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Real Time Industrial Noise Mapping with IoT Systems

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ABSTRACT
This article presents a development of an industrial noise mapping system using IoT device and ZigBee network. The measurement results of noise in laboratory conditions demonstrates good accuracy. The use ZigBee mesh network attends the battery life and range criterions.

This work shows a hardware selection, like MEMS microphones and SoC modules with real time system and ZigBee stack. The firmware strategy and Zigbee Cluster Library (ZCL) profile adaptations is also described

General Terms
Noise Mapping, Zigbee Network, MEMS microphone.

Keywords
Noise, Zigbee, MEMS, zigbee2mqtt, embedded systems.

1. INTRODUCTION
Most industries face significant challenges related to noise. Excessive noise can not only harm workers' hearing health but also affect productivity, safety, and overall workplace well-being. Therefore, industries are increasingly seeking effective noise monitoring solutions to ensure compliance with environmental and occupational health regulations, improve working conditions, and optimize industrial processes. With the ability to offer a comprehensive and effective noise monitoring solution, combined with the potential for integration with automation and industrial control systems, the proposed solution has significant market appeal. It addresses a critical need in modern industries and offers tangible benefits in terms of worker health and safety, regulatory compliance, and operational efficiency.

Countries worldwide have their own regulations and standards regarding noise control in industrial occupational environments, reflecting the global importance of this issue. As a result, companies in different regions and countries have a constant demand for effective noise monitoring solutions that can help them comply with these regulations and protect their workers.

Noise control in occupational environments is essential to preserve workers' hearing health, ensuring a safe and healthy work environment. Prolonged exposure to high noise levels can cause irreversible hearing damage, leading to hearing loss and other related health issues. According to the World Health Organization (WHO), it is estimated that over 600 million people worldwide suffer from hearing loss due to exposure to harmful noise in the workplace and other contexts. According to the 2019 National Health Survey (PNS) by IBGE, about 2.9% of Brazilians over 18 years old have some hearing impairment. Unfortunately, in Brazil, there is underreporting of Work Accident Communications (CAT) related to Noise-Induced Hearing Loss (NIHL). According to the Ministry of Labor's RADAR [1], only 4,074 CATs were filed due to noise between 2014 and 2021, while the total number of CATs during this period was 4,767,399, representing 0.08% of filed CATs.

Noise monitoring in industrial plants is often conducted sporadically, with few measurement points, either by automated electronic systems or manually by technicians on-site. This limited approach presents significant limitations. When done by electronic systems, noise monitoring may be restricted to just a few key points in the plant due to cost or infrastructure constraints. This results in limited coverage, making it difficult to identify specific noise sources or assess the spatial distribution of noise within the plant. Additionally, traditional electronic systems may not offer the necessary flexibility to adjust measurement settings or adapt to changing operational conditions.

On the other hand, when noise monitoring is conducted manually by technicians, the process is generally time-consuming and labor-intensive. Technicians need to move around the plant to take measurements at different locations with a Sound Level Meter (SLM), which consumes significant time and resources. Furthermore, the spatial coverage of measurements may be limited, as technicians may not be able to access all points in the plant easily, especially in complex or hard-to-reach environments.

In both cases, the sporadic and limited approach to noise monitoring can result in an incomplete understanding of noise levels throughout the plant, making it difficult to identify problematic noise sources or take effective corrective measures. This highlights the need for more comprehensive and efficient solutions, such as the hardware platform proposed in this project, which offers periodic noise monitoring throughout the plant, allowing for a more accurate and comprehensive assessment of the acoustic situation.

Given this scenario, the development of this proposed system presents itself as a promising and necessary solution. By offering continuous noise monitoring throughout the plant, the platform allows for a more comprehensive and accurate assessment of the acoustic situation. With wide spatial coverage and adequate measurement frequency, the platform enables early identification of excessive noise sources and the implementation of proactive corrective measures.

By offering a more comprehensive, accurate, and automated solution, the work aims to contribute to protecting workers hearing health, complying with environmental regulations, optimizing industrial processes, and detect machines malfunctions.

This paper describes a complete and integrated solution for noise monitoring in industrial plants, covering everything from designing and manufacturing a robust, low-cost, low-power hardware platform to implementing a scalable and efficient cloud infrastructure to manage and process the collected data. Preliminary results of the developed system indicate that the solution is viable for large industrial plants with up to 500 measurement endpoints using low-cost embedded systems and employing mesh networks.

