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LOW-COST SENSORS FOR NOISE MONITORING NETWORKS: A REVIEW2020

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ABSTRACT

Noise pollution reduction in the environment is a major challenge from a societal and health point of view. To implement strategies to improve sound environments, experts need information on existing noise. The first solution is based on the elaboration of noise maps using software, but with limitations on the realism of the maps obtained, due to numerous calculation assumptions. The second consider toe use measured data, in particular through professional measurement observatories, but in limited numbers for practical and financial reasons. More recently, numerous technical developments have opened up new prospects for the deployment of low-cost sensor networks for the assessment of sound environments. Over the past fifteen years, numerous experiments have been presented in this field, from proof of concept to operational implementation. The purpose of this paper is to review the literature in order to identify the expected technical characteristics to address the problem of noise pollution assessment, and lastly, to put forward the challenges that are needed for a massive deployment of low-cost noise sensors.

1. INTRODUCTION

Noise pollution is a major environmental pollution whose impact on health is now widely recognized [1]. As a result, many countries have implemented policies and strategies, for many years, to reduce noise pollution and to preserve quiet areas. In Europe in particular, Directive 2002/49/EC [2] introduces many rules on the assessment and management of noise environments, including the production of strategic noise maps, which are the starting point for the implementation of action plans to reduce noise pollution. Currently, noise maps are obtained by using sound mapping software tools, based on standards. However, for many reasons, such noise maps may be limited (lack of input data, limited type of sound sources, models hypothesis, no dynamic representation...). In situ measurements would therefore be an immediate solution to make these maps more realistic. Nevertheless, given the urban scale considered and the spatial variability of the sound environment, the number of measurement points to be considered would be very large to model the relevant variability of the

sound environment

Many major technical developments have emerged in the last decade, making it possible to develop low-cost capturing devices integrating transducers of different kinds, embedded processing systems and wired/wireless communication systems, while optimizing power consumption and reducing their size. Thus, the use of low-cost Sensor Networks (SN) can be a solution to the current limits of the noise observatories, by making it possible to reach a density of measurement points in a territory that is capable of providing a very rich acoustic information. The relevance of such a system relies on many elements, among which, the acoustic measurement quality, the resilience of the sensors, the implementation of a communicating and smart sensor network, but the purpose of the present work is to focus on the main element of such data gathering systems, namely the sensor.

For the past fifteen years, many researchers have proposed technical solutions for different noise applications. It therefore seems interesting to highlight the essential characteristics that must be considered for this new generation of acoustic sensors. Compared to recent articles that already present a review of the existing system [3–7], the present contribution, which is synthesis of a recent publication by the present authors [8], focuses on a detailed analysis of the technical solutions, highlighting their strengths and weaknesses, and showing how the rapid evolution of technologies can now fully meet the requirements for a successful deployment of modern noise SN.

2. LITERATURE REVIEW

2.1 General considerations

The study of the literature highlights some key aspects and respective design choices, but a full comparison is difficult for all points of interest due to a lack of description of the acoustic performance of the sensors, in terms of residual noise, sound level dynamic or frequency range. Also, different levels of maturity of the proposed low-cost sensors are found. Some developments were limited to the design of the sensors alone (without prototypes), others proposed proof-of-concept (POC) (prototypes and tests), and some others have proposed to deploy several sensors

in real urban areas in a quasi-operational framework. Cost estimates of the sensors given by the authors show that the objective of obtaining a low-cost acoustic sensor (less than 150 EUR) is clearly achieved, with relatively high signal processing capabilities when considering most recent studies [7, 9]. The question of the autonomy of wireless noise sensors (linked in particular to the operating mode of the sensor, such as activity time/sleep time, duration of measurements, number of calculated indicator) is not extensively studied in the literature. However, it should be noted that most of the latest achievements [7, 9, 10] mention noise sensors directly powered by an electrical network, which seems to illustrate the difficulty of developing wireless sensors with acoustic performances that are relevant to the task at hand.

