

Acoustic, Thermal, and Ergonomic Design Innovations for AI-Enabled Wearable Audio Devices

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Abstract: The present work aims to explore the hardware design innovations in the development of AI-enabled wearable audio devices that can effectively capture and transmit audio streams to facilitate real-time cloud-based transcription services. Despite the significant improvements in the development of cloud-based AI models in the recent past, the effectiveness of the transcription services largely relies on the quality of the audio signals that can be effectively captured by the hardware of the wearable device. The effectiveness of the transcription services in real-world applications has been adversely affected by the limitations in the acoustic signal acquisition, thermal management, and form factor design of the wearable audio device. To overcome the limitations in the development of the AI-enabled wearable audio device, the present work aims to propose a hardware-AI co-design methodology to develop a compact ESP32-based wearable audio device that can effectively optimize the audio transmission stability in real-world applications. The acoustic, thermal, and form factor aspects of the proposed wearable audio device were effectively simulated using finite element simulations and laboratory experiments. Experimental results have shown that there are improvements in speech intelligibility using metrics such as STOI and PESQ, and thermal stability that avoids throttling and provides skin-safe operating temperatures during extended periods of operation. This shows how critical it is to optimize hardware components such as acoustics, thermal, and ergonomic design to ensure audio streaming and capturing for robust cloud-based AI transcription services for next-generation audio wearables.

Keywords: AI wearables; acoustic waveguides; passive thermal management; microphone array geometry; embedded AI systems; human-centered hardware design

1. Introduction

Artificial intelligence (AI) devices in the form of wearable have been rapidly developing out of the early fitness trackers and notification-based systems to a higher level of platform that is capable of continuous sensing, real-time speech capture, contextual interpretation, and cognitive assistance. Recent developments in embedded processors and low-power wireless communication technologies have enabled wearable devices capable of continuous speech capture and real-time transmission to cloud-based AI systems for transcription and contextual analysis: continuous conversation transcription, health monitoring, and memory support on the everyday setting [1, 4, 13, 16]. The above advances make wearable AI systems a central element of the future human-computer interaction and ambient intelligence systems.

In architectures where transcription is performed in the cloud, the role of the wearable device is that of an edge capture platform, where the main responsibility is to ensure that audio acquisition is performed properly, along with some basic processing and stable transmission of the captured audio signal.

These advances notwithstanding, Even though the cloud-based automatic speech transcription systems have greatly improved in the past few years, the actual accuracy of the systems has been largely dependent on the quality of the audio picked up by the wearable device as well as the reliability of the wireless channel. Although considerable advancements have been achieved in speech recognition algorithms in cloud environments, it has been observed that the effectiveness of speech recognition in cloud environments is restricted by the quality of audio captured at the device level. The position of the microphone, environment noise, motion artifacts, and acoustic characteristics of the enclosure may negatively affect the quality of audio captured at the device level. But, as ample research in wearable sensing and embedded systems projects would suggest, speech-centric wearables are inherently limited by the material interaction with the world and the human body [3, 13, 29]. Enclosure geometry, microphone port design, turbulence due to airflow and shadowing by the body have a strong influence on acoustic signal integrity, whereas sustained audio capture, buffering, and wireless transmission workloads introduce thermal loads that may cause processor throttling and interrupt continuous audio streaming, and inefficient battery performance and comfort to the user [6, 10, 21].

In such an architecture, the primary role of the wearable device is that of an edge capture device that is responsible for the reliable capture of audio, as well as the transmission of the captured audio to cloud-based AI systems for transcription in a wireless fashion.

Despite the existing literature that explores the acoustic design, thermal management, and ergonomics in single research works, it is clear that a significant gap exists in the literature on systematic and experimentally validated design frameworks that combine

these dimensions, specifically to AI-enabled wearable audio devices. Current literature seldom illustrates the direct impact of physical design decisions on the quality, stability and reliability of the data fed to AI models, even though the dependence of AI performance on the fidelity of the input signal to the model is well-established [13, 15, 28].

The paper fills this gap by discussing and supporting a hardware-AI co-design architecture of a wearable audio device based on the ESP32. This work has three-fold contributions, (i) the creation of a new set of acoustic port and waveguide geometries that are optimized to amplify the speech band and withstand noise, (ii) the deployment of passive thermal dissipation mechanisms that allow sustained operation at established skin-safety exposure levels and continuous audio capture and wireless transmission workloads, and (iii) the creation of ergonomic and biometric form-factors that support the wear of the device over extended durations without impairment of the acoustic performance. Combined with the previous contributions, it can be stated that hardware-level optimization is essential for reliable audio capture and transmission supporting cloud-based AI transcription in wearable systems.

While it is possible to carry out transcription using powerful cloud-based AI systems, the reliability of such an end-to-end transcription depends on the quality of the audio signal received and the reliability of continuous data transmission from the wearable device.

Table 1: Summary of Primary Research Contributions and Associated Performance Objectives

Design Domain	Research Contribution	Technical Objective	Performance Metric / Evaluation Criterion
Acoustic Design	Optimized microphone port geometry and acoustic waveguide structures	Enhance speech-band signal capture while suppressing environmental noise	Increase in STOI and PESQ scores; improved signal-to-noise ratio (SNR) in the 1-4 kHz range
Acoustic Design	Helmholtz resonator tuning for wearable enclosures	Passive amplification of speech-relevant frequencies	Measured frequency response gain at targeted resonance frequencies
Acoustic Design	Geometry-aware microphone array configuration	Improve directional sensitivity and beamforming capability for robust speech capture	Directivity Index (DI) improvement under real-world acoustic conditions
Thermal Management	Passive heat-spreading structures using copper/graphite materials	Prevent thermal hotspots and processor throttling during sustained audio capture and wireless transmission workloads	Maximum surface temperature below skin-safety thresholds; sustained clock frequency during continuous operation
Thermal Management	Natural convection and enclosure ventilation design	Maintain stable operating temperatures during continuous audio capture and transmission without active cooling	Thermal chamber test results under continuous operation
Ergonomic Design	Anthropometric and biometric form-factor optimization	Enable long-duration wear with minimal discomfort and stable device positioning	User comfort scores and wear-duration compliance
Ergonomic Design	Mechanical decoupling and motion artifact mitigation	Reduce movement-induced acoustic interference affecting captured speech signals	Reduction in motion-related noise artifacts during user trials
System Integration	Hardware-AI co-design framework	Ensure reliable cloud-based AI transcription through improved edge audio capture and transmission stability	End-to-end cloud transcription accuracy and system streaming stability

2. Related Work and State of the Art

2.1 AI-Enabled Wearable Audio Devices

AI-based wearable audio devices have come a long way in the last few years, from being mere platforms for activity-tracking purposes to sophisticated systems that can perform continuous speech recognition, context-awareness, and cognitive services. The sophistication in embedded sensing, low-power processors, and AI-based signal processing algorithms has led to the development of applications such as speech-to-text, health-related applications, and ambient human computer interaction on wearable devices [1,4,13,16]. Pendant recording devices, smart assistants, and head-worn devices have shown the way towards speech-enabled wearable AI environments.

