may prevent serious complications, such as hearing loss or the development of ear tumors. To address this problem, we propose to use any commercially available earphones. The earable produces and records a high-frequency sound wave, thereby capturing the internal structural characteristics of the ear. However, in this report, we try to unravel the governing parameters that can help us understand the internal structure of closed ear-like hollow objects, thereby limiting our current scope.

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Abbreviations

SINR	**S**ignal-to-**I**nterference-plus-**N**oise **R**atio
ENT	**E**ar, **N**ose and **T**hroat
SNR	**S**ignal-to-**N**oise **R**atio
TDoA	**T**ime **D**ifference of **A**rrival
IMU	**I**nertial **M**easurement **U**nit
SSIM	**S**tructural **S**imilarity **I**ndex

Chapter 1

Introduction

1.1 Scope

The swift development in the semiconductor industry and better algorithms have made earphones an indispensable device. Current generation earphones have much more potential, which by par surpasses their use as simple sound emitting devices. Earphones or Earables can be used in augmented reality to play a 3D sound, track motion, or health. This enormous increase in computing power can be harnessed to solve a vast number of problems that can benefit from an earable device. One such field is healthcare.

Ear blockages are becoming increasingly common due to the increased amount of air pollution. These blockages can have adverse effects on one's ear if left untreated. Ear blockages can cause a continuous ringing sensation in one's ear or even hamper hearing capabilities. Suitable pieces of equipment are designed to diagnose ear structure deformation like an Otoscope which lights and magnifies the inner ear. However, most of the people do not consult an ENT specialist until the infection has advanced to severe stages. Often, these infections cause structural deformation of the ear, which can be detected early.

We consider this problem and base our solution approach on basic signal processing. We believe that signal processing of recorded responses can help us identify important governing parameters. The internal structure of the ear canal can be determined using the characteristic values of these parameters. Since direct experimentation on an actual human ear may result in ear damage or hearing loss, we choose a few hollow objects available in every household to conduct our experiments. Details about these objects will be discussed in the following chapters.

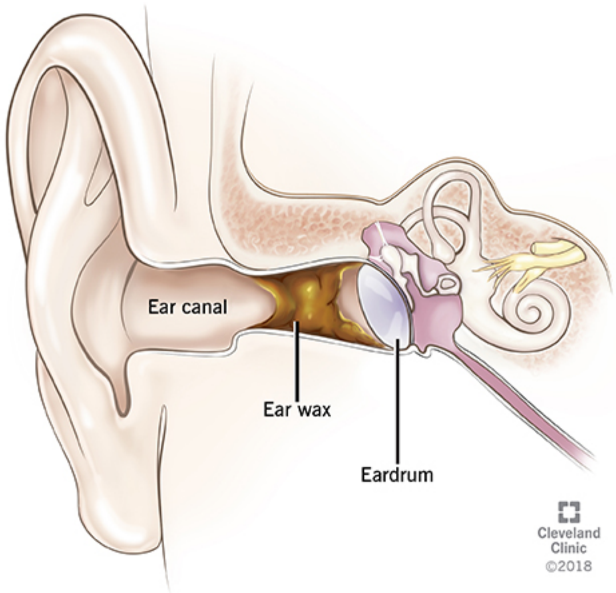

FIGURE 1.1: Illustrative Ear blockage. Taken from (1)

1.2 Motivation

While the idea of earable smart computing is compelling and promising, it is still in the earlier stages of development. Most of the existing use cases revolve around using face muscle vibration to solve the underlying problem statement. For example, Apple Airpods provides an innovative mic activation feature during voice calls which detect the vibrations in jaw muscles generated when one is speaking. This saves energy as well as reduces random noise significantly.

Recent years have witnessed tremendous efforts and advances in terms of computing power and the availability of various efficient nanotechnology. Nowadays, almost all devices have an embedded silicon chip that is capable of performing more than rudimentary computing. After the enormous success of wearable computing via smart wristwatches that provide useful healthcare information of the body below the neck, earables may cater to healthcare information related to a person's head.

1.3 Objective

In most of the current methods in the earable smart computing domain, one can observe their boundary limited to either using face muscles vibrations via specialized sensors or using a microphone array to solve acoustic authentication. Some methods tackle the problem of acoustic imaging but involve complex deep learning models. We believe that a much simpler solution using basic signal processing techniques can be proposed.

