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Literature Survey on Design and Fabrication of Acoustic Sensor with Application of Environment Monitoring

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Abstract: This paper presents a review of low-cost acoustic noise monitoring systems based on fundamental electronic and signal conditioning techniques. The reviewed systems utilize microphones to capture environmental sound signals, which are processed through stages such as biasing, amplification, and filtering to obtain stable and usable outputs. The conditioned signals are further analyzed to estimate sound levels, enabling effective observation of acoustic variations. The study focuses on analyzing methods used to improve signal quality and measurement reliability through better control of analog parameters such as gain and filtering. Compared to conventional low-cost systems, the reviewed approaches emphasize enhanced signal conditioning to reduce unwanted disturbances and improve consistency in measurements. The study highlights simple, cost-effective, and practical acoustic sensing techniques using core electronic components. This review provides an overview of efficient and adaptable acoustic sensing systems suitable for applications such as environmental monitoring, laboratory analysis, and small-scale industrial observation, with scope for future enhancement through advanced processing and extended functionalities.
Keywords: Acoustic Noise Monitoring; Electret Microphone; Signal Conditioning; Pre-Amplifier; Active Filter; Sound Pressure Level (SPL); Analog Signal Processing; Low-Cost Sensor.

I. INTRODUCTION

Noise pollution has become a significant environmental issue due to rapid urbanization, industrial growth, and increased transportation activities. Continuous exposure to high noise levels can lead to adverse health effects such as hearing loss, stress, and reduced productivity, making accurate and reliable noise monitoring essential for maintaining a safe environment. Conventional sound level meters provide high measurement accuracy; however, they are expensive, bulky, and not suitable for continuous or large-scale monitoring applications. To overcome these limitations, low-cost acoustic sensor systems based on fundamental electronic design have gained importance. These systems typically use microphones to capture sound signals, which are then processed through signal conditioning stages including biasing, amplification, and filtering to obtain a stable and usable signal.

The conditioned signal is further analyzed using basic signal processing techniques such as RMS-based sound pressure level (SPL) estimation, enabling real-time observation of noise levels. Proper design of the pre-amplifier and active filter stages plays a crucial role in improving signal quality by reducing unwanted noise components and enhancing relevant frequency components within the audio band. This paper focuses on the review and analysis of low-cost acoustic noise monitoring systems using core electronic components. The objective is to analyze simple, reliable, and cost-effective acoustic sensing approaches with improved signal conditioning and measurement stability compared to existing low-cost systems, making them suitable for applications such as environmental monitoring, laboratory analysis, and small-scale industrial observation.

II. LITERATURE SURVEY

In [1], the authors designed an IoT-based noise monitoring and control system using analog microphones, ESP32 microcontroller, ADS1115 (16-bit ADC), and Telegram-based remote communication for real-time noise detection. The system continuously measures sound levels and compares them with a predefined threshold of 20 dB, triggering alerts via LCD display, audio warning (DFPlayer Mini), and Telegram notifications when exceeded. The ADC provides 16-bit resolution for accurate signal digitization, and the system supports real-time monitoring in multiple locations (two-room setup). The system demonstrates stable Wi-Fi connectivity and low-power operation with battery support, ensuring continuous monitoring. Experimental results show effective detection of noise variations, though ambient interference (e.g., AC noise) affects accuracy, indicating need for advanced filtering.

In [2], the authors designed a real-time industrial noise mapping system using IoT with MEMS microphones and Zigbee mesh network (IEEE 802.15.4) for large-scale monitoring. The system measures sound in the frequency range of 20 Hz to 8 kHz using one-third octave bands, with data acquisition every 15 minutes and 1-minute sampling duration. Experimental results show measurement error less than 1 dB for tonal signals (250 Hz and 2 kHz) and global noise measurement of ~76.14 dB for an 80 dB input. The system supports network scalability up to ~500 sensor nodes with a communication range of ~100 m per node using mesh topology. It uses I2S-based digital MEMS microphones with RMS sound pressure calculation for accuracy. The work enables large-scale real-time noise mapping, while further improvement in high-frequency accuracy and calibration techniques can enhance performance.

