Design Earable Sensing Systems: Perspectives and Lessons Learned from Industry

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ABSTRACT

Earables computing is an emerging research community as the industry witnesses the soaring of True Wireless Stereo (TWS) Active Noise Canceling (ANC) earbuds in the past ten years. There is an increasing trend of newly initiated earable research spanning across mobile health, user-interfaces, speech processing, and context-awareness. Head-worn devices are anticipated to be the next generation Mobile Computing and Human-Computer Interaction (HCI) platform. In this paper, we share our design experiences and lessons learned in building hearable sensing systems from the industry perspective. We also give our takes on future directions of the earable research.

CCS CONCEPTS

• **Human-centered computing → Mobile computing**; • **Hardware → Emerging interfaces**.

KEYWORDS

Earable Computing; Wearable Devices; Mobile Computing

ACM Reference Format:
Xiaoran Fan and Trausti Thormundsson. 2023. Design Earable Sensing Systems: Perspectives and Lessons Learned from Industry. In *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing and the 2023 ACM International Symposium on Wearable Computing (UbiComp/ISWC '23 Adjunct), October 8–12, 2023, Cancun, Quintana Roo, Mexico.* ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3594739.3610673

1 INTRODUCTION

The demand for hearables is escalating with the surge of the headphone market [3, 4][1]. Earable computing has rapidly gained traction as a promising frontier in the realm of HCI. This nascent field has seen significant strides in miniaturization, sensor technology, and data processing, enabling the development of sophisticated ear-worn devices that offer a plethora of applications across various domains. The recent progress in earable computing spans from health monitoring [6, 9, 13] and biometric authentication [8, 14] to augmented reality [17] and personalized audio experiences [16]. These recent advances in earable computing are revolutionizing the way we interact with technology and amplifying the potential for seamless integration of intelligent systems into our daily lives.

Apple launched the first commercially successful TWS headphones in 2016 [2] and is credited for creating the TWS market. Now the share of ANC enabled headphones is soaring [3]. ANC headphones bring new light to the earable computing. ANC headphones put a feedback microphone inside the ear cup to sense the environment noise heard by the user. As this microphone hears the noise similar to the person does, the ANC circuit can create the anti-noise before sending the resulting signal to the headset speaker. To improve noise cancellation, the ANC headphones further leverage a feedforward microphone outside the ear cup to work collaboratively with the feedback microphone to expand the ANC bandwidth. The feedback and feedforward microphones open up new opportunities for many sensing applications. For example, when the headphones are tightly sealed with the human ear, there will be a coupling effect [10] established, which greatly amplifying low frequency sound in the ear canal. Hence many hearables health features can be realized by recording those body-induced vibrations propagating through the ear canal with feedback microphone passively. This idea has been extensively exploited in academia, prompting many exciting mobile applications including heart rate sensing, ear diseases diagnosis, respiration sensing, body activity recognition, *etc* [11, 12, 15, 18].

Besides the above mentioned benefits for sensory earable, the coupling effect is *the* fundamental reason that in-ear earbuds could create an adequate amount of bass response for music playback. However, this coupling effect is the Achilles heel of hearables, it magnifies the already excessive low-frequency sounds such as sounds due to body motion and wind and make own speech sound unnatural. When the ANC circuitry picks up the amplified low-frequency noise from the environment, this low-frequency noise can saturate the microphone, significantly reduce the dynamic range available for the signals of interest, cause audible artifacts, and make the ANC circuitry to become unstable. The low frequency noise unfortunately causes compromised ANC performances, hinders the audio quality, and even makes ANC earbuds to produce a high-pitched howling noise.

In this paper, we will describe how a solutions that is commonly used in ANC headphones to address this issue can impact earable sensory systems that utilize the ANC microphone subsystem.

It is important to point out that the solutions used in the industry to meditate these effects to optimize ANC performances, transparency mode performances, and voice pickup, can negatively affect many of the algorithms that have been proposed by the community. They are untold to the earabable computing community in the past. Also, often times overlooked by earable community,

[1]We use headphones to represent in-ear, supra-aural, and circumaural (*a.k.a.* , over-ear) listening devices throughout the paper.