To pursue our belief, we choose the problem of detecting ear canal structural deformation, which involves accurately measuring the governing characteristics of a deformed ear canal. Since acoustic experiments with high-frequency sound can damage a human ear, we, in this current work, use the commonly available hollow objects to understand the effects of various parameters like length, shape, the diameter of an object on initially released probe sound. We achieve this by analyzing the reflected sound in a minimal noise environment.

We plan to release a smartphone application, which will analyze the structural changes of the ear canal over time and issue an early warning to the user to consult an ENT specialist in case of deformations.

1.4 Work Done Till Now

Now that our objective is clear, we have conducted an experiment to study one possible approach direction where we cross-correlate the received signal with the original signal. We perform this experiment for two different hollow objects. The actual experiment set up and steps are discussed in a later chapter in more detail. Further, to mathematically convince that the delay patterns obtained from the two different objects are dissimilar, we also calculate the Structural Similarity Index (SSIM) for intra-class and inter-class comparisons.

Chapter 2

Related Works

In this section, we will go through different works carried out in the field of earable computing. One of the emerging fields is Speech Recognition at Low SINR Regimes. Many users, especially in public situations, prefer to speak in an undertone to their voice assistants with headphones. Furthermore, daily places such as shopping complexes, cafes, and public commute are loud. This indicates that speech commands at the earphones would be captured at low SINRs. Hats and scarves will significantly dampen speech impulses to the ear in the cold. Decoding speech in this low-SNR environment is a prominent issue since it is a complex problem in signal processing (2; 3). Authors of (4) think that artificial intelligence is an appropriate solution, but they see potential opportunities in signal processing.

Humans are born with the capacity to discern the 3D direction, θ, in which a sound travels before reaching their ears. This is feasible because sound enters the two ears at different times, and the brain infers the 3D angle by using this time difference of arrival (TDoA). Now, if two earbuds play the same sound with a temporal difference, Δ, the brain is fooled into thinking the signal came from direction θ. These are known as “binaural sounds,” and they are now being researched for use in virtual reality (5).

The two IMUs on each side of the earphones provide a chance to track numerous aspects of human motion. In recent years, there have been advancements in observing and recording the user's gaze direction by tracking head gestures (6; 7; 8). Subtle motions are more difficult to solve that have an indirect effect on the IMU (9).

Since human lungs produce a relatively minor vertical oscillation of the head as they inflate and deflate, recognizing breathing patterns is clearly challenging. The oscillation signal is most likely below the noise floor of earphones with cheap IMUs (10). Breathing sounds might be picked up by in-ear microphones. It may be possible to detect this using poor signal-detection techniques, such as those practiced in astronomy. We believe an earphone or eyeglass may be used to monitor heart rate power efficiently continuously. When a person eats, the mandible, or lower jaw, hinged at the back of the skull moves up and down. The teeth also make contact with each other, causing vibrations to travel along numerous surface routes to the ears (11). The IMU adds up all of these signals and displays differences depending on the activity's type and location.

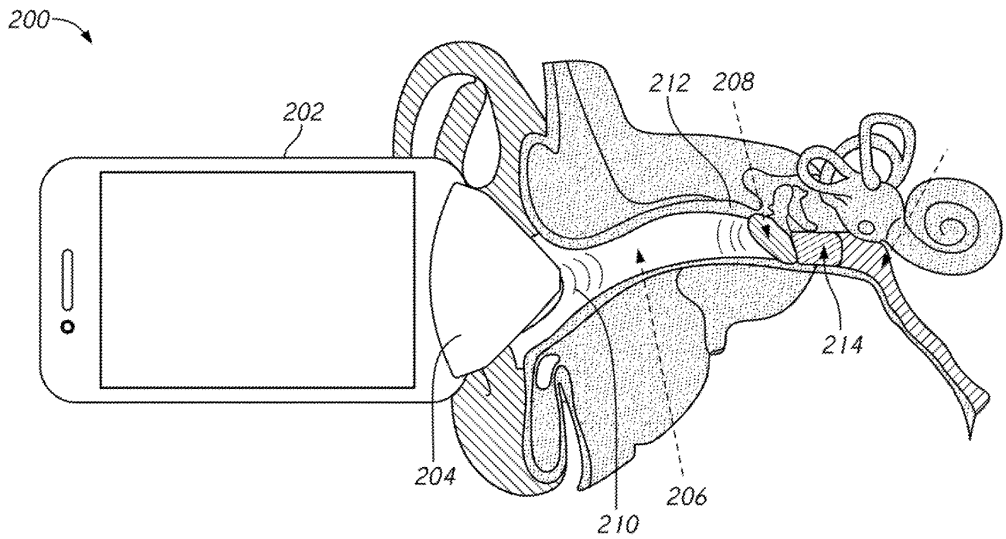

FIGURE 2.1: Method used by Chan et al. Taken from (12)