2. LITERATURE REVIEW

In [2] a comprehensive analysis of the methodologies and technologies used for monitoring, mapping, and modeling environmental noise is presented. The study addresses different noise measurement techniques, computational models applied to predict sound propagation, and the creation of noise maps, as well as the applications of these practices in noise pollution management. Initially, the article describes traditional noise monitoring methods, which include the use of professional Sound Level Meters (SLMs). These devices are accurate but limited in area coverage due to cost and the need for frequent manual intervention. The text also discusses the limitations of computational noise models, which, despite their ability to generate large-scale noise maps, often lack precision due to the complexity of input parameters and the variability of noise sources. The article highlights the evolution of noise mapping technologies, including projects like HARMONOISE and IMAGINE, which developed methods to assess road and rail traffic noise, as well as industrial scenarios. The introduction of the CNOSSOS-EU model by the European Commission is mentioned as an effort to standardize noise assessments in Europe. Finally, the article emphasizes the need for new approaches to noise mapping, suggesting that future systems should be able to measure noise in real time with high precision, classify noise sources in detail, and create dynamic maps that reflect temporal variations in environmental noise.

In [3] the development and implementation of a real-time noise monitoring system using Internet of Things (IoT) technologies and mobile computing is described. The main goal of the study is to provide a modular and scalable solution to improve acoustic comfort and occupational health in indoor environments. The work highlights the importance of acoustic comfort for well-being and productivity. High environmental noise is associated with various health issues, such as hypertension and stress. The research aims to create a system that not only monitors noise levels in real-time but also offers tools for data analysis and notification via mobile devices. The proposed solution, called iSoundIoT, consists of a FireBeetle ESP8266 microcontroller and a DFRobot analog sound level sensor. The system can measure sound levels and transmit data via Wi-Fi to an SQL server. This data is accessible through a web portal, iSoundWeb, and a mobile application, iSoundMobile. The setup allows building managers to monitor noise levels in real-time and receive notifications when levels exceed predefined limits. Results from laboratory tests indicate that the system is effective in sound supervision and provides continuous real-time data. Average sound levels ranged between 47.35 and 52.99 dBA. The system proved to be a useful tool for improving acoustic comfort and occupant well-being, allowing for quick interventions when necessary.

In [4] the use of collaborative Industrial Internet of Things (IIoT) for noise mapping, especially in industrial environments, is explored. The research discusses the negative impacts of environmental and occupational noise on human health and the importance of noise mapping as the first step in addressing noise pollution. Currently, the most common methods for noise monitoring involve SLMs and model-based computational simulations. However, these methods have significant limitations. SLM measurements are accurate but impractical on a large scale due to cost and labor intensity. On the other hand, computational simulations, although efficient for large areas, often lack precision due to the complexity of input parameters. The article proposes a collaborative IIoT-based framework for next-generation noise mapping. This framework offers real-time accurate measurements, detailed classification of noise sources, dynamic mapping, and human-centered visualization. The article also discusses the main challenges and suggests future research directions, including the need for the development of low-cost sensors, more efficient data processing algorithms, and strategies for integrating collected data with environmental management systems.

Finally, in [5] a detailed analysis of using machine learning to predict noise-induced hearing loss is provided. The authors highlight both the benefits and limitations of this method concerning prevention and early intervention of hearing loss. They present a comprehensive review of the current literature, examining different machine learning techniques and their applicability in predicting hearing loss. Additionally, the authors discuss ethical and practical issues associated with using data to develop predictive models. In summary, the article offers valuable insights for researchers and professionals in the auditory field interested in the potential of machine learning to improve the detection and treatment of noise-induced hearing loss.

3. INDUSTRIAL NOISE MEASUREMENT AND DATA COMMUNICATION

The developed system utilized a real-time microcontroller system with a mesh network communication stack based on the IEEE 802.15.4 standard and Zigbee to meet the requirements for range and scalability. The measurement system consists of a MEMS microphone that communicates with the microcontroller through a standard I2S digital interface [6].

The following subsections provide a brief literature review on industrial noise measurement and the architecture of the developed hardware and software.