UbiComp/ISWC '23 Adjunct , October 8–12, 2023, Cancun, Quintana Roo, Mexico

ACM ISBN 979-8-4007-0200-6/23/10.
https://doi.org/10.1145/3594739.3610673

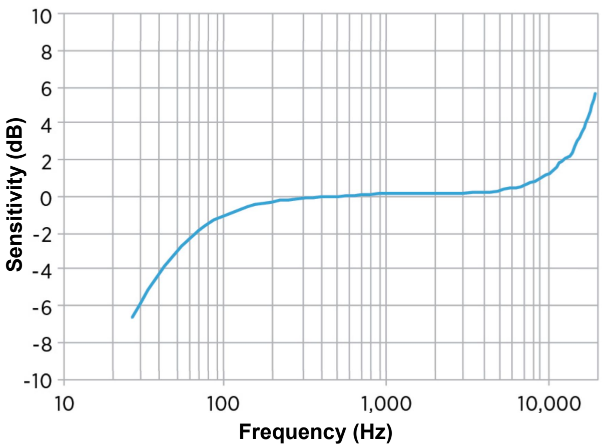

Figure 1: The frequency response of a microphone used in TWS ANC headphones [1]. The low-frequency is intentionally attenuated to prevent the microphone from saturation.

that the primary function of hearables is *audio. i.e.* music playback, telephony (speech), noise cancelation, and the battery life to support them. From an industry point of view, earable sensing systems are better to be designed to improve these primary functions of hearables instead of compromising them. Based on this principle, we discuss some plausible future directions for earable computing in this paper.

2 THE MIST AND UNTOLD CONSTRAINTS FOR TWS ANC HEARABLE SYSTEMS

In order to support the primary functions of TWS ANC headphones, especially the ANC features, the hardware is usually deigned with special specifications. These special designed hardware components are not revealed to the earable computing research community in the past. Some of the envisioned sensory earable features from the research community might be heavily affected by these untold design specifications. We next discuss them in details.

2.1 Built-in High-pass Filtering in Microphones

Due to the coupling effect on the feedback microphones and the wind noise on the feedforward microphones, the microphones can easily get saturated in the wild. The general design idea is to reduce the low-frequency signal picked by the microphones as much as possible. Therefore, the microphones in consumer-grade ANC headphones are preferred to have built-in analog high pass filter with a low cut-off frequency (< 50 Hz). Specifically, in the context of TWS ANC headphones, this is majorly due to the following concerns:

- Audio Artifacts: Without a high-pass filter, the ANC system may unintentionally amplify low-frequency sounds captured by the microphone. This can introduce audio artifacts, such as distortion or an unnatural sound signature, which is termed as *boomy*. These artifacts can interfere with the perception and clarity of higher-frequency sounds, leading to a less satisfying listening experience. Also, when the microphone receives phase distorted high-frequency signals due to microphone saturation, the ANC circuitry is likely to start oscillating, causing *howling* issues. The howling sound can possibly be built up to an exceedingly high level and damage the user's hearing.
- Limited ANC Performance: The excessive low-frequency energy caused by body motion or wind noise is greatly amplified in the ear canal due to the coupling effect. The microphone can be easily dominated or even saturated by the low-frequency signals. In this case, there are two potential problems that could affect the ANC performances. Firstly, if the signal goes into the digital ANC circuitry contains low-frequency components that can not be effectively reproduced by drivers in earbuds, it will be very challenging to design the ANC digital filters. Secondly, the *dynamic range* for the signal of interest is significantly compromised, directly hinder the optimal operation of ANC and transparency mode. This is because the key enabler for ANC and transparency mode is the correct measurement of the surrounding sound by microphones.

Figure 1 shows the frequency response of a typical microphone employed in TWS ANC headphones (Knowles SPH1642HT5H-1 [1]). The lower frequency sensitivity is substantially reduced by the built-in analog high pass filter. As a result, many hearable features and applications demonstrated in earable sensory systems that reply on passive listening [5, 11, 12, 15, 18] are challenging to be deployed on commercial ANC headphones. This is because those passive sensing systems utilize heavily on the low frequency part (< 3 Hz) of the microphone signals for their sensing tasks.

2.2 Nonlinearity

Nonlinearity is unavoidable in speaker drivers for all headphones. In a simplified case, if there are only two tones f_1 and f_2 in the music content, the nonlinearity will make the driver generate not just f_1 and f_2, but also $f_1 + f_2$ and $f_1 - f_2$. The $f_1 - f_2$ part could be in the lower frequency region (< 20 Hz) even if we apply a high pass filter to remove the below 20 Hz audio contents in the original music data. Nonlinearity is more severe when the driver is under a strain (*e.g.* playing louder music). Besides, the speakers of ANC headphones will play anti-noise (ANC mode) or environment sound (transparency mode). Transparency mode in ANC headphones allows external sounds to pass through, making the wearer aware of their surroundings, which will further put a strain on the speaker drivers and easily make the drivers go into nonlinear mode. Note that those nonlinear effects are very difficult to remove by using adaptive filtering or other signal processing methods. Because they are usually unpredictable and uncontrollable. Therefore, those earable sensory systems rely on weak low frequency signal might end up with hard-to-remove interference due to the driver nonlinearity.