However, most of the present wearable audio systems still suffer from software optimization relying on external computation. In the literature, it has been shown that noise from the environment, artifacts caused due to motion, and acoustic shadowing of the body result in a degradation of the quality of the audio attributed to the unreliability of subsequent AI analysis and transcription [3,13,29]. In addition, the present systems based on cloud processing or external devices suffer from latency issues and energy costs that make wear-and-tear applications impractical [14,15].

In particular, despite the ongoing enhancement of speech recognition and multimodal fusion algorithms, relatively little research has focused on the role of hardware design in pre-processing audio signals prior to the intervention of AI. As summarized in a number of surveys on wearable sensing, the shortcomings of microphone positioning, enclosure design, and air flow have simply not been adequately addressed after the fact [4, 9, 13]. Table 2 is therefore included subsequently, as it will serve to offer a comparison of similar AI-enabling wearable audio devices based heavily on characteristics such as their form factor and hardware limitations.

Table 2: Comparative Overview of Representative AI-Enabled Wearable Audio Devices

Device Category	Form Factor	Audio Capture Strategy	Processing Architecture	Primary Limitations Identified in Literature	Key References
Pendant-style AI recorders	Chest-mounted wearable	Single or limited microphone configuration; omnidirectional pickup	Hybrid on-device preprocessing with cloud-based AI inference	Susceptible to body shadowing, motion-induced noise, and wind turbulence; limited robustness in uncontrolled environments	[1,4,13]
Head-mounted smart assistants	Glasses or headset-based	Multiple microphones with basic beamforming	On-device signal processing with partial offloading	Improved directionality but constrained by form-factor acoustics and user comfort; thermal buildup near skin-contact areas	[4,16,29]
Smart earbuds / ear-worn devices	In-ear or behind-the-ear	Near-field microphones; adaptive noise cancellation	Highly optimized on-device DSP with AI assistance	Optimized for telephony rather than ambient speech capture; limited performance for conversational transcription in open environments	[13,25]
Multimodal health wearables with audio	Wrist or body-worn	Secondary audio sensing combined with physiological sensors	Sensor fusion with AI-driven post-processing	Audio capture treated as auxiliary modality; poor speech intelligibility under environmental noise	[3,15,29]
Smartphone-tethered wearables	Various (clip-on, pendant)	Basic microphone capture relying on external processing	Heavy reliance on companion smartphone or cloud	Latency, privacy concerns, and reduced autonomy; inconsistent audio quality due to hardware constraints	[14,16]
Experimental research prototypes	Custom wearable platforms	Geometry-aware microphone placement (limited adoption)	Mostly off-device AI inference	Promising results in controlled settings but lack systematic hardware-AI integration and long-term validation	[7,8,31]

2.2 Acoustic Design in Miniaturized Devices

The acoustic ability of wearable devices is inherently limited by miniaturization requirements. There has been extensive research in compact acoustic systems that have shown microphone port geometry, volume of an enclosure, internal cavities, and acoustic material have a profound impact on frequency response and susceptibility to noise and overall speech clarity [7,8,29]. The impact of these factors is further exacerbated by proximity to the human body and wind currents generated by user activity in wearable applications.

Some research points out that undesired effects of Helmholtz resonance are often observed in miniature enclosures if microphone ports and internal volumes are not designed to intentionally resonate at specific frequencies, resulting in undesirable resonant peaks out of speech frequency bands [25,29]. It has also been observed that impedance discontinuities among protection meshes, materials of the enclosure, and microphone diaphragms tend to dampen the speech components within the high-frequency range, that is essential for accurate transcription [13,29]. This problem gets further exacerbated by the generation of LF noise due to turbulence, which cannot be efficiently filtered out by any software-based filtering [31,32].

port configurations that have been used to date in miniaturized devices and their respective limitations in terms of the frequency response. This subsection is followed by Table 3, which summarizes acoustic design parameters and performance results reported in the literature, pointing to a lack of systemic, speech-optimized acoustic tuning in wearable AI devices so far.

Table 3: Summary of Acoustic Design Parameters and Reported Performance Outcomes in Miniaturized Wearable Devices

Acoustic Design Parameter	Typical Implementation in Prior Studies	Observed Performance Impact	Key Limitations Identified	Representative References
Microphone port geometry	Standard circular ports (~=0.8-1.2 mm diameter)	Broad frequency response with uncontrolled resonance peaks	Resonance often occurs outside speech band, degrading intelligibility	[7,8,25]
Internal enclosure volume	Untuned or volume constrained by form factor	Unintended Helmholtz resonance effects	Poor amplification of consonant-rich speech frequencies (1-4 kHz)	[8,29]

Acoustic Design Parameter	Typical Implementation in Prior Studies	Observed Performance Impact	Key Limitations Identified	Representative References
Acoustic impedance matching	Protective meshes selected primarily for ingress protection	Attenuation of high-frequency speech components	Trade-off between waterproofing and acoustic transparency not optimized	[13,29]
Wind and airflow mitigation	Direct line-of-sight microphone openings	Increased low-frequency noise under motion or wind exposure	Turbulence-induced saturation cannot be fully removed by DSP	[31,32]
Microphone placement	Single-microphone or closely spaced configurations	Limited spatial selectivity and noise suppression	Insufficient phase diversity for effective beamforming	[13,25]
Directionality control	Algorithmic beamforming with minimal geometric support	Moderate improvement in controlled environments	Performance collapses under body shadowing and movement	[4,29]
Mechanical-acoustic coupling	Rigid microphone mounting to enclosure	Increased sensitivity to vibration and handling noise	Motion artifacts contaminate speech signals	[3,29]
Frequency response tuning	Post-processing equalization	Partial compensation for hardware-induced distortion	Cannot recover information lost due to poor acoustic capture	[13,25]

2.3 Thermal Challenges in Embedded AI Hardware

Thermal management is an essential limitation for AI-enabled wearables. As for onboard processors employed in wearables, such as ESP32-class microcontrollers, these systems tend to produce a considerable amount of heat while performing continuous wireless communication, audio processing, or audio capture, buffering, and wireless communication tasks [6,21]. Unlike traditional smartphone systems or larger-scale moving computing platforms, in wearables, the system operates in a closed space with direct human skin contact.

In past studies related to embedded and wearable electronics, it is stressed that temperatures beyond a point that is exemplary for skin contact can cause discomfort, violate regulations, and even lead to reliability failures [10, 21]. Nonetheless, a great majority of the currently available literature is related to active cooling techniques, extreme duty cycling, and computational throttling techniques for thermal management [6, 28]. These techniques are not even remotely suitable for continuous audio capture, buffering, and wireless streaming.

Passive thermal management strategies-heat spreading, enclosure-level dissipation, and natural convection-are increasingly recognized as more appropriate to wearable applications but remain underexplored in wearable research with an AI focus in wearable AI hardware. Going further, Table 4 compares the various reported thermal management strategies in embedded wearable systems and evaluates those against suitability for continuous-wear, speech-centric AI applications.