3.1 Industrial Noise Measurement

This subsection presents a brief literature review on industrial noise measurement. In [7], aimed to create industrial noise maps. In their summary, they write that "to produce representative noise maps, a large amount of information is needed, including, among others, on-site environmental noise measurements. Thus, mobile collection emerges as a possible solution to enhance data acquisition [...]. Moreover, a set of mobile measurements suggests that mobile collection is indeed possible, improving the spatial-temporal granularity of noise measurements without compromising accuracy, although certain requirements must be met to ensure representativeness."

To create a noise map based on measurements, the levels shown must be representative, which requires a large amount of data. The measurement equipment must meet minimum accuracy requirements, which can increase sampling costs. Consequently, producing a noise map becomes a complex task that demands many resources. However, advances in sensing technology and cloud data access have enabled real-time data acquisition and transfer at a lower cost than individual collection at points of interest.

The use of MEMS to develop street noise meters, arranged in a circular form to create a type of unidirectional microphone with 5 sensors, is evident. The average is what matters in this case. The articles referenced in [8] and [6][9] discuss projects very similar to what we aim for. Reading these articles, the desired characteristics are similar: low cost, use of MEMS, determination of sound pressure in one-third octave bands in the range of 20 Hz to 8 kHz, using I2S as the protocol for obtaining data from the MEMS. According to [8] do not concern themselves with measurement time, measuring continuously and not transmitting data over the internet, but rather keeping the data at the collection site and displaying it on a local indicator. It is essentially the construction of a stand-alone sound pressure meter.

The work [10] presents noise measurement in rural areas, with data transmitted over the internet. The article discusses the practical implementation of an autonomous SLM based on MEMS, capable of recording one-minute time samples and wirelessly transmitting sound level values in one-third octave bands in the range of 20 Hz to 8 kHz, every 15 minutes. This work is very similar to what we aim to achieve, and thus we will highlight the requirements and results found. Table 1 summarizes the literature review conducted.

Table 1. Literature review

Ref	***Title***	**Resume**
[7]	*A low-cost noise measurement device for noise mapping based on mobile sampling*	It involves creating a noise map of streets or areas of a city, based on 5 MEMS arranged in a circular pattern to measure ambient noise from streets, sidewalks, and squares.
[11]	*Practical experience in noise mapping with a MEMS microphone based distributed noise measurement system*	The article discusses: (a) the added value of including experimental measurements in the noise mapping process and (b) the potential of MEMS microphones in measurement applications.
[12]	*Single-Mode Wild Area Surveillance Sensor With Ultra-Low Power Design Based on Microphone Array*	This article aims to monitor moving vehicles. In terms of hardware, a unique dual-core architecture and MEMS microphone are adopted to reduce energy consumption and node size. In terms of software, energy consumption is reduced by special algorithms.
[13]	*Low-cost sound level meter based on a digital microphone for room acoustics applications (translated title)*	This work aims to create a low-cost sound pressure level meter to meet the needs of newly graduated engineers and enthusiasts in the field of acoustics.
[8]	*MEMS digital microphone and Arduino compatible microcontroller: an embedded system for noise monitoring*	This study developed a high-quality (and cost-effective) prototype method for an embedded noise monitoring device based on a digital I2S MEMS microphone and an Arduino-compatible microcontroller called Teensy. Its small size and low power consumption are also advantages designed for the project.
[9]	*Implementation and performance assessment of a MEMS-based Sound Level Meter*	It discuss the practical implementation of an autonomous SLM based on MEMS, capable of recording one-minute samples and wirelessly transmitting sound level values in one-third octave bands in the range of 20 Hz to 8 kHz, every 15 minutes.
[14]	*AN446 Tutorial for MEMS microphone*	Important STM tutorial on the physics of MEMS microphones.

3.2 Hardware and software architecture

In the development of the data measurement and transmission system, a SoC (System on Chip) platform was used with support for a real-time operating system, featuring a network stack for the 802.15.4 standard (Zigbee), powered by a battery. Figure 1 shows the hardware architecture.

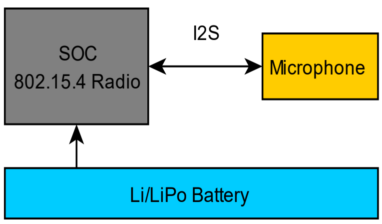

Figure 1. Hardware architecture

The SOC used has extensive documentation as well as numerous modules available on the market. Given the need for communication with the MEMS microphone via the I2S protocol at high acquisition rates, as well as data transmission to the Zigbee network at well-defined intervals, a real-time operating system was chosen to support the system firmware.