In [3], the authors analyzed capacitive sensor readout circuits for MEMS-based sensing systems, focusing on analog front-end, ADC, and post-processing architectures for improved signal acquisition. The system highlights that typical sensor readout systems achieve SNR in the range of 60–120 dB, while touch-based systems operate at 30–80 dB due to external noise. The ADC used in such systems requires resolution of 10–20 bits and sampling rates from tens of SPS up to ~200 kSPS for acoustic signals. The study discusses techniques like charge amplification, charge integration, and chopper stabilization for noise reduction and signal accuracy. It also identifies parasitic capacitance and signal degradation as key limitations affecting performance. The work provides a strong foundation for sensor design, while further optimization in low-power high-accuracy embedded implementations is required.

In [4], the authors designed a distributed hierarchical wireless acoustic sensor network (WASN) using SLTB004A sensor nodes, ESP32 relay nodes, and Jetson Nano for central processing to perform A-weighted SPL measurement and sound classification. The system operates at a sampling rate of 8 kHz with 16-bit resolution (128 kbps), which is compressed to ~34.29 kbps using ADPCM for efficient transmission. The mesh network handles ~68.58 kbps data rate, with packet size of 240 samples (~56 ms) and achieves very low packet loss (~0.504 sec over 12 hours). The processing delay is ~1.016 s for 1-second audio, and SPL measurement shows accuracy within ~0.5–1 dBA compared to standard meter. The system supports scalability up to ~175 sensor nodes per central unit for large-area monitoring. However, the work emphasizes network architecture and transmission efficiency, indicating scope for further optimization in compact sensing and simplified hardware design.

In [5], the authors presented a comprehensive review of distributed acoustic sensing (DAS) techniques based on Rayleigh backscattering in optical fibers, focusing on system principles, performance parameters, and recent advancements. The system operates using optical time domain reflectometry (OTDR), coherent OTDR (COTDR), and phase-sensitive OTDR (Φ-OTDR) to detect external disturbances such as vibration, strain, and acoustic waves along the fiber. The sensing mechanism relies on changes in refractive index and fiber length due to external physical effects, which modulate the phase and amplitude of the backscattered light. The position of disturbances is determined using round-trip time of the scattered signal ($z = c\sigma / 2n$), enabling distributed sensing along long distances. The system uses narrow linewidth lasers (<100 kHz), photodetectors, and signal demodulation techniques such as IQ demodulation and phase demodulation for accurate detection. Performance improvements are discussed in terms of spatial resolution, frequency response, signal-to-noise ratio, sensing distance, and fading suppression techniques. The study highlights that DAS systems can achieve high sensitivity, long-distance monitoring (tens of km), and wide application areas such as perimeter security, earthquake detection, railway monitoring, and energy exploration. However, challenges such as polarization fading, coherent fading, system complexity, and cost still limit large-scale deployment.

In [6], the authors reviewed design approaches for low-frequency noise measurement systems (LFNM) using low-noise amplifiers, cross-correlation techniques, and FFT-based spectral analysis for accurate noise characterization. The system focuses on low-frequency ranges typically from sub-Hz to a few kHz, where 1/f noise dominates electronic devices. The study highlights the use of high-resolution ADCs (16–24 bit) and long-duration acquisition (up to several minutes to hours) for accurate spectral estimation. It emphasizes that measurement systems achieve very high sensitivity with noise floors in the nV/√Hz range using correlation-based methods. The design requires ultra-low-noise preamplifiers and stable bias circuits to minimize external interference. The work provides a strong foundation for precision noise measurement, while further improvements in compact, real-time embedded implementations are required for practical sensor applications. In [7], the authors presented a comprehensive study on low-cost acoustic sensor networks for urban noise monitoring, focusing on sensor design, network architectures, and deployment strategies. The work analyzed multiple implementations using microcontrollers, MEMS/electret microphones, and wireless protocols such as IEEE 802.15.4 and Wi-Fi. The study identified typical operating ranges of 20 Hz–20 kHz frequency response, dynamic range around 70–100 dB, and sampling rates up to 48 kHz, with most systems achieving ±1.5 to 2 dB accuracy compared to standard sound level meters. The authors concluded that low-cost sensors can provide reliable large-scale monitoring with acceptable accuracy for smart city applications. However, the study highlights the need for improved calibration, stability, and large-scale deployment optimization, indicating scope for enhanced performance and robustness in future systems.