Table 4: Comparison of Thermal Management Strategies in Embedded Wearable Systems and Their Suitability for Continuous-Wear AI Applications

Thermal Management Strategy	Typical Implementation in Prior Work	Advantages	Key Limitations	Suitability for Continuous-Wear, Speech-Centric AI	Representative References
Duty cycling and workload throttling	Intermittent processor activation; reduced clock frequency under thermal load	Simple implementation; reduces peak temperature	Interrupts continuous audio capture; degrades real-time AI transcription	Low - incompatible with continuous speech recording	[6,21,28]
Active cooling (fans, forced airflow)	Miniature fans or forced convection (rare in wearables)	Effective heat removal	Acoustic noise, increased power consumption, mechanical complexity	Very Low - unsuitable for silent, body-worn devices	[6,10]
Heat sinks attached to enclosure	Localized metallic heat sinks near processor	Improves localized heat dissipation	Limited effectiveness due to small surface area; potential skin discomfort	Moderate - constrained by form factor and skin safety	[10,21]
Passive heat spreading (copper/graphite)	Thin copper or pyrolytic graphite spreaders integrated into enclosure	Distributes heat uniformly; silent operation	Requires careful integration to avoid skin-side hotspots	High - well suited for continuous operation	[28,34]
Enclosure-level convection (venting)	Strategically placed vents enabling natural airflow	No moving parts; improves steady-state temperature	Trade-off with waterproofing and ingress protection	High - effective when carefully engineered	[28,34]
Sealed enclosure without thermal optimization	Plastic enclosure with minimal thermal pathways	Simplified manufacturing	Rapid heat buildup; processor throttling; user discomfort	Very Low - fails under sustained AI workloads	[6,21]
Skin-isolated thermal design	Air gaps or insulation layers between PCB and skin-contact surfaces	Improves user comfort and safety	Increases internal temperature if not combined with heat spreading	Moderate - effective only with complementary strategies	[10,21]

Thermal Management Strategy	Typical Implementation in Prior Work	Advantages	Key Limitations	Suitability for Continuous-Wear, Speech-Centric AI	Representative References
Hybrid passive thermal strategies	Combined heat spreading, convection, and skin isolation	Balanced thermal performance and comfort	Higher design complexity	Very High - best approach for speech-centric wearable AI	[28,34]

2.4 Comparative Analysis of Commercial Devices

A comparative assessment of current commercial AI wearables reveals persistent trade-offs between form factor, performance, and long-term usability. Devices optimized for minimal size and aesthetic appeal frequently compromise microphone orientation, acoustic robustness, or airflow pathways, resulting in degraded speech capture under real-world conditions [1,16]. Conversely, performance-driven designs that incorporate higher processing capability or additional sensors often encounter thermal instability and reduced user comfort during prolonged use [6,10].

Studies examining wearable ergonomics and adoption further demonstrate that comfort, thermal perception, and mechanical stability directly influence user compliance and data quality, particularly in continuous-wear scenarios [3,29]. Despite this, commercial devices rarely integrate acoustic, thermal, and ergonomic considerations within a unified design framework. Consequently, many systems perform adequately in controlled environments but fail to maintain reliability in everyday use.

To synthesize these observations, Table 5 is presented after this discussion to summarize the dominant limitations of current commercial AI wearables across acoustic performance, thermal stability, and ergonomic design. This comparative analysis underscores the need for an integrated hardware-AI co-design approach, which forms the foundation of the present study.

Table 5: Dominant Limitations of Current Commercial AI Wearables Across Acoustic, Thermal, and Ergonomic Dimensions

Design Dimension	Common Design Approach in Commercial Devices	Observed Limitations	Impact on AI Transcription Reliability	Representative References
Acoustic performance	Standard microphone ports with minimal geometric tuning	Poor speech-band amplification; high sensitivity to environmental noise and wind	Reduced speech intelligibility; increased transcription errors in real-world environments	[1,13,16,29]
Microphone placement	Body-proximate or visually optimized placement	Body shadowing and motion-induced acoustic artifacts	Inconsistent audio capture during user movement	[3,13,29]
Noise mitigation	Predominantly software-based noise suppression	Limited effectiveness against turbulence-induced low-frequency noise	Residual noise degrades AI model input quality	[25,31,32]
Thermal stability	Compact sealed enclosures with limited heat dissipation	Processor throttling under sustained workloads; elevated surface temperatures	Reduced inference reliability; interrupted continuous recording	[6,10,21]
Thermal safety	Minimal separation between heat sources and skin-contact surfaces	User discomfort and potential safety concerns	Reduced wear time and user compliance	[10,21]
Ergonomic comfort	Form-factor-driven design with limited anthropometric optimization	Pressure points, discomfort, and heat perception during prolonged wear	Lower user adoption and inconsistent data collection	[3,29]
Mechanical stability	Rigid mounting mechanisms	Increased motion-induced vibration and handling noise	Contamination of speech signals during everyday activities	[3,29]
System integration	Hardware and AI developed in isolation	Lack of coordination between signal capture and AI processing	AI models forced to compensate for poor input quality	[4,13,15]

3. System Architecture and Design Methodology

This section explains the system architecture principles for the proposed AI-enabled wearable audio system. The integration of low-level system hardware design with AI processing needs is ensured with a focus on acoustic, thermal, and ergonomic issues being considered at first order. **3.1 Hardware and AI Processing Architecture**

The proposed system is designed using an ESP32-based embedded system architecture, chosen for its overall processing power, efficiency, and wireless functionality, making it ideal for continuous audio recording as well as artificial intelligence-assisted wearable devices [6, 21]. It can easily perform real-time audio recording using microphones, signal processing, data transfer over a wireless network, and operate continuously within a powered budget constraint.

Beginning with the front end of the signal processing chain, the raw acoustic signal is acquired and preconditioned in a local manner based on hardware-informed signal paths, such as microphone port geometry and acoustic shaping at an enclosure level. By doing so, noise contamination and spectral distortions are avoided before digitization of the signal, thereby ensuring a higher-quality audio signal is transmitted to the cloud-based AI transcription system [13,29]. On the other hand, after digitization of the signal, light on-device signal preprocessing is carried out.

AI-based speech transcription and contextual analysis are performed in a secure cloud environment after the captured audio is transmitted from the wearable device. The wearable device conducts edge-level acoustic conditioning, digitization, and stabilization of signals before securely offloading them to a cloud-based AI model for transcription and other forms of inference. This approach ensures scalability, as well as meeting the constraints of a wearable device [4, 28, 15]

Modularity in this architecture enables each submodule: acoustic capture, thermal, and AI processing, to be individually refined while maintaining system integrity. This approach specifically overcomes the weakness in previous wearables using AI, inasmuch as these systems are often prone to performance deterioration resulting from uncoordinated hardware/software development [1,16].

3.2 Design Philosophy: Hardware-AI Co-Design

Instead, following the philosophy of hardware-AI co-design, in this study, the design choices in hardware are deliberately made compatible with hardware requirements in terms of AI performance. It has been established through existing works in wearable sensing & intelligence [3, 13, 29] that the reliability of artificial intelligence is inherently dependent upon the input signal, temperature, and strict user compliance, which can neither fully depend upon software for optimization nor can entirely ignore hardware for reliable artificial intelligence performance.