2.2 Detailed analysis

2.2.1 Sensor platform

The choice of the sensor platform determines the main functionalities and characteristics of the sensors. Three main families can be distinguished: (1) MCU based existing platforms; (2) specifically developed electronic boards; (3) Mini PC. The use of existing platforms (1) simplifies the sensor development by using components that have already been optimized in terms of energy consumption (TelosB, CiNet, Teensy USB, Tmote), including all the components needed to develop an environmental sensor (radio communication module, ADC, storage memory, connectors for other sensors, etc.). However, the lack of autonomy and the reduced computing capabilities have motivated researchers to develop their own electronic boards (2). Lastly, The main interest of using (3) a Mini PC, lies mainly in increased computing power, allowing more advanced digital audio processing and functionalities.

2.2.2 Data transmission protocol

Choosing a relevant communication protocol for a sensor network normally depends on several parameters, such as the distance between nodes and sinks, data rate, network topology... The use of a wired network is obviously the simplest and most effective solution to ensure data transfer under ideal conditions. This solution will be probably feasible in the future, given the growing number of cities developing smart and connected systems. Nevertheless, the expected spatial density of noise sensors requires dating the use of radio transmission, as most past experiments have envisaged. As a first solution, the GSM protocols could be considered. However, such transmission protocols are not cost effective for very dense sensor networks because with one subscriber identity module (SIM) card is required per sensor. Looking at the available data rates, the LPWAN technologies like LoRaWAN and Sigfox would not allow data transmissions with a sufficient efficiency; the Wi-Fi and the Bluetooth protocols would be more efficient, but the battery life will be too limited for an application without constant energy and for an efficient coverage of an urban area. Zigbee and 6LoWPAN, based on

802.15.4 specification, present both maximum range and data rates that are compatible with the noise SN.

2.2.3 Microphones

As mentioned by several authors [11, 12], the microphone is a critical element of the noise sensor. The literature review shows that three types of microphones are considered: (1) electret condenser microphones (ECM), and the more recent MEMS microphones that can be either (2) analog or (3) digital. The replacement of ECM microphones using MEMS ones was justified by the authors on the basis of their acoustic performances that were *a priori* more interesting for their use in acoustic measurements [13, 14]. In addition, MEMS microphones have reduced dimensions, are relatively reliable and durable, and above all are produced at a lower cost. The use of MEMS therefore was considered particularly relevant in the context of the implementation of low-cost sensor networks, specifically for urban noise monitoring.

2.2.4 Frequency weighting

Most acoustic indicators for the assessment of environmental noise require frequency weighting (generally A-weighting) to take into account the sensitivity of the human ear to certain frequencies. Since the calculation of acoustic indicators, such as equivalent sound levels, is integrated within the sensors, this weighting should be done as a pre-processing, using analog or digital filtering. Analog filtering makes it possible to overcome the computing limitations of the microprocessor but constrains the nature of the acoustic indicators at the output of the sensors. Conversely, digital filtering offers more flexibility, but at the cost of reducing the possibility of real time computation if the microprocessor is not powerful enough, and potentially reducing autonomy.

2.2.5 Frequency equalization

The acoustic acquisition chain generally has a frequency response curve that is not as "flat" as expected, creating a bias on the measured audio signal, and therefore on the calculated acoustic indicators. Some authors therefore propose to compensate the frequency response of the acquisition chain by implementing an equalization filter but it requires a significant workload on the microprocessor.

2.2.6 Noise indicators

The choice of output acoustic indicators is very important for designing the sensors in terms of expected computational and power resources. A temporal integration for calculating an equivalent sound level over a given integration time (1 s for example), will require far fewer resources than the calculation of frequency band spectra. Such time integration can easily be processed by a system based on an MCU with battery, while a frequency analysis will require more resources, as proposed today by a mini PC, with a wired power supply. While the measurement duration is often indicated in the literature, the temporal periodicity is rarely specified. The transmission of audio

signals is clearly not a priority, for obvious technical reasons: network bandwidth, storage on sensors and servers, and energy consumption but more importantly for privacy concerns. The calculation of acoustic indicators directly within the sensors, and then their transmission, is the only relevant solution.

2.2.7 Other considerations

Renterghem et al. [11] have studied the effect of temperature, humidity and wind, on the sound levels measured by electret and MEMS microphones. It was shown that applying an air temperature correction may have a positive effect on the long-term measurements. The effect of ambient temperature on the sensitivity of a MEMS sensor was also investigated by Barham and Goldsmith [15] showing that the variation in sensitivity would increase with frequency and temperature. Conversely, [10] have not seen significant variation of MEMS microphone sensibility with temperature. Procedures were also proposed by [16, 17] to evaluate the evolution of acoustic performances of MEMS and electret microphones, when exposing to stressing conditions. However, the results mentioned above should be considered as points of attention, since the observed effects may vary due to many design factors.