In [8], the authors proposed a smart wireless acoustic sensor network (WASN) architecture for real-time urban noise monitoring and mapping in smart cities. The system integrates distributed sensor nodes, signal processing, and network communication, enabling measurement of key acoustic parameters such as LAeq, Lden, Lday, Lnight, and percentile levels (LA10, LA50, LA90) along with frequency-based analysis. The network supports continuous monitoring with 1-second resolution data acquisition and large-scale deployment for dynamic noise mapping. The study highlights that such systems can achieve real-time data transmission and automated noise map generation for urban environments. The authors conclude that WASN-based systems are effective for large-scale monitoring and policy-making support. However, efficient large-scale deployment, calibration consistency, and system optimization remain important areas for further enhancement.

In [9], the authors designed and implemented a DSP-based acoustic sensor system for outdoor noise monitoring in smart cities using a dual-channel architecture with a digital signal processor (TMS320C5502) and 24-bit ADC (CS5344). The system performs real-time computation of 86 acoustic parameters, including Leq, peak level, max/min levels, percentile levels (L1–L99), and octave/one-third octave band analysis. The sensor operates over a frequency range of 63 Hz to 8 kHz (limited by electret microphone) and supports sampling rates up to 108 kHz with a dynamic range of ~80 dB. Electrical testing shows compliance with Type 1 sound level meter standards (10 Hz–20 kHz), while acoustic performance aligns with Type 2 standards due to microphone limitations. The system enables real-time monitoring and wireless deployment, demonstrated through a network deployed in Málaga with minute-level data transmission. The work concludes that DSP-based sensors provide high accuracy and flexibility for smart city noise monitoring. However, improvement in microphone quality (e.g., MEMS) and EMI robustness can further enhance performance and scalability.

In [10], the authors designed a low-cost configurable acoustic sensor for smart WASN applications using an ARM Cortex-A53 (Raspberry Pi 3) processor with MEMS microphone and IoT connectivity (WiFi/3G). The system supports configurable sampling frequencies up to 48 kHz with 16/32-bit resolution, enabling real-time sound processing and classification. The microphone operates in a frequency range of 50 Hz–15 kHz with SNR ≈ 65 dB(A) and supports effective measurement in 31.5 Hz–16 kHz A-weighted range. The system processes data with CPU usage ~55–75% and RAM usage ~8.5%, and transmits only Leq values and labels to reduce bandwidth load. The complete sensor system is implemented at a low cost of ~139€, supporting scalable smart city deployment. However, the system primarily focuses on sensor configurability and deployment, indicating scope for further enhancement in high-accuracy sensing and advanced noise classification models.

In [11], the authors developed a Wireless Acoustic Sensor Network (WASN) system for real-time urban noise monitoring and acoustic event recognition using CNN-based classification. The system uses acoustic sensors with a frequency range of 20 Hz–20 kHz, sampled at 44.1 kHz with 8-bit PCM encoding for sound acquisition. The study employs ADPCM compression (4:1 ratio) to reduce transmission data while maintaining signal quality. Experimental results show sound level measurement error below 1 dB (0.47 dB quiet, 0.93 dB noisy), indicating high accuracy. The CNN model achieved up to 97.3% classification accuracy for acoustic events and ~91–93% accuracy after compression, with minimal performance loss. The system demonstrates efficient real-time monitoring but faces challenges in power management, data transmission load, and noisy outdoor environments.

In [12], the authors reviewed Wireless Acoustic Sensor Networks (WASN) for environmental noise monitoring using IoT-based distributed sensor nodes. The system measures equivalent noise level (LAeq in dB) and transmits data to a central cloud server for real-time noise mapping. The network supports sampling frequencies up to ~40 kHz and low data rates (few bytes/sec per node), enabling scalable deployment. Hybrid architectures using high-capacity and low-capacity nodes improve efficiency and coverage. The system achieves continuous monitoring with wide-area coverage and reduced cost (~50% lower than traditional methods). However, the work mainly focuses on noise level measurement (LAeq) without detailed classification of individual noise sources, indicating the need for advanced signal processing in future systems.

