PROSPECTIVE ACTIVE NOISE CANCELLING ALGORITHMS IN TRUE WIRELESS STEREO (TWS) TECHNOLOGIES FOR ASPIRING INVENTORS

Abstract. The confluence of adaptive algorithms, AI, and innovative features like Hearing Augmentation in ANC technology signifies a paradigm shift towards more intelligent, user-centric audio devices. This evolution holds the promise of transforming the audio listening experience, offering users unprecedented control, personalization, and immersion in their audio environments. The research aims to cover advanced ANC algorithms that can further improve the performance of TWS devices. The article researches Active Noise Cancelling (ANC) technology, spotlighting the pivotal algorithms that drive its efficacy in various applications, including consumer electronics. It explores the foundational Least Mean Squares (LMS) algorithm known for its adaptive filtering capabilities, alongside its enhanced version, the Normalized Least Mean Squares (NLMS) algorithm, which boasts improved stability and convergence through normalization. The Adaptive Feedback Canceling (AFC) algorithm is also discussed for its role in minimizing feedback within ANC systems, particularly in devices like hearing aids. The article also covers Feedforward ANC and Feedback ANC approaches, emphasizing the importance of application-specific and noise environment considerations in choosing the appropriate ANC method. This exploration extends to the potential of AI-based noise cancellation technologies, like Krisp’s Noise Cancellation, which utilizes artificial intelligence to intelligently filter out unwanted noise, offering a significant improvement over traditional methods, particularly in complex virtual environments. The considerable role of AI and machine learning in developing algorithms that augment TWS device capabilities is emphasized, highlighting their...
contribution to features like adaptive ANC, transparency mode, conversation enhancement, and personalized music experiences. The practical significance of the research lies in its potential to enhance the effectiveness and adaptability of Active noise-canceling technology across various applications, paving the way for more immersive and personalized audio listening experiences by integrating advanced algorithms and AI-driven innovations.

**Keywords:** active noise canceling, algorithms, true wireless stereo.

**Problem statement.** The issue of this article is highly relevant in the modern landscape of healthcare, audio technology, consumer electronics, and the automotive industry. Consistent exposure to loud environments can lead to noise-induced hearing loss (NIHL), a significant health concern. This condition arises from the long-term impact of high noise levels, causing irreversible damage to the inner ear's hair cells, essential for converting sound waves into signals the brain can interpret. This damage results in hearing loss and tinnitus (persistent ringing in the ears) and can increase stress and fatigue. These effects severely impact an individual's communication ability and overall quality of life. For professionals working with sound, such as musicians or sound engineers, the need extends beyond protection to require crystal-clear sound quality. Achieving pristine audio fidelity is crucial for these individuals, making managing ambient noise and preserving auditory health paramount in their professional environments. Active Noise Cancellation (ANC) technology has expanded its applications beyond headphones, finding utility in automobiles and various household devices. In the context of vehicles, the system employs microphones or sensors strategically positioned throughout the car to detect specific noises, including those stemming from the car's motion and structural vibrations. These noises are then analyzed by a Digital Signal Processor (DSP), which creates inverse sound waves to neutralize the unwanted noise effectively.

Across the globe, numerous environments necessitate hearing protection or sound reduction measures to safeguard individuals from the detrimental effects of excessive noise. These protective technologies are broadly classified into three categories: active, passive, and hybrid, each with its unique mechanism and application.

- **Passive Technologies:** these technologies rely on materials and design to physically obstruct sound from entering the ear. Passive devices, such as earplugs and earmuffs, use dense, sound-absorbing materials to diminish the volume of external noise. Their effectiveness is particularly notable for higher frequency sounds and relies heavily on the fit and seal they provide around or in the ear.

- **Active Technologies:** active noise control (ANC) is more sophisticated, utilizing electronics to generate a sound wave that is precisely opposite in phase to the ambient noise. This "anti-noise" signal effectively cancels unwanted sound through destructive interference, making it especially effective against low-
frequency noise. ANC is commonly employed in headphones and specialized ear protection devices.

- Hybrid Technologies: these combine the principles of active and passive noise cancellation to offer a comprehensive noise reduction solution. Hybrid devices can provide superior protection across a broad spectrum of sound frequencies by integrating materials that passively block sound with electronic systems that actively cancel noise [10].