In general, a bare-metal application tends to be more energy-efficient, uses less memory, and, in some cases, runs faster. For applications with simple to moderate complexity, it is a sufficiently good solution. However, the application can easily become quite complex, as is the case with this project, due to the use of complex hardware resources such as wireless networking, USB, and I2S (microphone). This is where the use of a real-time operating system (RTOS) becomes advantageous. Additionally, bare-metal programming is no longer recommended by Nordic as noted [15]. Thus, the programming model used in the project's firmware is illustrated by Figure 2, which specifically uses Zephyr as the RTOS.

In the case of this project's application, the elements illustrated in Figure 2 where the gray boxes refer to hardware elements, the blue boxes to operating system-related elements, the green boxes to the Zigbee network (Zboss stack), and the yellow boxes refer to application tasks. Figure 2. Software architecture

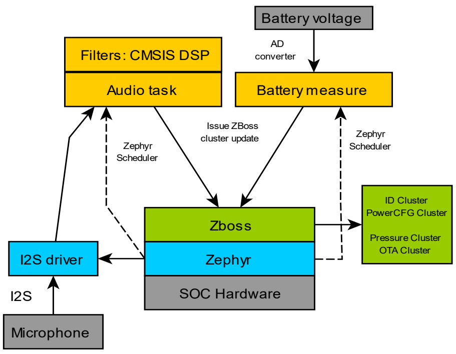

Figure 2. Software architecture

Where:

- **Audio Task**: Scheduled every 15 minutes to perform 1 minute of measurement. The data is filtered according to the eighth-octave bands, and the root mean square (RMS) value for each frequency is calculated. The CMSIS DSP library was used to implement the filters, maximizing the ARM core hardware resources. The audio task is scheduled by the Zephyr RTOS.
- **Battery Measurement**: The ADC reading is very fast. Therefore, after the audio measurement, a battery voltage measurement is performed.
- **ZBoss:** Zigbee stack used by Nordic in SOCs. Each device can be configured as an end-device or router, implementing clusters that export the data. The Zigbee Cluster Library does not provide for acoustic pressure. The pressure cluster with extended parameters was used.

3.3 Zigbee Network

Zigbee is a short-range, low-power wireless communication protocol. It is used in Internet of Things (IoT) devices, such as smart bulbs, sensors, and digital locks. The network operates at a frequency of 2.4 GHz using the IEEE 802.15.4 physical layer standard, which allows devices to connect at a theoretical distance of up to 100 meters. Communication between devices is conducted through a mesh network, where each device can communicate with other devices, extending the network coverage. The protocol is standardized, allowing devices from different manufacturers to work together properly (Zigbee protocol). Zigbee network devices can be classified according to two criteria, as illustrated in Figure 3:

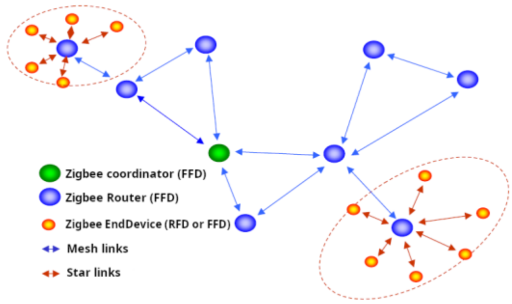

Figure 3. Zigbee network topology

Devices can be either Full Function Devices (FFD) or Reduced Function Devices (RFD). FFD (Full Function Device): Devices that have all the functionalities of the Zigbee network. They can act as coordinators, routers, or end devices. RFD (Reduced Function Device): Devices with limited functionalities. They can only act as end devices. Devices can be coordinators, routers, or end devices.

- **Coordinator**: device responsible for starting and managing the Zigbee network. It is the only device that can route data between networks.
- **Router**: device that extends the range of the Zigbee network. It can communicate with other FFD and RFD devices.
- **End Device**: device that cannot route data. It can only communicate with other FFD devices.

The choice of the appropriate Zigbee device type depends on the application. For this work, it was considered that there is no existing Zigbee network infrastructure in the deployment environment. Thus, the following types of devices were required/implemented:

- Coordinator: the SONOFF Zigbee 3.0 USB Dongle Plus was used as the coordinator, as illustrated in Figure 2, connected to a computer or single board computer (Raspberry or BeagleBoard).
- Router: a firmware was created using the with support for noise measurement and in router mode. This device needs to be powered by an external source to ensure the routing of packets in the mesh network.
- End Device: this mode is used by most devices in the work, powered by batteries.