In [13], the authors developed and deployed low-cost acoustic detection algorithms on the AudioMoth platform using MEMS microphone, ARM Cortex-M4 processor (48 MHz), and onboard signal processing (Goertzel + HMM/CNN comparison) for environmental monitoring. The system supports sampling rates up to 384 kHz with 16-bit resolution, covering a wide frequency range of 20 Hz–192 kHz. The bat detection algorithm achieved F1 score ≈ 0.961 (precision 0.994, recall 0.931, AUC 0.975), while the cicada detection achieved F1 ≈ 0.982 (precision 1.0, recall 0.964, AUC 0.998). The gunshot detection system achieved F1 ≈ 0.75 (precision 0.92, recall 0.64) with effective detection up to ~500 m and sound threshold ≈ 60 dB. The system operates with low power consumption (≈5 mA listening, up to 40 mA recording) enabling long-term deployment. However, the work focuses on event-based detection rather than detailed classification of diverse urban noise sources, indicating scope for advanced intelligent noise analysis systems.

In [14], the authors designed and implemented a low-cost noise sensor using an electret condenser microphone, amplifier circuit, and microcontroller, aimed at continuous noise monitoring in occupational environments. The sensor operates over a frequency range of 20 Hz–20 kHz and was optimized for 60–95 dBA measurement range using FFT-based A-weighted sound level calculation. The system achieved ±2 dBA accuracy compared to a Type-2 sound level meter, with 92% of sensors meeting this criterion and an overall bias of 0.83% in the 75–94 dBA range. The results confirmed strong agreement with reference devices, especially at higher sound levels, with correlation ~0.999. The study concludes that low-cost sensors can provide reliable real-time monitoring for industrial environments. However, performance at lower sound levels (<75 dBA) requires improvement, indicating scope for enhanced sensitivity and wider dynamic range in future designs.

In [15], the authors designed and implemented a low-cost urban noise monitoring sensor network using MEMS microphones, STM32L4 microcontroller, and IEEE 802.15.4 (6LoWPAN) wireless communication for real-time smart city deployment. The system operates with a sampling rate of 32 kHz and computes acoustic parameters such as LAeq, LZeq, and third-octave band analysis (20 Hz–12.5 kHz) with 125 ms resolution. The MEMS microphone supports a frequency range of 20 Hz–20 kHz, SPL range of 35–105 dB(A), and frequency response within ±2 dB (100 Hz–10 kHz). The network achieves communication range >200 m, bit rate ~2 kbps, and packet error rate <5% in outdoor conditions. Experimental results show temperature stability with variation <0.5 dB and reproducibility ~0.3 dB, comparable to standard sound level meters. The system enables scalable, low-cost urban monitoring, while further improvements in long-term environmental robustness and optimization of sensor calibration can enhance performance.

In [16], the authors designed a high-sensitivity acoustic sensor using electrospun piezoelectric PVDF nanofibre webs for direct acoustic-to-electric signal conversion. The sensor demonstrated a very high sensitivity of 266 mV/Pa, which is more than 5× higher than conventional PVDF film sensors (≈42.5 mV/Pa). It effectively detects sound in the low to mid-frequency range (20–2000 Hz) with strong response especially around 220 Hz, and generates voltage outputs up to ~3.1 V at 115 dB sound pressure. The device showed increasing output with sound pressure levels from 60–115 dB, making it suitable for high-noise environments. The study concludes that nanofibre-based sensors provide superior sensitivity and frequency resolution for noise detection. However, optimization for broader frequency response and integration with practical monitoring systems presents further development opportunities.

In [17], the authors designed a low-cost self-testing noise measurement sensor using a microphone–speaker closed-loop system with frequency sweep excitation (80 Hz–20 kHz) to evaluate sensor health. The system performs a 16-second frequency sweep test and computes a quality factor Q (range 0–1) using cross-correlation, where healthy sensors show Q ≈ 0.97–0.98 with standard deviation ≈ 0.001–0.015. The sensor operates reliably in outdoor temperatures from −13°C to 38°C and performs hourly testing over long-term deployment (3–6 months). Experimental results show failure detection accuracy up to 100% for MK-type sensors, with false positives reduced using threshold $T(n) = M - 5\sigma$. The system cost is ~€50 per sensor (target <€10 future) enabling scalable deployment. The work enables reliable sensor fault detection, while further improvement in failure classification and robustness to environmental interference can enhance performance.