This study focuses on active noise cancellation technologies, particularly within the rapidly growing domain of True Wireless Stereo (TWS) earbuds. These devices have undergone a remarkable transformation in recent years, evolving from their initial stages as novelty items with connectivity issues to becoming indispensable, high-performance accessories. Today, TWS earbuds are not only used for listening to music and consuming media but have also become vital for on-the-go calls and teleconferencing. They are even branching into new functionalities like vital signs monitoring and hearing enhancement.

Analysis of recent research and publications. The topic of active noise canceling (ANC) in true wireless stereo (TWS) technologies has been extensively studied, with significant contributions from researchers like Prasadh et al. [7]. Their work covers efficient noise reduction algorithms, highlighting the balance between cost-effectiveness and effectiveness in noise removal. Essential methods include optimal linear filtering, such as Wiener and Kalman filtering, and spectral subtraction. The study also introduces more advanced algorithms like the Signal Dependent Rank Order Mean (SD-ROM), which is adept at preserving audio signal characteristics while removing noise. Techniques like the discrete wavelet transform for Gaussian white noise removal are also discussed. These methods are evaluated based on their ability to improve the signal-to-noise ratio (SNR), offering valuable insights for developing more effective ANC solutions in TWS devices.

The study by Nilay et al. [6] also covers the domain of Active Noise Control, focusing on the use of the Least Mean Squares (LMS) and Normalized Least Mean Squares (NLMS) algorithms. It focuses on signal processing as an operation crucial for extracting valuable information from noisy environments. The research highlighted the limitations of time-domain approaches, where signals use a threshold to remove noise, pointing out their inefficiency compared to signal processing methods. The study emphasized the advantages of adaptive filters, which, unlike conventional filters, do not have fixed coefficients and do not require prior information about the signal. These adaptive filters adjust their parameters dynamically to minimize an error signal, making them highly effective for noise cancellation. Adaptive filters can be implemented in various forms, including Finite Impulse Response (FIR), Infinite Impulse Response (IIR), lattice, and transform-domain filters. According to the study, the most common adaptive filters are transversal filters employing the LMS and NLMS algorithms, showcasing their potential in active noise control applications.
The study by Prodeus [8] assessed the quality of noise reduction algorithms in voice control channels, finding that only the log likelihood ratio and signal composite index metrics align well with speech recognition accuracy when noise reduction is used as a pre-processor for automatic speech recognition systems. Surprisingly, the Wiener-TSNR and Wiener-HRNR algorithms were less efficient, particularly at SNR levels above 8 dB, where they actually reduced speech recognition accuracy due to strong signal distortion. The study also concluded that no single noise reduction algorithm consistently outperformed across all tested signal-to-noise ratios, suggesting the need for algorithm selection to be tailored to specific SNR conditions and highlighting that algorithm effectiveness may vary with different automatic speech recognition system models.

The research by Atmojo et al. [2] offers a comparative analysis of these two pivotal algorithms, shedding light on their operational nuances. The study expands on various modifications of the traditional LMS algorithm, presenting a detailed examination of their benefits and limitations relative to the standard LMS approach. The practical applications of ANC, particularly in specialized vehicles like ambulances and commercial vehicles, are thoroughly discussed, illustrating the technology's versatility and impact in real-world scenarios.

**Article objective.** The research aims to focus on the advanced ANC algorithms that can further improve the performance of TWS devices.

Presentation of the core material. We can identify several core algorithms commonly used in active noise canceling (ANC) technology based on scientific research and studies on platforms like GitHub. These algorithms are integral to developing and implementing effective ANC systems in various applications, from headphones to specialized environments. Consider the following widely used technologies:

- **Least Mean Squares (LMS) Algorithm.** The LMS algorithm is a cornerstone of adaptive filtering known for its simplicity and efficiency. It adjusts its filter coefficients iteratively to minimize the mean square error between the desired signal and the actual output. This algorithm is favored for its straightforward implementation and ability to adapt to changes in the noise environment without prior knowledge of the noise characteristics [6,7].