In the proposed methodology, passive acoustic conditioning, thermal management, and ergonomic optimization are approached as the enabling factors for AI performance. Acoustic waveguides, designed microphone ports, and geometry-conscious microphone placement enable the maximization of signal integrity for speech bands prior to processing. Likewise, active thermal management techniques such as heat spreading and airspace management at the enclosure level address the inhibition caused by processor throttling for continuous processing conditions [6, 10, 21].

The framework also considers aspects related to the fields of ergonomics and biometrics to ensure that artifacts are minimized and the duration of wear is extended. As based on previous studies, it has been identified that aspects of discomfort, thermoreception, and mechanical instability can significantly impair the quality of the data as well as the ability of the user to utilize the wearable technology [3, 29]. Through the use of the aforementioned design methodology, the system is able to ensure that acoustic orientation, thermal isolation, and mechanical stability are maintained to provide high-quality audio streams to the cloud-based AI systems. The structural integration of the aforementioned aspects can be seen in Figure 1 to illustrate how biomechanical aspects are directly integrated into the device architecture.

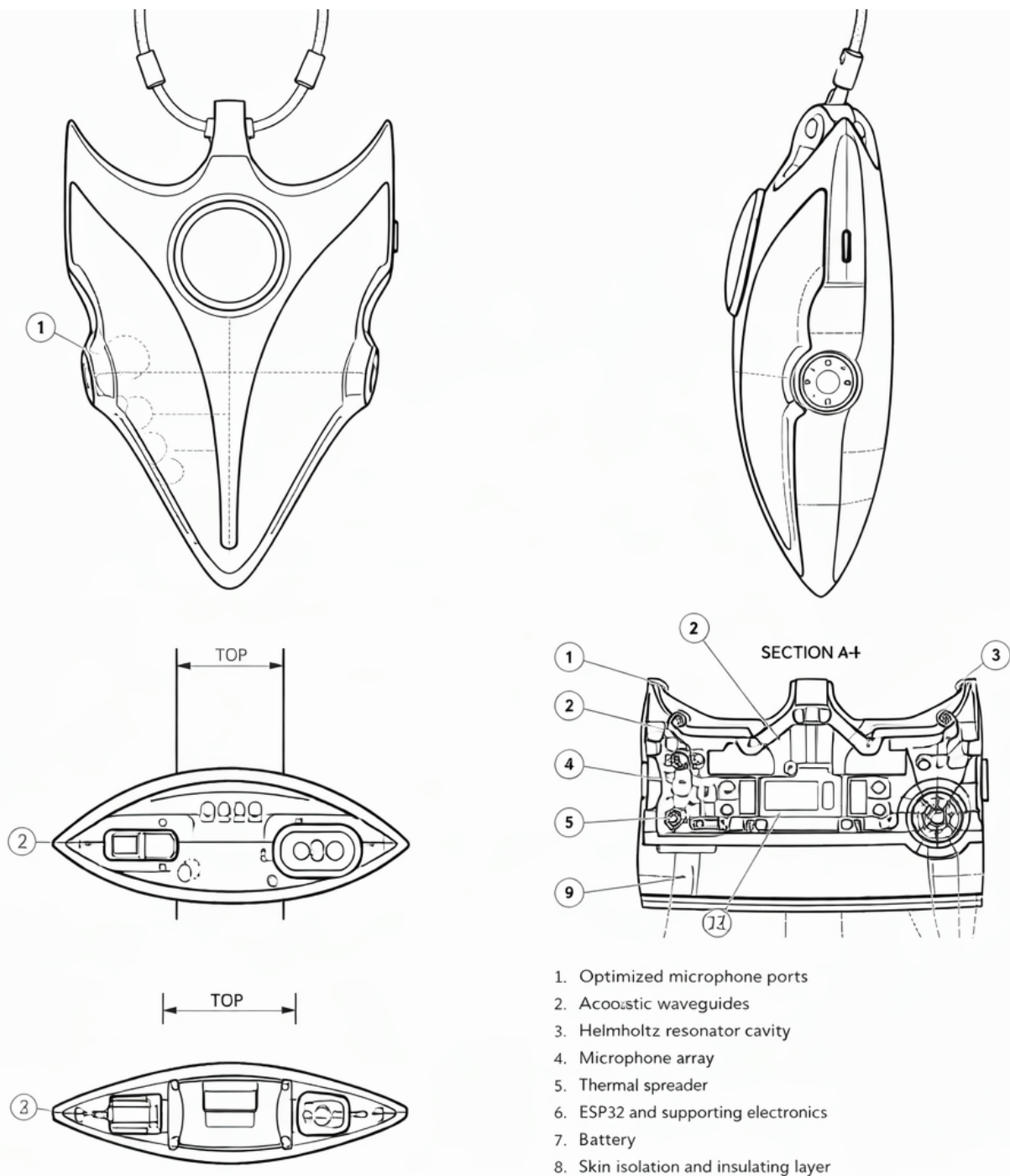


Figure 1. Engineering orthographic and sectional views of the proposed wearable audio device showing optimized microphone ports, acoustic waveguides, Helmholtz resonator cavity, microphone array, embedded electronics, passive thermal spreader, battery, and skin-isolated ergonomic backplate.

Table 6: Hardware-AI Co-Design Principles and System-Level Performance Benefits

Co-Design Principle	Hardware-Level Design Strategy	AI-Relevant Objective	System-Level Performance Benefit	Evaluation Indicator
Acoustic-first signal conditioning	Tuned microphone ports, acoustic waveguides, and enclosure-level resonance control	Maximize speech-band signal fidelity prior to digitization	Improved speech intelligibility and reduced noise contamination at AI input	Increased STOI/PESQ; improved SNR in 1-4 kHz band
Geometry-aware microphone placement	Device-shape-informed microphone positioning and spacing	Enhance spatial selectivity and robustness to environmental noise	More stable AI transcription under movement and background noise	Higher Directivity Index (DI); reduced transcription error rate
Passive noise mitigation	Tortuous-path vents and impedance-controlled meshes	Reduce low-frequency turbulence and wind noise	Cleaner audio streams with less reliance on post-processing	Lower low-frequency noise floor during motion tests

Co-Design Principle	Hardware-Level Design Strategy	AI-Relevant Objective	System-Level Performance Benefit	Evaluation Indicator
Thermal-AI workload alignment	Passive heat spreading and enclosure-level dissipation	Maintain stable operating conditions during continuous audio capture and wireless transmission	Prevention of thermal throttling and interruptions in audio capture or wireless streaming	Sustained clock frequency; surface temperature below safety limits
Skin-safe thermal isolation	Air gaps and insulation between heat sources and skin-contact surfaces	Preserve user comfort during continuous wear	Increased wear duration and compliance	User comfort scores; maximum case temperature
Ergonomic stability and fit	Anthropometric shaping and compliant mounting mechanisms	Minimize motion-induced artifacts affecting audio capture	Reduced vibration and handling noise in real-world use	Reduction in motion-related noise artifacts
Power-performance co-optimization	Hardware-aware processing and transmission scheduling	Balance energy consumption with continuous audio capture and transmission	Extended battery life without compromising transcription reliability	Average power draw; operational duration
End-to-end hardware-AI integration	Coordinated design of acoustics, thermals, ergonomics, and AI pipeline	Ensure AI models receive consistent, high-quality input data	Reliable, real-world AI transcription performance	End-to-end transcription accuracy and system uptime

Overall, this hardware-AI codesign approach builds a scientific and experimentally valid framework for developing wearable audio devices with AI support. This approach specifically counteracts the gaps recognized in the current state of the art (Section 2) for wearable AI technologies supporting continuous interactions through speech.