In [18], the author proposed wireless acoustic sensor networks (WASN) using distributed microphones with DSP-based signal enhancement (beamforming, DANSE algorithms) for large-area acoustic monitoring. The system highlights clock synchronization error of ~40 ppm (≈40 µs/sec or 0.144 s/hour) affecting multi-node sampling accuracy. It addresses constraints such as high communication bandwidth requirement for real-time audio streaming and need for low input-output delay in distributed processing systems. The study emphasizes scalability using distributed processing instead of centralized fusion, reducing computational load per node. Performance improves with increased number of microphones and spatial diversity, enhancing SNR compared to single sensors. However, the work mainly focuses on network-level signal processing, indicating scope for optimized low-cost sensor-level implementation and compact embedded design.

In [19], the authors designed and implemented a wireless sensor network (WSN) for noise monitoring using IEEE 802.15.4 communication (CC2420, JN5148) with a multi-hop tree topology, synchronization (SYNC2SINK), and link-state routing (RSSI-based). The system performs continuous noise sampling with 1-second resolution and transmits 72 bytes of data every 5 seconds per node. The network operates with a 5 s cycle (4.5 s sensing + 0.5 s transmission) and achieves time synchronization error of ~0.0767 ms. Experimental results show packet delivery ratio (PRR) up to ~96% (single-hop with 14 nodes) and improvement of ~10% PRR using RSSI threshold (~−75 dBm / LQI ≈ 90) in multi-hop scenarios. The system enables large-area real-time monitoring with low-cost deployment, but focuses mainly on network communication and synchronization, leaving scope for enhanced signal processing and noise classification.

In [20], this work, the authors designed and implemented a low-cost wireless noise monitoring sensor using an electret microphone with analog amplification and A-weighting filtering techniques. The system operates with a sampling rate of 33 kHz, providing an effective frequency range up to 16.5 kHz. A dual-gain amplification method (GH = 390, GL = 10) is used to enhance the dynamic range beyond 60 dB, enabling measurement of sound levels up to approximately 100.98 dB. The system achieves high accuracy with deviations of ±0.86 dB (indoor) and ±1.69 dB (outdoor), along with a strong correlation factor of 0.99493 when compared to a standard sound level meter. The work demonstrates an efficient DSP-based noise measurement approach suitable for real-time monitoring, while further improvements in processing capability and system scalability can enhance performance for advanced applications.

Table I. Comparative Analysis

Paper	Method / Technology Used	Frequency Range	Sampling Rate	Accuracy / SNR / DR	Key Feature
[1]	IoT + ESP32 + ADC	-	-	16-bit ADC	Real-time monitoring and alert system
[2]	IoT + Zigbee + MEMS Mic	20 Hz–8 kHz	-	<1 dB error	Industrial noise mapping with high accuracy
[3]	Capacitive MEMS Readout Circuit	-	up to 200 kSPS	SNR 60–120 dB	High precision sensor interface design
[4]	Hierarchical WASN	-	8 kHz	0.5–1 dB accuracy	Scalable system (~175 nodes)
[5]	Distributed Acoustic Sensing (DAS)	Wideband	-	High SNR	Long-distance sensing (km range)
[6]	Low-Frequency Noise Measurement	Sub-Hz to kHz	-	nV/√Hz noise floor	Ultra-sensitive low-frequency detection
[7]	Low-cost Acoustic Sensor Network	20 Hz–20 kHz	up to 48 kHz	±1.5–2 dB	Smart city deployment
[8]	Wireless Acoustic Sensor Network	-	-	-	Real-time noise mapping (LAeq, Lden, etc.)
[9]	DSP-based Acoustic Sensor	63 Hz–8 kHz	up to 108 kHz	~80 dB dynamic range	Computes 86 acoustic parameters
[10]	Configurable Sensor (ARM + MEMS)	50 Hz–15 kHz	up to 48 kHz	SNR ~65 dB	Low-cost (~139€) scalable design
[11]	WASN + CNN Classification	20 Hz–20 kHz	44.1 kHz	<1 dB error	97.3% classification accuracy
[12]	WASN Review System	up to ~40 kHz	-	-	Large-scale monitoring architecture
[13]	AudioMoth + AI Algorithms	20 Hz–192 kHz	up to 384 kHz	F1 score ~0.98	Low-power event detection
[14]	Low-cost Noise Sensor	20 Hz–20 kHz	-	±2 dB accuracy	Industrial monitoring reliability
[15]	MEMS Urban Sensor Network	20 Hz–20 kHz	32 kHz	±2 dB accuracy	Large deployment (>200 m range)
[16]	Nanofibre Acoustic Sensor	20–2000 Hz	-	High sensitivity (266 mV/Pa)	High sensitivity detection
[17]	Self-testing Noise Sensor	80 Hz–20 kHz	-	Q ≈ 0.97–0.98	100% fault detection capability
[18]	WASN Signal Processing	-	-	-	Beamforming improves SNR
[19]	WSN Communication System	-	1 sec sampling	96% PRR	Sync error ~0.076 ms
[20]	Low-cost Wireless Sensor	up to 16.5 kHz	33 kHz	±0.86 dB accuracy	Correlation 0.99493