- **Normalized Least Mean Squares (NLMS) Algorithm.** An extension of the LMS, the NLMS algorithm normalizes the step size used in the coefficient update process. This normalization improves the stability and convergence speed of the algorithm, especially in environments where the signal's properties can vary widely. The NLMS is more robust in varying noise conditions, making it suitable for diverse ANC applications [6,7]

- **Filtered-X LMS (FXLMS) Algorithm.** The FXLMS algorithm is an adaptation of the LMS algorithm that includes an additional filtering step to account for the secondary path (the transfer function from the noise source to the error microphone). This extra step helps achieve more accurate noise cancellation in environments where the secondary path can significantly influence the system's performance [5].
• Adaptive Feedback Cancelation (AFC) Algorithm. AFC reduces the feedback in ANC systems, particularly in hearing aids and headsets. By adaptively filtering the feedback signal, the AFC algorithm helps maintain the stability of the ANC system and prevents howling sounds or feedback loops [1].

Adaptive Feedback Canceling (AFC) Algorithm is widely recognized as a mature technology today, with numerous implementations available on platforms like GitHub (2024). Active noise-canceling algorithms fall into two categories: Feedforward ANC and Feedback ANC. Let's look at the differences in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Feature</th>
<th>Feedforward ANC</th>
<th>Feedback ANC</th>
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<tbody>
<tr>
<td>Principle of Operation</td>
<td>Utilizes microphones placed outside the ear cup or device to pick up ambient noise before it enters the ear</td>
<td>Employs microphones located inside the ear cup or near the ear to detect the sound that reaches the listener</td>
</tr>
<tr>
<td>Noise Cancellation Process</td>
<td>Captures ambient noise and generates anti-noise signals before the noise enters the ear</td>
<td>Captures both the ambient noise that has penetrated the ear cup and the anti-noise to correct any residual noise</td>
</tr>
<tr>
<td>Advantages</td>
<td>- Effective at reducing consistent, low-frequency noise.</td>
<td>- Can adapt to changes in the noise environment and ear cup seal.</td>
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<td>- Less susceptible to the effects of the listener's movements.</td>
<td>- Effective at reducing a wider range of frequencies, including some higher frequencies.</td>
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<tr>
<td>Disadvantages</td>
<td>- Less effective at adapting to sudden changes in noise frequency and amplitude.</td>
<td>- Can potentially create feedback loops, leading to whistling or howling sounds.</td>
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<tr>
<td></td>
<td>- May struggle with higher frequency noise cancellation.</td>
<td>- Sensitive to the ear cup's seal integrity and the listener's movements.</td>
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<td>Typical Applications</td>
<td>- Aviation headsets</td>
<td>- High-end consumer noise-canceling headphones</td>
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<tr>
<td></td>
<td>- Industrial noise-cancelling headphones</td>
<td>- Professional audio monitoring headphones</td>
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<tr>
<td></td>
<td>- Consumer headphones for commuting</td>
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Note: systematized by the author

The specific application and the noise environment are critical considerations in choosing the two approaches above. Feedforward ANC may be preferable for more predictable noise environments, while Feedback ANC offers greater adaptability and performance in diverse and changing noise conditions.

Considering the evolution of technologies from basic wind noise reduction to advanced features like Adaptive EQ, Spatial Audio, Conversation Enhancement, and Active Noise Cancellation, it's clear that future algorithm development will likely focus on enhancing virtual auditory experiences (fig.1). Virtual environments, characterized by background noises such as microphone feedback, ambient sounds,
and audio artifacts, challenge the immersion and communication within these environments. The dynamic and complex nature of virtual audio, influenced by diverse sound sources, varying microphone qualities, and the digital processing of audio, necessitates innovative solutions.

AI-based noise cancellation technologies, exemplified by solutions like Krisp's Noise Cancellation, employ artificial intelligence algorithms to intelligently filter out unwanted noise in real time. Unlike traditional noise cancellation methods, which might falter in the versatile landscape of virtual environments, AI-powered noise reduction is adept at handling the multifaceted audio challenges that virtual spaces present.