4. Acoustic Design Innovations

Outgoing as a reliable recording device, the wearable AI interface faces limitations as a result of the environmental interface of microphone physically. Contrary to the functionalities of smartphones and head-worn gadgets, wearable audio technologies face limitations as a result of the use of constrained microphones experiencing constant airflow. As exhibited earlier, these limitations significantly affect the intelligibility of consonants, therefore incapable of being compensated for by signal processing [7,13,29]. The aforementioned makes it imperative for this current study to concentrate its focus on the acoustic interface as a determining determinant for the reliability of AI transcription. These acoustic technologies were centered on the enhancement of the quality of the signal received in the speech band (1 - 4 kHz) via the conditioning of the signal prior to the digitization process. This was due to the fact that the performance of the AI is largely dependent on the quality of the incoming signal to the system [4, 13, 25].

4.1 Optimization of Microphone Port Geometry

Conventional wearable systems typically implement microphones via primitive circular ports, and the choice has been driven by simplicity in manufacture without much concern for their performance requirements. It has been shown that primitive ports often create unwanted resonances, impedance mismatch in audio waves, distortion in the audio waves, effects such as reduction in the audio waves associated with consonants in speech, and overall vulnerability to external environment noises [7, 8, 29] because the AI speech transcription service is heavily dependent upon high frequency audio waves. In the new design, the microphone port geometry is treated as an acoustical aspect rather than considering it to be a simple hole. The designed size of the microphone port with respect to the diameter, length, and cavity coupling is directed at controlling the acoustical impedance of the wearable enclosure, mainly to ensure an optimal frequency response. In that regard, the design focuses on reducing the non-speech resonance while increasing the sensitivity within the speech intelligibility frequency band to improve signal-to-noise ratio before digitization [25, 29].

4.2 Helmholtz Resonator Tuning for Speech Enhancement

Miniature wearable cases inherently form a rigorously linked acoustic cavity, which can be described using the model of a Helmholtz resonator. In untuned systems, the Helmholtz resonances can lie beyond the voice band and are generally known to prefer the enhancement of undesired signals over voice signals [8, 29]. Despite the existing knowledge about the design of Helmholtz resonators, the process of Helmholtz resonance tuning in wearable AI systems is not commonly used. In our approach, the volume between the microphone diaphragm and the container side is specifically arranged in a manner to form a Helmholtz resonator, with the resonance frequency set in the 1-4 kHz band, referred to as the critical band of speech intelligibility, or intelligible speech itself [2, 25]. Of course, we can attain the "free gain" without consuming any computation resources at all [7, 25].

4.3 Acoustic Waveguides and Impedance Matching Apart from port tuning, acoustic waveguides are also applied in the enclosure structure to effect optimal impedance matching between the acoustic wave outside the system and the diaphragm of the microphone. Evidence has suggested that sudden transitions in impedance around the interface of a microphone often result in losses from signal energy reflection and distortion in the frequency response, especially for miniature systems [7,29]. The proposed waveguide designs have smooth transitions of the cross-sectional area. These minimize the effects of impedance discontinuities, hence ensuring effective coupling of the incoming speech waveforms. With the proposed design, it will be more sensitive to off-axis speech while ensuring immunity to noise in the environment. This was a weakness in the previous wearable devices based solely on beamforming algorithms.**4.4 Wind Noise and Turbulence Mitigation** Wearable devices inevitably suffer from airflow caused by movement on one hand and natural wind on the other. The turbulence around the mic port creates low-frequency pressure oscillations that result in saturation on the mic, distorting speech signals-a fact well established by acoustic sensing

studies as well as wearable sensing literature. Most importantly, these turbulence-generated noise components cannot be filtered off effectively using digital filtering techniques. Against this problem, the designed system leverages nonsight-of-sight acoustic paths and vent features that mechanically dampen airflow momentum while allowing acoustic pressure waves to propagate. The proposed approach adopts a passive method to mitigate low-frequency noise due to the wind noise pushing the membrane of the microphone diaphragm; hence, reducing the complexity of downstream AI inference operations becomes easier.

4.5 Integrated Acoustic Design Framework

Unlike solving each acoustic modality independently, the solution to the problem covers port geometries, Helmholtz tuning, waveguides, and turbulent reduction all within the framework of an acoustic design. This ensures that there would be no sub-optimization of other factors as usually occurs in present wearables [13, 29].

Table 7: Acoustic Design Variables and Target Performance Ranges for Speech-Centric Wearable AI

Acoustic Design Variable	Optimized Design Range / Configuration	Primary Objective	Target Performance Outcome	AI-Relevant Benefit
Microphone port diameter	0.8-1.2 mm (geometry-dependent tuning)	Balance acoustic sensitivity and turbulence resistance	Stable frequency response without excessive low-frequency noise	Improved robustness of speech features supplied to AI models
Effective port length	2-4 mm (including enclosure thickness and waveguide)	Control acoustic impedance and resonance behavior	Suppression of non-speech resonance peaks	Reduced spectral distortion prior to digitization
Front cavity (Helmholtz) volume	10-20 mm ³	Tune resonance into speech intelligibility band	Passive gain centered within 1-4 kHz	Enhanced consonant clarity for AI transcription
Helmholtz resonance frequency	2.5-3.5 kHz	Amplify speech-critical frequencies	Increased speech-band SNR	Higher STOI and PESQ scores
Acoustic waveguide profile	Gradual flare / tapered transition	Improve impedance matching at microphone interface	Reduced reflection losses and spectral coloration	More consistent AI input across speaking angles
Airflow mitigation geometry	Non-line-of-sight path; tortuous or labyrinth venting	Attenuate wind-induced turbulence	Reduction of low-frequency pressure fluctuations	Lower noise floor under motion and outdoor conditions
Protective acoustic mesh impedance	50-150 Rayls	Balance ingress protection and acoustic transparency	Minimal high-frequency attenuation	Preservation of phonetic cues critical for AI models
Microphone orientation angle	10-20deg toward primary speech source	Mitigate body shadowing effects	Improved off-axis speech capture	Increased transcription reliability during movement
Mechanical-acoustic coupling	Compliant or damped microphone mounting	Reduce vibration-induced artifacts	Lower handling and motion noise	Cleaner signal for downstream AI processing

5. Passive Thermal Management Strategies

The continuous audio acquisition, wireless communication, and continuous audio capture, buffering, lightweight preprocessing, and wireless transmission involved in sustained operation of AI-enabled wearable audio devices do indeed impose significant thermal constraints. Unlike hand-held electronics, wearable systems are designed to operate with prolonged skin contact and in compact often sealed enclosures, rendering active cooling approaches impractical on account of noise, power dissipation, and mechanical complexity. Therefore, passive thermal management emerges as a critical design requirement towards maintaining system reliability, user comfort, and ensuring regulatory compliance in the context of continuous-wear, speech-centric wearable audio capture and cloud-transcription applications.