The ear canal is one of the "inlets" into the human body, and advances at the confluence of earables and healthcare are already underway. (13; 14) show that it is possible to monitor blood pressure, identify sleep phases, and perhaps even quantify distress from inside the ear canal. Mobile phones can detect in-ear infections by emitting sound waves from the phone speaker (15), while (11) indicates possibilities for in-mouth tooth detection using earphones. In the patent submission (12), the authors use the built-in microphone and speaker of cellphones to check for the presence of middle ear fluid, which can be used in Otitis media diagnosis. The findings show that a smartphone has the capabilities to be a minimal and reliable diagnostic tool for identifying middle ear fluid.

Our approach is also at the intersection of earables and healthcare. We attempt to apply simple signal processing techniques instead of Deep learning approaches. This decision is core to our work as we are convinced that basic signal processing can provide an initial solution and perhaps might serve as a basis for more complex learning-based approaches.

Chapter 3

Experiments and Results

In this section, we present the experimental setup and experiments conducted. We then discuss a few inferences that can be drawn from the experimentation results.

We start with a brief discussion about the environmental conditions under which all the experiments are conducted. We will also discuss about the choice of material for ear-like hollow objects and their significance. We will also present the specifications of a simple smartphone application that is used to facilitate the experimentation and minimize the possibility of human errors.

3.1 Experiment Setup

To conduct acoustic-based experimentation, one has to make sure to comply with a number of precautions. These experiments are pretty sensitive to noise in the surrounding, the acoustic reflectance of the object's material, and characteristics of chirp used as probe sound.

Due to resource constraints, we could not acquire a soundproofed room to serve as an optimal experimentation environment. The nearest equivalent is a closed room at midnight when there is no external noise source. Although the ambient noise is inevitable in the actual use case scenario, we have maintained the noise component to negligible for the initial analysis of the reflected signal.

Figure 3.1: Object ED.

Object material has to be chosen carefully as it has tremendous effects on the quality of reflected sound. Every surface has a different reflectance coefficient. Some surfaces like metals also produce a resonant sound which may cause hindrance in our experiment. We make sure that the chosen material behaves similarly to the actual ear canal. Research studies have found that tubes made of hard plastic material were suitable for studying the effect of different ear canal shapes when a probe sound is emitted in the canal, as they could not cause resonance effect and offer similar reflectance as the ear canal. We are using two hollow objects, named ED and Sip, to understand the effect of depth on reflected sound - (1) ED (Fig. 3.1) - A recyclable cylindrical object closed at one end with 35 cms depth. (2) Sip (Fig. 3.2) - a commonly available cylindrical container closed at one end with 17 cms depth.

FIGURE 3.2: Object Sip.

The choice of probe sound for studying the internal structure of the ear is crucial. We draw inspiration from pulse-coded radar, which offers a high signal-to-noise ratio. We choose a high-frequency (15 kHz) pulse code modulated signal, shown in Fig. 3.4, with 0.25 mm amplitude as our probe sound.

We also developed a simple Android 11 based application, as shown in Fig. 3.3, to perform the steps of the experiment with reasonable accuracy. The application is able to play a custom probe sound in .wav format for a customizable playing time and record the reflected sound for a customizable record time. The rationale behind developing an application over built-in voice recorder applications is to have control over the various default raw audio processing algorithms employed by the built-in application. The application is designed to record unprocessed raw responses with a sampling rate of 44.1 kHz and a bit rate of 128 kbps. Another vital feature of the application is that it supports accurate play-record repetition cycles and saves each recorded clip for analysis.

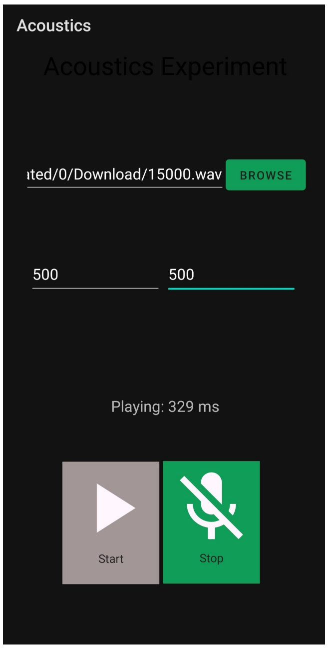

FIGURE 3.3: Android application playing-recording the probe sound of 15 kHz frequency and 500 ms of play and record time.