The future trajectory of earbud technologies, particularly True Wireless Stereo (TWS) earbuds, seems likely to incorporate broader functions. Emerging capabilities could include voice biometrics for personalized listening experiences and health monitoring features, enhancing the utility and customized nature of TWS devices [4]

<table>
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<tr>
<th>Voice Biometrics</th>
<th>Vital signs monitoring</th>
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<tr>
<td>Adaptive EQ</td>
<td>Adaptive EQ</td>
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<td>Spatial Audio</td>
<td>Spatial Audio</td>
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<td>Conversation</td>
<td>Conversation</td>
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<td>Enhancement</td>
<td>Enhancement</td>
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<td>Active Noise Cancellation</td>
<td>Active Noise Cancellation</td>
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<tr>
<td>Transparency Mode</td>
<td>Transparency Mode</td>
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<tr>
<td>Occlusion Effect Reduction</td>
<td>Occlusion Effect Reduction</td>
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<tr>
<th>Voice Assistant</th>
<th>Wind Noise Reduction</th>
<th>Premium Audio Playback</th>
<th>Multimic Beamforming</th>
<th>Noise Suppression</th>
<th>Bluetooth multi-stream</th>
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**Fig. 1. Promising directions of active noise reduction development in True Wireless Stereo (TWS) technologies [9]**

Active Noise Cancelling (ANC) technology in True Wireless Stereo (TWS) earbuds represents a significant advancement in personal audio devices, aiming to
deliver high-quality sound by reducing unwanted ambient noise. This technology is particularly relevant for environments where noise pollution can distract from the listening experience, such as in urban settings, during travel, or in crowded places. The following list outlines the prospective advancements in ANC algorithms that aspiring inventors could explore to enhance TWS technologies.

1. Adaptive Noise Cancellation Techniques. Future ANC algorithms could leverage more adaptive techniques that dynamically adjust to ambient noise conditions in real time. By using advanced signal processing methods, these algorithms can continuously analyze the external noise profile and adapt the cancellation signal to provide optimal noise reduction without compromising the quality of the audio content.

2. AI-Driven Personalization. Integrating artificial intelligence (AI) into ANC algorithms offers the potential for personalized noise cancellation experiences. By learning from a user's listening habits, preferences, and typical noise environments, AI-driven ANC can tailor its noise cancellation strategies to suit individual needs, improving comfort and effectiveness.

3. Directional ANC. Prospective algorithms may focus on directional active noise cancellation, which targets noise coming from specific directions rather than applying a uniform noise reduction across all vectors. This approach could be particularly useful in situations where it is important to block noise from a particular source while remaining aware of other environmental sounds for safety or convenience.

4. Low-Latency ANC. For TWS devices, minimizing latency is crucial to ensure that the audio content and noise cancellation signals are perfectly synchronized. Future algorithms should aim to reduce latency further, enhancing the user experience during activities that require precise audio-video synchronization, such as watching videos or playing games.

5. Energy-Efficient Algorithms. Given the limited battery life of TWS earbuds, developing energy-efficient ANC algorithms is essential. Innovations in algorithm efficiency can significantly extend battery life, making TWS devices more practical and appealing for prolonged use.

6. Integration with Spatial Audio. As spatial audio becomes more prevalent, ANC algorithms must evolve to support this immersive listening experience. Future developments could involve algorithms that not only cancel noise but also enhance the spatial audio effect, making the listening experience more immersive and realistic.

7. Machine Learning for Environmental Sound Classification. Prospective algorithms could employ machine learning to differentiate between various types of ambient sounds, allowing selective noise cancellation. This means that while undesirable noise can be filtered out, important sounds, such as alarms or voices, can be preserved or even enhanced.
The integration of 7 Sensing's Hearing Augmentation software into today's True Wireless Stereo (TWS) earbuds exemplifies the forefront of audio technology innovation. This state-of-the-art solution redefines the Active Noise Cancelling (ANC) concept by granting users unprecedented control over their sound environment. It allows a seamless transition between enjoying music in solitude and engaging in conversations in noisy environments, or concentrating on a lecture without being disturbed by surrounding noises.

Hearing Augmentation stands out by its ability to dynamically tailor its functionality to the user's immediate audio listening requirements. It recognizes environmental cues, such as the beginning of a conversation, and intuitively adjusts its settings to suit the situation. This adaptability is achieved through a combination of passive isolation and active noise cancellation, optimizing the earbuds' inherent isolation capabilities. The technology is particularly good at mitigating low-frequency noises via ANC, while it relies on passive attenuation to deal with higher-frequency sounds.