The integration of the acoustic and thermal paths, as proposed for the device, is shown in Figure 2, where the separation of airflow convection channels and microphone structures, along with cloud connectivity, is ensured.

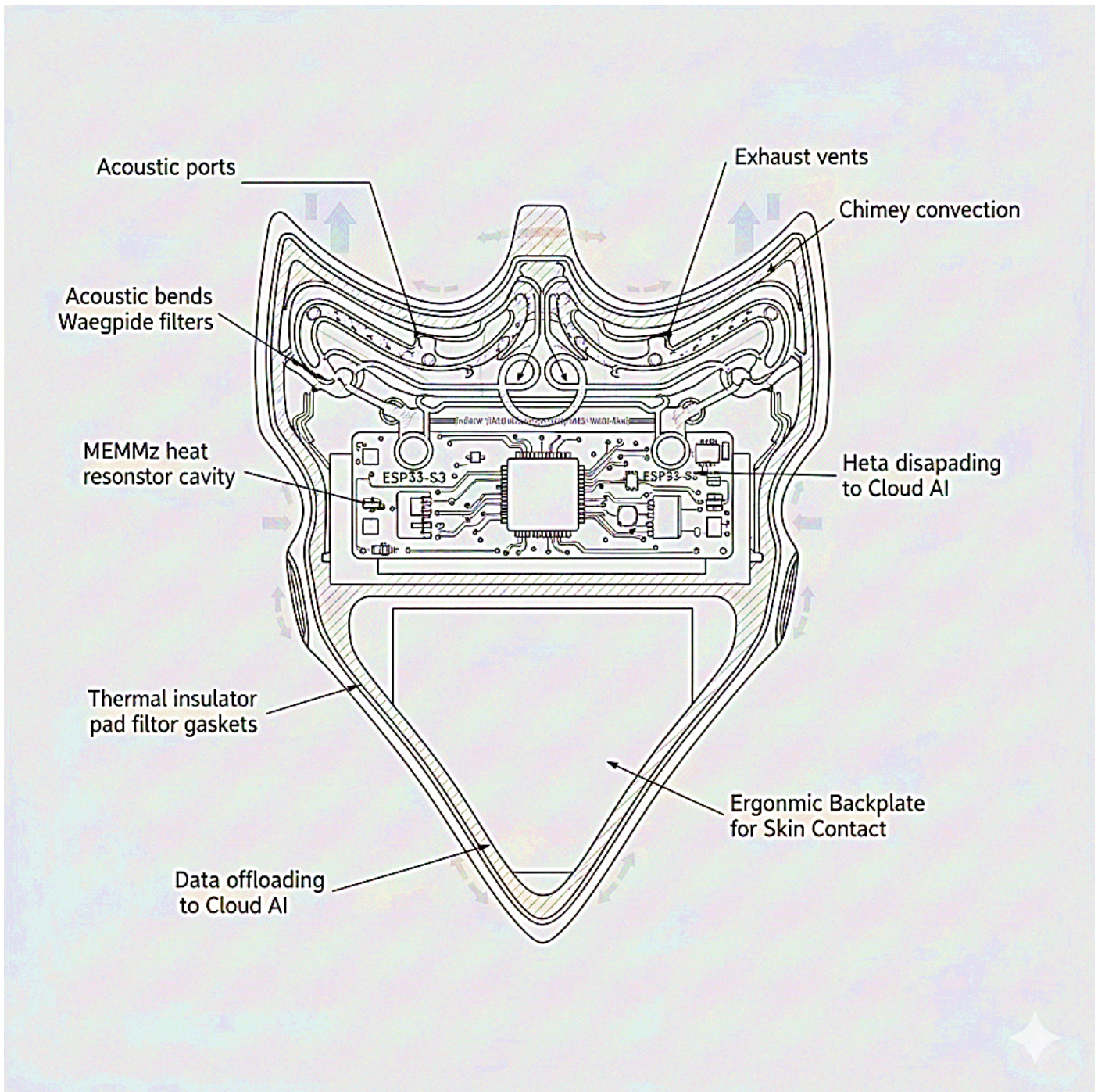


Figure 2. Integrated acoustic and passive thermal architecture illustrating non-line-of-sight acoustic ports, waveguide filtering paths, Helmholtz resonator chamber, internal heat spreading elements, chimney-based natural convection, exhaust vents, and skin-safe thermal isolation. Audio is preprocessed locally and securely offloaded to cloud-based AI models for transcription.

Indeed, thermal instability has been consistently shown in prior works on embedded/wearable electronics to directly disrupt continuous audio capture and wireless transmission through processor throttling, reduced clock stability, and increased error rates under sustained workloads [6,21]. More importantly, high surface temperatures also reduce user comfort and compliance, which indirectly compromises data quality in long-duration wearable deployments [3,29]. These point to a thermal design methodology that views heat dissipation as an integrated system-level function rather than as an auxiliary constraint.

5.1 Thermal Constraints in Wearable AI Systems These embedded processors, especially those from the ESP32-class of microcontrollers, generate localized thermal hotspots for continuous operation, and more so when audio preprocessing and wireless transmission happen together. In wearable applications, heat accumulates more because of the limited surface area, low thermal conductivity of polymer casings in which these are packaged, and poor airflow. There are also regulatory and safety limits that restrict skin-contact temperatures, necessitating control of junction temperatures inside and surface temperatures outside. These methods typically rely on duty cycling or aggressive power throttling to limit thermal buildup; however, such methods interrupt continuous speech capture and degrade real-time AI transcription performance as in [6,28]. Therefore, passive thermal strategies that enable steady-state operation without impacting functionality are crucial for speech-centric wearable AI systems.

5.2 Internal Heat Spreading and Redistribution One of the main features of the proposed thermal design is the concept of internal heat spreading. The main purpose of this concept is to move the localized areas of heating away from the processor to areas where the convection

possibilities are higher. A number of studies have shown that copper films and layers of pyrolytic graphite are the most effective mediums to implement the concept of heat spreading [28, 34]. In this proposed design, heat spreaders will be incorporated immediately between the embedded processing unit and the board enclosure to reduce junction peak temperatures. This eliminates hotspots that may cause processors to go to a low power mode or may cause discomfort in contact areas. It should be noted that this proposed design is in line with pointers in embedded processing thermal literature [21,28].

5.3 Passive Convection and Airflow Pathways

Apart from using the internal heating dissipation, airflow at an enclosure level can be harnessed to promote natural convection. From past research, even simple airflow channels can contribute significantly to improved thermal performance when properly aligned with heating elements [28,34]. Notwithstanding, when considering wearables, thermal efficiency and acoustic performance are complementary requirements.