3.2 Experiment

We conducted the following steps with both the ED and Sip containers. The container is placed horizontally on the floor, with its curved surface touching the floor. The smartphone is slightly (1-2 cms) inserted into the container, and a probe sound is played using the application. The application is configured to play the chirp for 500 ms and record the reflected sound for another 500 ms. We then analyze the recorded sound using the Signal processing toolbox available under the Matlab application.

3.2.1 Signal processing steps

To analyze the recorded signal reflected from the internal structure of the container, we employ a very fundamental principle in Physics. When an acoustic signal is reflected from a surface, it experiences a phase change while the frequency remains

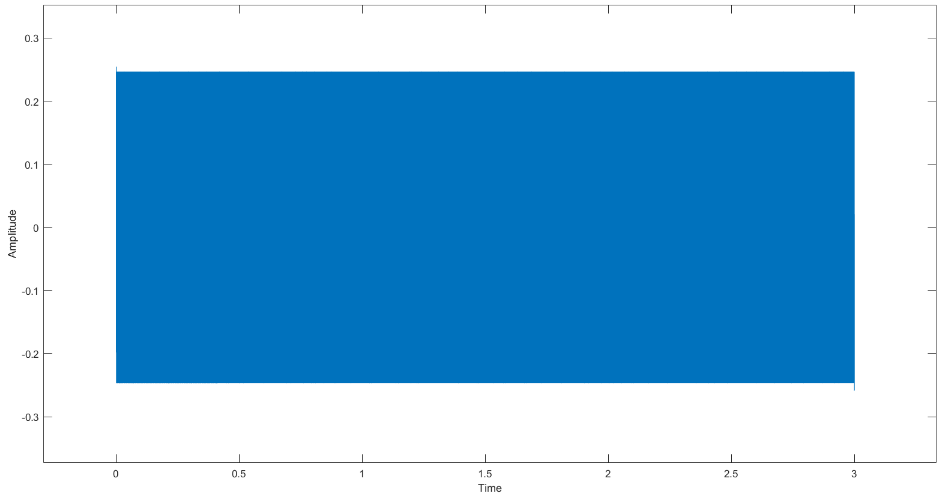

FIGURE 3.4: Amplitude vs time curve for used probe sound.

constant. When correlated with the original signal, this phase-delayed signal unravels the multi-paths through which the reflected signal gets back to the smartphone. We believe that these multi-paths are unique for a container and can help in understanding the internal structure of the subject at hand.

For cross-correlation calculation, we use the `xcorr` function available in Matlab. The official Matlab documentation (16) reads, "The result of `xcorr` can be interpreted as an estimate of the correlation between two random sequences or as the deterministic correlation between two deterministic signals. The true cross-correlation sequence of two jointly stationary random processes, x_n and y_n is given by

$$R_{xy}(m) = E\{x_{n+m}y_n^*\} = E\{x_n y_{n-m}^*\}, \tag{3.1}$$

where $-\infty < n < \infty$, the asterisk denotes complex conjugation, and E is the expected value operator. `xcorr` can only estimate the sequence because, in practice, only a finite segment of one realization of the infinite-length random process is available."

As an advanced step in the signal processing pipeline, we used Structural Similarity Index (SSIM) for intra-class and inter-class comparisons. For this, we plotted cross-correlation for each recorded cycle and used SSIM over each pair of two plots. The Structural Similarity Index (SSIM) is a perceptual metric that quantifies image quality degradation caused by processing such as data compression or by losses in data transmission. The official Matlab documentation (17) reads, "The SSIM Index quality assessment index is based on the computation of three terms, namely the luminance term, the contrast term, and the structural term. The overall index is a multiplicative combination of the three terms.

$$SSIM(x, y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)} \tag{3.2}$$

where μ_x, μ_y, σ_x, σ_y, and σ_{xy} are the local means, standard deviations, and cross-co-variance for images x, y."

3.3 Results

In this section, we discuss the plots obtained from the above experiment and put our inferences. As shown in Fig. 3.5 and Fig. 3.6, each of the 8 plots represent one cycle of recording. The top amplitude vs. time plot represents the recorded signal, and the bottom plot represents its cross-correlation with the input signal in Fig. 3.4.