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Table II. Different Sensor Analysis

Sensor Type	Freq Range (Hz)	SNR (dB)	Dynamic Range	Output	Use Case
MAX9814	20–20k	62	High	Analog 1.25v	General audio
MAX4466	20–20k	60	Medium	Analog 0-vcc	Low-cost sensing
INMP441	60–15k	61	High	I2S	IoT, smart devices
ICS43434	50–20k	65	High	I2S	High accuracy
SPH0645LM4H	100–10k	65	High	I2S	Voice systems
ADMP401	100–15k	62	Medium	Analog 0.8-2v	Embedded systems
Knowles SPU0410	20–20k	59	Medium	Analog 0.7-2v	Wearables
MP34DT05	100–10k	63	High	PDM	Smart sensors
LM393 Module	50–10k	Low	Low	Analog/Digital	Basic detection
KY-038	50–10k	Low	Low	Analog/Digital	Beginner projects
Analog Electret Mic	20–20k	55	Medium	Analog mV range	Custom design

III. RESEARCH GAP

1) Existing low-cost acoustic sensing systems are largely based on standard sensor modules with fixed characteristics such as sensitivity, gain, and predefined signal conditioning, which limits flexibility in performance optimization for different environments.
2) The accuracy of noise measurement in such systems is highly dependent on proper calibration, amplification, and filtering; however, inadequate signal conditioning introduces noise interference, leading to unstable measurements and reduced reliability.
3) Environmental acoustic signals are dynamic and consist of multiple frequency components, requiring effective filtering and controlled signal processing to obtain a clean and meaningful representation of the signal.
4) Many existing systems lack fine control over key analog parameters such as gain adjustment, filter tuning, and noise suppression, which directly impacts the precision of sound pressure level (SPL) estimation.
5) Additionally, several available sensor modules are application-specific and not easily adaptable, creating limitations in usability across different noise conditions and monitoring scenarios.
6) Therefore, further improvement is required in developing low-cost acoustic sensing systems with enhanced signal conditioning, tunable analog parameters, and improved measurement stability for reliable and versatile noise monitoring application

IV. APPLICATIONS

1) General Acoustic Sensing Systems: Low-cost acoustic sensors can be used for capturing sound signals with proper signal conditioning and can serve as input units for various embedded and signal processing applications.
2) Smart Cities: Acoustic sensing systems can be integrated into smart city infrastructure for continuous environmental noise monitoring and real-time data analysis.
3) Educational Institutions: Acoustic monitoring systems can be used in schools and colleges to analyze surrounding acoustic conditions and support a better learning environment.
4) Residential Areas: Noise monitoring systems can be utilized in residential regions to observe environmental noise levels and study their impact on daily life.

5) Industrial Areas: Acoustic sensors can be employed to monitor machine-generated sound signals for industrial observation and safety-related applications.
6) Traffic Monitoring: Acoustic sensing systems can be installed near roads and highways to analyze traffic-related noise patterns and environmental acoustic variations.

V. CONCLUSION AND FUTURE SCOPE

This paper presented a review of low-cost acoustic sensing systems based on fundamental electronic signal conditioning techniques for environmental noise monitoring applications. The reviewed studies demonstrate that microphones combined with biasing, amplification, filtering, and basic signal processing techniques can effectively capture and analyze environmental sound signals. Various approaches discussed in the literature highlight the importance of proper signal conditioning, calibration, and filtering in improving signal quality, measurement stability, and overall system performance. The reviewed systems also show that low-cost acoustic sensing techniques provide simple, practical, and cost-effective solutions suitable for applications such as environmental monitoring, laboratory analysis, smart city systems, and small-scale industrial observation.