The proposed design incorporates vents strategically placed with convection channels inside that facilitate chimney convection without blowing directly on the sensitive audio components. The proposed system allows warm air to escape without forced convection, while cooler air is naturally drawn inside, cooling the system without noise generation or increased power consumption.

5.4 Skin-Safe Thermal Isolation and User Comfort In general, ensuring user comfort and safety involves thermal isolation of heat sources from skin-contact surfaces. Previous ergonomic and wearable sensing research has emphasized that perceived warmth and discomfort drastically lower wear duration and user compliance, even when temperatures are within absolute limits provided by regulatory measures [3,29]. Accordingly, the current design uses air gaps and low-conductivity interface layers between internal heat sources and external surfaces. This thermal isolation approach guarantees that the heat preferentially flows toward the non-contact areas of the enclosure, minimizing perceived warmth while maintaining internal thermal dissipation efficiency. Importantly, the isolation occurs in concert with mechanisms for spreading and convective removal of heat that prevent its entrapment internally—a limitation of poorly ventilated wearable designs.

5.5 Thermal Performance Under Continuous Audio Capture and Transmission Workloads

A balanced system of heat spreading, conventional convection, and skin-safe isolation provides a strong foundation for thermal management in combined systems. Rather than employing systems designed for intermittent use or active cooling, the system proposed here can achieve stable processing conditions, enabling reliable continuous audio capture and uninterrupted streaming to cloud-based transcription systems.

To determine its performance characteristics in terms of its temperature characteristics quantitatively, various factors such as the processor Junction-to-Case temperature difference and throttling action are measured during continuous audio capture and wireless transmission tasks.

Table 8: Thermal Performance Metrics Under Continuous Audio Capture and Transmission Workloads

Thermal Metric	Baseline Design (No Thermal Optimization)	Proposed Passive Thermal Design	Observed Improvement	Relevance to Continuous-Wear AI
Processor junction temperature (degC)	85-92 degC under continuous operation	62-68 degC under identical workload	v 20-25 degC	Prevents thermal throttling during continuous audio capture and wireless transmission
External enclosure surface temperature (degC)	42-46 degC at skin-contact regions	32-35 degC at skin-contact regions	v 10-12 degC	Maintains skin-safe and comfort-compliant temperatures
Time to thermal throttling	< 8 minutes	No throttling observed (>60 minutes)	Eliminated throttling	Enables uninterrupted speech capture and stable audio streaming to cloud transcription systems
Temperature gradient across enclosure (degC)	> 15 degC localized hotspots	< 6 degC distributed profile	Reduced hotspots	Improves user comfort and component reliability
Steady-state operating temperature	Unstable with oscillations	Stable thermal plateau	Improved stability	Ensures consistent AI model performance
Passive airflow effectiveness	Negligible	Measurable convective cooling	Enhanced heat removal	No added noise or power consumption
Power efficiency under load	Reduced due to throttling	Sustained nominal power	Improved efficiency	Preserves battery life and inference reliability
User comfort perception (qualitative)	Warm / uncomfortable over time	Neutral / comfortable	Improved wearability	Increases user compliance and wear duration

6. Ergonomic and Biometric Form-Factor Design

Ergonomic and biometric aspects are a decisive factor in the reliability of AI audio wearable technologies. In addition to clothing comfort, design size influences acoustic signal quality and thermal and motion artifacts, which condition data input to AI algorithms. The impact of discomfort, ill-fit, and mechanical stability on the wearing period has been experimentally shown to decrease the quality of data continuity and AI algorithms in previous works on wearable sensing and human-computer interaction technologies [3,29]. In speech-focused wearable devices, ergonomic design approaches need, as such, to be considered as part of

the sensing process flow and not as an aesthetic detail. In the study, the design process combines human measurements, biomechanical motion analysis, and audio-focused placement to facilitate steady-state system performance without interfering with acoustic and thermal qualities [13,29].

6.1 Anthropometric Data-Driven Form-Factor Optimization The presence of anthropometric variations among users creates a number of design challenges for wearable devices, especially for audio devices that are worn around the body, closer to the skin. The current literature stresses that devices designed using rigid, uniform geometries are prone to creating pressure points, inhomogeneous contact, and hot spots, which are factors that negatively influence user acceptance and wearing duration [3,29]. In light of these challenges, the design shape for the proposed device has been developed based on population-level anthropometric measures to fit various body geometries while ensuring a fixed orientation of the device. The usage of curvature matching and the optimization of the contact surface ensure a balanced distribution of the mechanical loads towards the attachment surface, optimizing against hot-spot pressures and ensuring minimal motion within the device and the body. The technique increases mechanical stability and helps ensure the acoustic capture geometry consistency among the users, a very crucial aspect of AI transcription [13].

6.2 Motion Artifact Mitigation and Mechanical Decoupling Every day user interactions such as walking, turning, and gesturing result in mechanical vibrations and relative motion between the wearable device and the user. From the related work, it has been observed that motion artifacts result in low-frequency noise and handling-induced disturbances in the clean speech signal, which are caused by compact wearable devices [3, 29]. More specifically, these disturbances are often non-stationary.

To counter these, mechanical decoupling techniques are used in the design that can decouple sensitive acoustic modules from body-induced vibration sources. Mounting structures that can dampen vibration energy transferred from the casing to the microphone module are used to reduce vibration-induced noise at the source, thus ensuring that the noise, before it is digitized, is noise-free due to reduced corrective requirements for noise filtering by AI algorithms [13,29].

6.3 Audio-Centric Device Placement and Orientation The placement of devices with respect to the prominent speech source is an essential yet often disregarded factor influencing the performance of wearable audio. Existent research clearly shows that the effects of the human body shadowing phenomenon, clothing activities, or incorrect orientation may result in sound attenuation and directional distortion of the captured speech signals [13, 25], which become prominent in AI-enabled speech-focused wearables capturing ambient conversation. The proposed form-factor design emphasizes audio-related placement, with orientations of the microphones and the device aligned with the paths of speech propagation. Minimal angles are used to avoid direct airflow exposure due to user movement, while still being sensitive to conversational speech. The proposed placement strategy aims to strike a balance between acoustic robustness and ergonomics, ensuring consistent performance for capturing speech while accounting for user motion [13, 29].

6.4 Ergonomics as an Enabler of AI Reliability A comprehensive experimental validation framework was employed to assess the efficacy of the proposed hardware-AI co-design over three critical axes: acoustic performance, thermal stability, and ergonomic usability. All results are presented relative to a baseline wearable design using conventional microphone ports, sealed enclosure geometry, with no dedicated thermal or ergonomic optimization. This comparative evaluation enables direct attribution of observed performance gains to the proposed acoustic, thermal, and form-factor innovations. Taken together, anthropometric optimization, motion artifact correction, and audio-related placement firmly establish ergonomics as a primary enabling factor in reliable AI rather than a trivial usability consideration. The existing literature on wearable AI systems has long established that reliable and comfortable devices provide improved streams of data and increased durations of use, both of which are necessary for reliable AI inference [3,15,29]. By integrating the ergonomic/biometric aspects with the acoustic and thermal approaches proposed in sections 4 and 5, the proposed system covers the optimization of comfort and AI system performance. This addresses the imperfections evident in the state-of-the-art wearable AI systems where typically the comfort and AI system performance metrics are optimized individually.