We can clearly observe the difference in cross-correlation plots of object ED and Sip. Although, it is too early to make a factual inference about the governing characteristics of an object's internal structure. Further to support our observation that correlation plots are different, we also plot structural similarity index for intra-class and inter-class comparisons. For this, we compute the SSIM index for each pair in the Cartesian product of both classes' sets. As in Fig. 3.7, we can observe that the inter-class SSIM index is low as compared to the intra-class SSIM index.

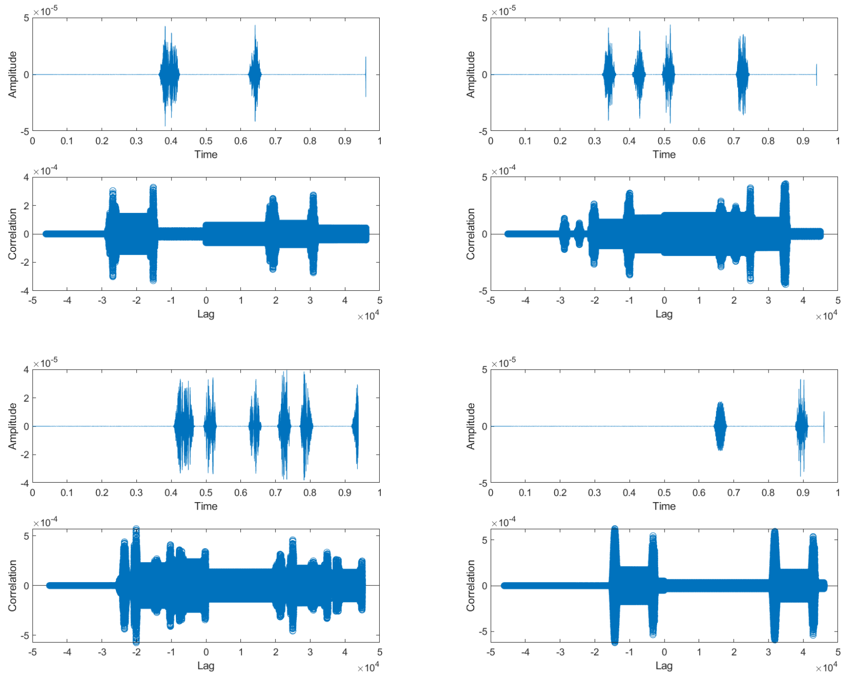

FIGURE 3.5: Correlation values with probe sound for ED container.

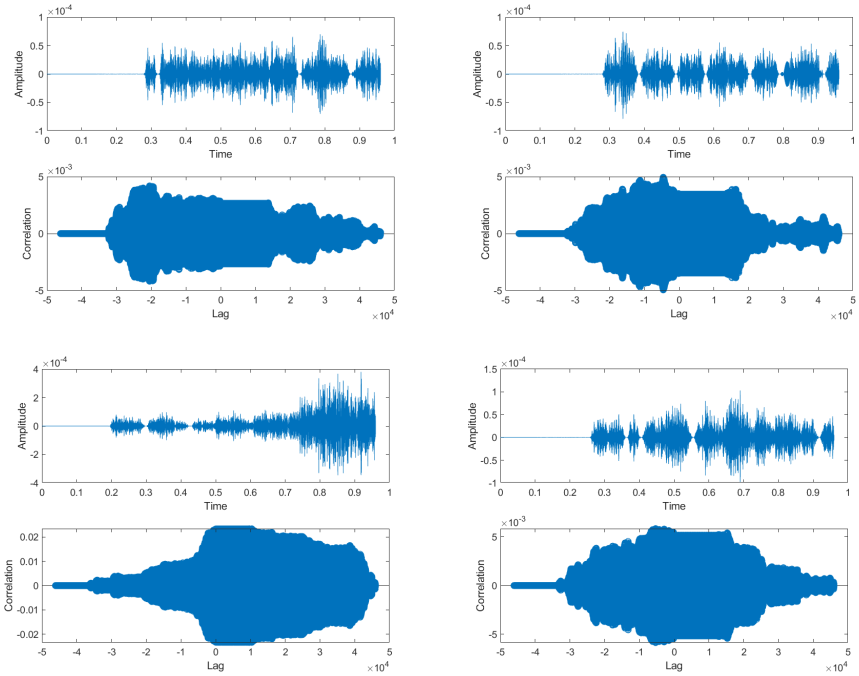

FIGURE 3.6: Correlation values with probe sound for Sip container.