Future improvements can focus on enhancing sensor sensitivity, optimizing dynamic range, improving filtering techniques, and increasing measurement accuracy under different environmental conditions. Additional advancements in signal processing, wireless communication, and scalable monitoring architectures can further improve the performance and adaptability of low-cost acoustic sensing systems for real-world applications.

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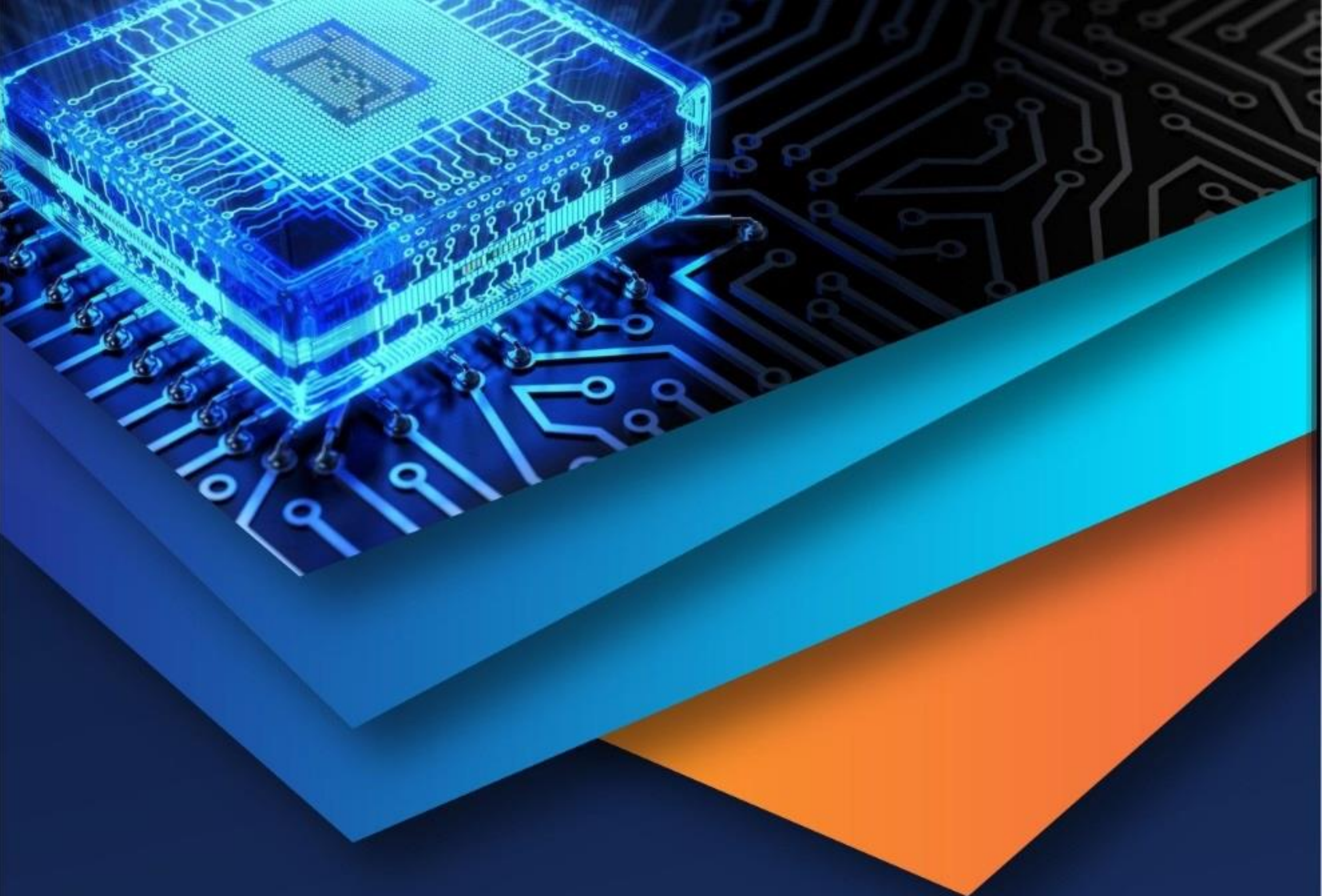

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