One of the important components of applications using the Zigbee network is the Zigbee Cluster Library (ZCL) (Zigbee Cluster Library). The ZCL is an open-source library that provides an interface for developing Zigbee applications. The ZCL defines a set of clusters, which are groups of attributes and methods that allow Zigbee devices to communicate with each other. The ZCL is divided into two levels:

- API Level: provides an interface for developing Zigbee applications.
- Protocol Level defines the clusters and the attributes and methods they contain.

The API level of the ZCL provides a set of functions and classes that enable developers to create Zigbee applications.

These functions and classes provide an interface to the protocol level of the ZCL, which is responsible for implementing the clusters and the attributes and methods they contain.

The ZCL clusters are organized into profiles, which are sets of clusters designed for a specific type of device or application. For example, the Zigbee Home Automation profile defines clusters for smart bulbs, sensors, and digital locks.

The ZCL attributes are values that can be accessed or modified through the methods of the clusters. In the case of this project implementation, there is no specific profile for acoustic noise; therefore, the pressure cluster was used with the attributes Pressure Measurement Information Attribute Set and Extended Pressure Measurement Information Attribute Set (**PMAS** - Zigbee Cluster Library). The relationship between pressure attributes and noise attributes is illustrated in Table 2.

Table 2. Noise Attributes Mapped to the ZCL Pressure Cluster.

PMAS	Acoustic Pressure
measuredValue	rms global
minMeasuredValue	rms 125 Hz
maxMeasuredValue	rms 250 Hz
tolerance	rms 500 Hz
scaledValue	rms 1000 Hz
minScaledValue	rms 2000 Hz
maxScaledValue	rms 4000 Hz
scaledTolerance	rms 8000 Hz

Attributes typically support read, write, and report access. Read access allows an attribute to be read by another device on the network, write access allows modifications, and report access enables the attribute to be read periodically or sent by the device itself when a new value is generated. Report access is useful because all attribute values are sent synchronously, either periodically or when updated by the sensor device, without the need for an explicit read command from the gateway or another network device.

Another important customization of the ZCL in this work involves the type of access for the attributes. Only the `measuredValue` supports report access, so a new pressure cluster was created to support reporting for all other attributes. Thus, new values are sent by the sensor every 15 minutes, according to the noise reading interval. The device receiving the data must be configured to create a binding, as will be explained in the section about the Gateway.

The firmware implements four clusters: Basic, Identification, Pressure, and FOTA. When configured as an End-Device, the Power Config cluster is also implemented to report the device's battery level. The Basic cluster provides attributes and commands to determine basic information about the endpoint. The Identification cluster allows the device to be set into identification mode, which provides a way to locate and identify the device. The customized pressure cluster is used to send acoustic noise data.

4. SYSTEM DEVELOPMENT

The measurement system, as previously described, consists of a data processing and transmission module, a MEMS microphone, and a battery. The current prototype uses a module from Seed Studio, connected to a main PCB. To connect the MEMS microphone, a PCB was developed with connectors compatible with the microphones, compatible with the I2S standard. A specific PCB was also developed for the IP57 PDM microphone. This microphone was chosen because it supports an IP57 protection rating. Thus, this PCB incorporates PDM to I2S conversion circuits using the Analog Device ADAU7002ACBZ-RL integrated circuit.

Figure 4 shows the main PCB of the system with the module mounted.

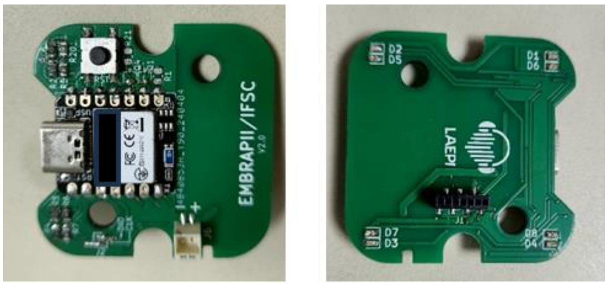

Figure 4. Left: top view. Right: bottom view (microphone PCB connection side) of the mounted main PCB.

Figure 5 shows the PCB for I2S microphones.