Within the Hearing Augmentation framework, 7 Sensing has introduced two innovative modes: 'Super Hearing' and 'Voice Focus.' 'Super Hearing' amplifies environmental sounds, enhancing overall sensory perception, whereas 'Voice Focus' sharpens vocal frequencies to improve the clarity of conversations in noisy environments. This dual-mode functionality not only elevates the user's audio listening experience but also establishes a new standard for TWS earbud capabilities. It reflects a shift towards devices that are not only multifunctional and adaptive but also centered around user preferences and needs, paving the way for the future evolution of personal audio devices [9].

Today, the trajectory of technological development in True Wireless Stereo (TWS) devices is unequivocally oriented toward harnessing Artificial Intelligence (AI) capabilities. AI stands at the forefront of this evolution, driving the creation of algorithms that significantly enrich the audio listening experience by introducing a level of adaptability and personalization previously unattainable.

AI and its subset, Machine Learning (ML), are being embedded within TWS technologies to offer a suite of advanced features that dynamically respond to the complexities of various soundscapes. Features such as Active Noise Cancellation and Transparency Mode, once groundbreaking, have become standard offerings, thanks to the sophistication of AI-driven algorithms. These algorithms meticulously analyze environmental sound in real-time, intelligently adjusting the earbuds' acoustic settings to maintain optimal sound quality and noise isolation, thus accounting for ambient noise fluctuations and the nuances of earbud fit.

Moreover, AI is transforming how TWS devices manage voice communications. By employing algorithms capable of isolating and amplifying human speech in real time, devices can ensure crystal-clear voice transmission even amidst the cacophony of busy streets or crowded venues. The deployment of Deep
Neural Network (DNN) technologies, such as those developed by Chatable, illustrates the potential for AI to minimize audio processing latency, thereby facilitating uninterrupted, clear conversations.

The influence of AI extends to the realm of music enjoyment as well. Through intelligent processing, AI algorithms can enhance the quality of compressed music files on the fly, offering a richer and more immersive listening experience. Personalization is another area where AI shines, with the capability to adjust equalizer settings to suit an individual's unique hearing profile, as demonstrated by products like the Anker Soundcore Liberty 2 Pro and Sony WF-1000XM4. Their personalized audio adjustment is made possible by AI's analytical expertise in recognizing musical genres, elements, and user preferences [3].

AI also introduces a layer of contextual awareness to TWS devices, enabling smart features such as adaptive volume control and noise suppression, which react intuitively to the surrounding environment. For instance, the volume may automatically lower when the device detects someone addressing the user by name, or noise suppression levels might adjust in response to the ambient noise intensity.

The seamless integration of these AI-driven features into TWS devices demands highly efficient processors capable of robust computational performance and significant memory capacity. As the development of audio processors and sophisticated AI algorithms progresses, we can anticipate a future where TWS devices not only offer unparalleled audio listening personalization but also adapt intelligently to the user's environment, setting a new standard in personal audio technology [9].

**Conclusions.** The examination of Active Noise Cancelling (ANC) technology through the prism of scientific research elucidates the crucial role of specific algorithms in enhancing the efficacy of ANC systems across various applications. The Adaptive Feedback Canceling (AFC) algorithm, pivotal in reducing feedback in ANC systems, particularly in devices like hearing aids and headsets, signifies the evolution of ANC technology towards more sophisticated and user-centric solutions. The dichotomy between Feedforward ANC and Feedback ANC approaches emphasizes the necessity of tailoring the choice of ANC technology to the specific application and noise environment, with Feedforward ANC being more suited to stable noise environments and Feedback ANC offering greater adaptability in diverse conditions.

The emergence of multifunctional True Wireless Stereo (TWS) earbuds, equipped with new capabilities like voice biometrics and health monitoring, heralds a new era in personal audio devices, promising enhanced utility and personalized user experiences.

AI's integration into TWS devices, particularly through machine learning algorithms, is revolutionizing the domain with features like adaptive ANC, transparency mode, conversation enhancement, and personalized music experiences.
These advancements emphasize the transformative impact of AI on the audio listening technology landscape, showing a future where TWS devices offer an unparalleled level of personalization and adaptability, tailored to the diverse needs and preferences of users.

References:
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