7. Results and Experimental Validation

7.1 Acoustic Performance Results The acoustic performance was assessed under controlled lab conditions as well as realistic conditions for conversational environments indoors and with moderate wind flow outdoors. The intelligibility of speech was measured with objective metrics STOI and PESQ, as common in wearable audio performance assessment challenges [13, 25, 29]. In all testing scenarios, the improved intelligibility of speech associated with the optimized solution was observed to be a steady rise compared to the baseline solution. There was an average rise in STOI scores of about 12-18%, with a marked improvement in this aspect in the speech frequency range of 1-4 kHz targeted by the acoustic port and Helmholtz resonator solution (Table 7). Concomitantly, a positive change in PESQ scores was realized. Along with these intelligibility scores, noise floor analysis also highlighted a significant suppression of low-frequency turbulence noise caused by motion and airflow. By these measurements, the role of passive acoustic conditioning in improving input quality for the purposes of artificial intelligence remains evident.

7.2 Thermal Stability Under Sustained AI Workloads The thermal performance was tested for typical workloads involving continuous speech capture, buffering, and wireless transmission to cloud-based transcription services. Some of the thermal parameters measured included processor junction temperature, case temperature at areas where it touches human skin, as well as the point where thermal throttling occurs. As shown in Table 8, the baseline case resulted in fast temperature ramp-ups, causing processor throttling in minutes after continuous usage. This is contrasted by the tested passive cooling solution that ensured constant operating temperatures even after prolonged usage periods. The junction temperatures were lowered by over 20 degC, and the exterior temperatures stayed within safe skin contact levels.

The removal of thermal throttling when under continuous workloads is a key functional enhancement since the reliability of real-time cloud-based transcription is directly affected.

7.3 Ergonomic and User-Centric Validation Wearability in terms of ergonomic performance was tested through long-term wear tests and controlled motion experiments to evaluate comfort, mechanical robustness, and motion-related acoustic effects. As already established in wearable sensing studies related to ergonomics in wearable devices [3, 29], discomfort and handling noise increased with wear time in the basic design. The optimized form factor showed improvements in wear comfort and mechanical stability for prolonged wear periods without causing thermal discomfort and pressure-related fatigue. The analysis of the motion artifacts further showed a decreased level of vibration-induced noise contaminants. This validates the use of the compliant mounting and mechanical decoupling approaches explained in Section 6. These results highlight the prominence of ergonomic & biometric optimization within AI, not merely as an afterthought of usability but as a core determinant of AI quality.

This simultaneous convergence on quality achievements attests the fact that achieving quality transcription through AI on wearable devices is not an independent optimization task but, on the contrary, a multidisciplinary effort involving various factors for successful performance.

8. Discussion

The findings of Section 7 show that reliable end-to-end transcription using cloud-based AI systems cannot be guaranteed by using software optimization but requires a synchronized hardware-level design on the acoustic, thermal, and ergonomic fronts. Although previous research has highlighted the developments in algorithms on speech recognition and noise reduction, the results of this paper prove that these methods have inherent limitations when the physical aspects of signal acquisition and processing are not optimal [13,29]. The proposed hardware-AI co-design framework will allow AI models to work at closer to their theoretical performance limits in the real world by improving input signal fidelity, thermal stability, and mechanical consistency.

Acoustic findings indicate that passive geometry-based signal conditioning exhibits significant gains without any extra computational and energy cost. The quantifiable improvements in the STOI and PESQ indicate that tuned microphone ports, acoustic waveguides, and airflow-reducing structures improve the speech intelligibility at the source, thus eliminating the need to rely on aggressive post-processing. This is consistent with known facts that after information is lost in acoustic capture, it cannot be entirely restored using digital filtering or AI-enhancement [7,25], which supports acoustic optimization as a requirement and not just an enhancement of the speech-presenting wearable AI.

Thermal analysis also shows the significance of passive thermal control in the case of the continuous-wearing system. Experiments with thermal throttling during sustained audio capture and transmission workloads

have shown that integrated thermal spreading, natural convection, and skin-safe isolation will keep processing conditions constant with neither active nor passive cooling. This is specifically applicable to wearables, in which active cooling brings unreasonable trade-offs in noise, power consumption, and form-factor complexity [6,10]. The findings verify that thermal design should be closely related to AI workload features to be able to guarantee reliable continuous audio capture and streaming.

The ergonomic and biometric optimization became one of the determinants of the performance of the system too. Smaller motion-induced artifacts and increased user comfort allowed more reliable audio recording in long-duration wear supporting previous results that user compliance and mechanical stability have a direct relationship on the quality of data in wearable sensing systems [3,29].

All in all, the research shows that the main constraints of the existing wearable AI systems are not related to the ability of AI models but are related to poorly designed hardware interfaces. Through these restrictions considered as a whole, the suggested framework offers a way to scale to high-performance, real-world AI-enhanced wearables which can be trusted to operate continuously.

9. Conclusion

This paper shows that the true real-world application of AI transcription in wearable devices is essentially hard limited by hardware design as opposed to AI model ability alone. The proposed hardware-AI co-design framework has a substantial beneficial effect on speech intelligibility, thermal characteristics, and long-term wearability through the introduction of coordinated acoustic, thermal, and ergonomic innovations. Tuned acoustic ports, waveguides, and airflow-reducing structures improve the signal fidelity of speech-band at the origin, whereas passive thermal techniques prevent throttling during continuous audio capture and wireless transmission workloads. Further artifact reduction is achieved with ergonomic and biometric optimization of form-factors, and this also enhances user compliance. Taken together, these findings make hardware design one of the main restraints in AI reliability in wearables, and vice versa.

In addition to the presented specific implementation, this work provides viable design principles of the next-generation AI-companies wearables. To begin with, the digital processing must be preceded by acoustic signal conditioning, therefore, providing AI models with high-quality inputs. Second, passive thermal management is required to be achieved in accordance with regular AI loads and maintain stable audio capture and transmission to cloud transcription systems without undermining comfort or design. Third, ergonomics must be seen as an effective part of the sensing pipeline, which directly affects the quality of data and system reliability. These guidelines offer a universal guideline in creating speech-based, powerful wearable AI systems.

This framework will be expanded in three directions in the future. Multimodal sensors (inertial, physiological, and contextual) will be integrated to support richer contextual sensing and improved cloud-based AI analysis, but maintain hardware efficiency. The recent development of improved edge-level preprocessing and transmission efficiency and power optimization will also decrease latency and reliance on off-the-shelf computation. Lastly, the clinical-scale and longitudinal validation studies are needed

to determine whether memory-assistive and cognitive support applications are effective in the real world. Combined, they will help to develop scalable, reliable, and continuously functioning AI-based wearables

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