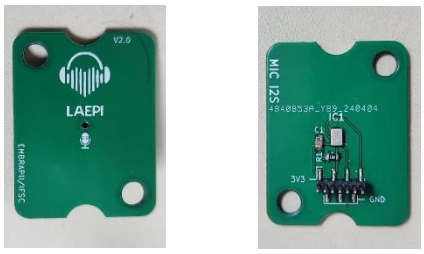

Figure 5. Left: top view. Right: bottom view of the PCB for the PDM microphone.

Figure 6 shows the PCB for the PDM microphone.

Figure 6. Top view of the PCB for the PDM microphone.

A fairing was also developed within the scope of the work to accommodate the measurement system. Figure 7 shows one of the designs selected for prototyping.

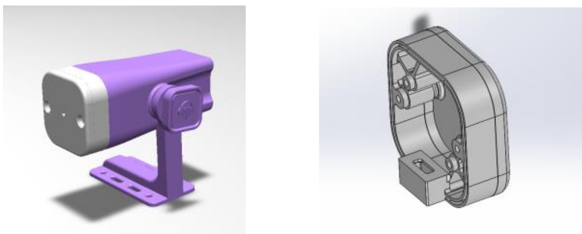

Figure 7. Model of the system fairing.

Figure 8 shows a 3D prototyping of selected fairing.

Figure 8. 3D prototype of selected fairing.

5. RESULTS

To evaluate measurement accuracy, tests were conducted in a semi-acoustic chamber. Reference noises were generated, and prototype measurements were compared to those of a calibrated Bruel & Kjaer 2245 sonometer. It is important to note that no microphone calibration was performed during these tests. Sound levels for two tonal noises are presented in Table 3.

Table 3. Prototype measurements

Frequency	Sound level (db) (Tonal noise: 81.41db 250Hz sin waveform)	Sound level (db) (Tonal noise: 71.15db 4kHz sin waveform)
125Hz	55.82	27.55
250Hz	**81.91**	26.51
500Hz	55.84	25.83
1kHz	49.24	28.37
2kHz	45.53	36.85
4kHz	42.58	**76.01**
8kHz	48.36	60.91
Global	81.94	76.14

Furthermore, we tested using 80 dB broadband noise, with the device registering 76.14 dB. According to our tests, for tonal noise at frequencies of 250 Hz and 2000 Hz, the error was less than 1 dB. Measurements and comparisons at higher frequencies were found to be more susceptible to errors.

We also conducted an environment-relevant test to evaluate Zigbee network performance and gateway connection to the database. Our acoustic noise sensor network is illustrated in Figure 9, comprising six end-devices (green nodes), three routers (blue nodes), and one coordinator/gateway (star node). A large amount of data was generated, with intermittent connection issues commonly observed in wireless networks, but overall Zigbee proved to be a very robust mesh network.

Figure 9. Zigbee network evaluation.

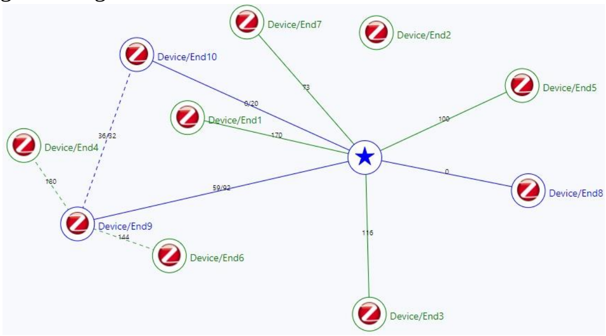

Figure 10 shows a plot of global noise measurement for eigth devices.

Figure 10. Database and API evaluation.

6. CONCLUSIONS

This work presented the development of an innovative industrial noise mapping system using a low-cost, low-power IoT device with applications in medium and large industries. The innovation of the proposal is the use of a large scale (high density) of sensors that allow real-time and automatic mapping of noise sources, enabling proactive noise control interventions, ensuring that the noise thresholds specified in national and international standards can be respected. The adoption of a low-power mesh network meets the requirements for battery life and scalability. Among the challenges faced, we can highlight the selection of the most suitable MEMS microphone for the project requirements, adaptations in ZCL profiles, and product design requirements such as dust and humidity resistance. The developed prototypes showed good accuracy for the desired application. Future work includes the addition of new sensors for environmental parameters and the use of artificial intelligence techniques to use the system for predictive maintenance of machines based on noise monitoring.

7. ACKNOWLEDGMENTS

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