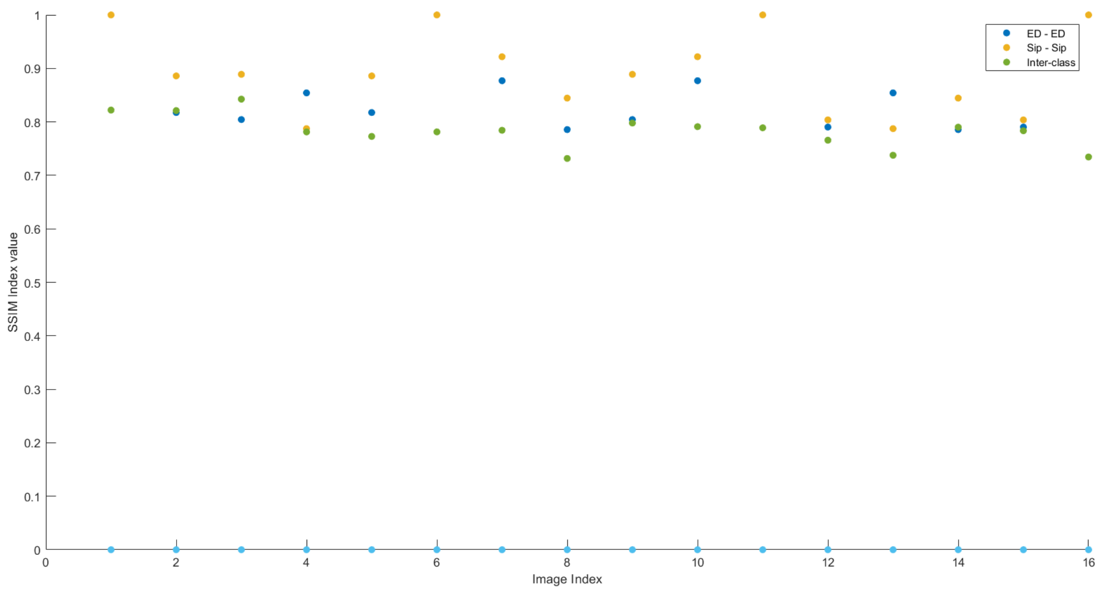

FIGURE 3.7: Intra and Inter-class SSIM Index values.

Chapter 4

Conclusion and Future Works

4.1 Conclusion

In this report, initially, we talk about the current state of wearable computing. Sound is actually the only frequency band in which machines and humans can establish two-way communication. After many significant advancements in the semiconductor and earable computing paradigm, the earphone-as-a-compute device is gaining wide popularity. The central selling point for speech interaction is the minimal effort, and fast responsiveness one gets from the computing devices. The field is still in the early stages of development but is quite promising.

We also talk about various works that have already been done, such as motion and health tracking, which uses built-in IMUs in the earphones. Healthcare is one of the crucial fields which can benefit from such advancements. In fact, some of the existing works discuss that it is possible to monitor blood pressure, identify sleep phases and quantify distress just from the inside of the ear canal. Our problem is also at the intersection of earables and healthcare. Detecting structural deformation of the ear canal may help in the early treatment of the underlying cause and prevent any chronic complications from surfacing. We want to monitor and track these structural changes over time and notify the user if they need to consult an ENT specialist.

Further, we believe that this can be achieved using traditional signal processing approaches, and there is no immediate need for learning-based methods. In virtue of this, we conduct a simple experiment to study the governing characteristics of the internal structure of hollow objects using a probe sound. The recorded response is cross-correlated with the original signal to unravel the multi-paths. We believe that the delay pattern of obtained multi-paths is unique to the internal structure of that container and can be used to analyze changes or any deformation. This is evident from the SSIM Index calculation, which shows better intra-class similarity than inter-class similarity for two different objects.

Although a concrete conclusive argument is not possible at this stage, but this simple experiment gives us confidence that, indeed, the research direction is promising.

4.2 Future Scope

Our primary goal is to develop a structural deformation tracking pipeline that can provide users with early access to significant changes to their ear canal, which might lead to severe complications if left untreated. In future work, we will want to conduct more accurate experiments with an actual 3D model of a human ear. We also want to analyze the effect on delay patterns by making changes to the internal structure of the hollow objects. This will help us develop a mobile application that can track structural deformations over time when paired with the earphone.

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