2.3 Implications on Earable Systems

Besides the above mentioned two aspects, the coupling effect is known for extremely sensitive to the seal. From the industry perspective, it's hard to justify deploying an unreliable solution to the mass-market products. As a result, because of the combination of all these drawbacks and constraints, passive listening approaches that reply on sensing weak low-frequency (< 3 Hz) signals are hardly viable on commercial ANC earbuds.

3 CORE ANTICIPATES IN THE FUTURE HEARABLES

In the realm of HCI, hearables are emerging as a transformative technology, seamlessly integrating into our daily lives and redefining the way we interact with computers and the digital world. The holistic vision of hearables as an integral part of HCI envisions a future where users can use their headphones to effortlessly control and engage with their digital environment, multitask with ease, and gain insights into their well-being through a seamless fusion of intelligent audio interfaces, personal data analysis, and context-aware earable computing. These anticipated future intelligent hearable scenarios are expected to lead to a higher user demand for better comfort, better transparency mode, better listening experience, and better ANC mode. Next, we discuss some major anticipated features for future TWS ANC earbuds and hearables in general.

Improved Sound Quality: This will be achieved through the use of new audio codecs and technologies, including but not limited to spatial audio, harmonics augmentation, hi-res audio, improved transducer and mechanic designs. While most current sensory earable research in the mobile computing community doesn't focus on this area, improving sound quality is still the most influential direction for headphones. There are many sensing related research such as audio personalizing and noise reduction that can potentially bridge the earable computing community and traditional acoustic society.

Improved Noise Cancellation and Transparency Modes: Future TWS ANC earbuds are expected to offer even more effective noise cancellation, reducing both low-frequency and high-frequency ambient sounds. This could involve advanced algorithms, multiple microphones, and enhanced noise isolation techniques. Many current ANC earbuds offer a transparency mode that allows ambient sounds to pass through, enabling users to be aware of their surroundings. Future models may enhance this feature by providing adaptive customizable levels of transparency or using AI to selectively filter or enhance certain sounds (super human hearing). The adaptive transparency mode depends heavily on the context awareness, which relies on the core research direction in earable computing - sensing.

Better Comfort: As the ANC and transparency mode become better, and headphones become more integral to the HCI, the need for long-term wearability increases. The ideal earbuds should have a more natural transparency mode with superb comfort, as natural as wearing glasses.

More Personalized Experiences: Earbuds may incorporate advanced software and sensors to create personalized sound profiles based on individual hearing characteristics. This could optimize audio output through measuring the head/pinna related transfer function (HRTF/PRTF) to suit the user's unique hearing abilities. On the other hand, integration with personalized virtual voice assistants, such as Siri, Google Assistant, or Alexa, may become more desired due to the emerging generative AI (GAI) technologies. Users could access various personalized functionalities, including personal voice agent, smart home control, and information retrieval, by interacting with their earbuds.

Improved Voice Processing: The future of voice processing for TWS ANC headphones is expected to bring significant advancements in speech recognition, voice quality, and overall voice communication experiences. Such as improved voice recognition, beamforming and directional audio, environmental noise suppression, voice enhancement in poor communication channel, voice activity detection, multilingual support, voice biometrics, etc.

Health and Fitness Tracking: Hearables could become more integrated with health and fitness monitoring. They might include sensing methods for heart rate monitoring, respiration monitoring, blood oxygen level measurement, and activity tracking, allowing users to track their fitness metrics conveniently.

Biometric Authentication: TWS ANC earbuds may feature biometric authentication capabilities, such as "fingerprint" or voice recognition, for secure access to devices or applications.

Extended Battery Life: Battery life is a crucial factor for earbuds. Future models are expected to provide longer playtime and standby time while maintaining a compact form factor. Advancements in battery technology and power management could contribute to improved battery life. Optimizations in hearable chip designs and Sensoryless earable [7] computing could also help extend the battery life.

4 CLOSING THOUGHTS

In this experience paper, we share ANC hearable sensing system design insights and constraints from industrial perspectives. Comparing to many papers in the earable computing community, we provide more practical constraints and conservative views for guiding the earable system design. We We believe creating this sharing-and-learning feedback loop between industry and earable commuting research community could truly make the hearables to be the next generation mobile computing and HCI platform.

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