3. NOISE SENSOR DESIGN FOR LOW-COST NETWORKS

3.1 Expected Characteristics of Noise Sensors

Referring to conventional measuring systems in environmental acoustics, one could try to compare the acoustic performance of low-cost sensors with Class-1 or Class-2 devices for 'expertise' or 'control' environmental noise measurements. However, as pointed by [18], there are situations where Class-1 or even Class-2 systems give measurement results whose very high accuracy is not necessarily in line with the practical use made of these data. This is particularly the case in the strictest application of the European Directive 2002/49/EC on the assessment of environmental noise. This is also highlighted in [19], mentioning that low-cost acoustic sensor characteristics are already quite consistent, in term of metrological capabilities, with what is expected from a strategic noise map. For more specific needs, the most important guideline is to be aware with the technical limitations of the systems developed, and to ensure that the exploitation of the collected data is consistent with these limitations.

Noise indicators of interest to describe urban noise environments are calculated on the basis of 1 s or 125 ms data. They cover at least equivalent sound levels as well as statistical indicators, and, sometimes, emergence indicators such as the number of exceedances at given thresholds. Finally, some authors have introduced more demanding indicators for specific uses, such as the time and frequency second derivative (TFSD) [20] to describe voice and bird sounds, which requires a good temporal and spectral response of the sensors. Consequently, the expected characteristics of noise sensors are guided by the amplitude of

the sound levels encountered and the spectral information of the sources to be characterized. The characterization of urban noise environments, from quiet areas to the noisiest events, assumes a linear sensor response in a range from 30 to 105 dB(A).

3.2 Sensor Platform and Components

The choice of the platforms and components for the sensor development is mainly determined by the questions of how the sensor is connected to the network, how the sensor is powered, and what are the expected sensor output indicators. A sensor that transmits data by radio will be limited by the maximum data rate of the transmission protocol, as well as the distance and visibility to the nearest gateways or relays. The power supply mode will determine the computational and storage features of the sensor, as well as the operating conditions depending on the energy recovery mode (battery change or power supply using renewable energy). Several technical solutions can be considered, each with different components/functionalities—a sensor connected with a wired connection to the electrical network and to the data network; a sensor powered to the electrical network through a wired connection, but transmitting data by radio wave; an autonomous energy sensor (possibly also acting as a relay) transmitting data by radio wave.

3.2.1 Wired Sensor Platform

With regard to the experiments presented in the literature, the choice of a Mini PC constitutes an optimal choice with regard to the low-cost, the computing and storage capacities, the connectivity with other modules (radio, other sensors...), the remote maintenance and update of the system, the change of some modules (since not all modules are integrated into the motherboard of the Mini PC but just connected). Among all possible solution, the R-Pi family seems an excellent choice given the many accessories and modules available, but also given the presence of a very active community.

3.2.2 Wireless Sensor Platform

The development of a stand-alone sensor is more complex as it must meet many requirements. The nature of the acoustic indicators to be produced (continuous sound levels and spectra) requires a powerful microprocessor; the dynamics of the sound levels to be measured requires quantification by the ADC of at least 16 bits (96 dB of dynamics), ideally 24 bits to take advantage of a wider dynamic range (144 dB), which needs the use of a 24 or 32 bits MCU, as in the STM32 series.

3.2.3 Microphone and ADC

The acquisition chain (microphone, gain amplifier, ADC) is the other essential element to consider. Most of the achievements have focused either on ECMs or on MEMS, combined with an external ADC. Feedback from the literature review has shown the sensitivity of the acoustic signal to electrical and radio frequency interference, causing

an increase in the residual noise. This is why some authors have recently turned to digital MEMS (the analog-to-digital conversion is performed inside the microphone), which seems today an optimal choice. In addition, using a digital MEMS microphone with an I2S interface, it is unnecessary to use an external codec.

The choice of sampling frequency depends mainly on the spectral band of analysis, which depends on the expected sensor application. The optimum corresponds to the audible frequency band 20-20k Hz, covered by most MEMS microphones, which implies a standard sampling frequency of 44.1 or 48 kHz. While such a sampling frequency is not a problem for a wired sensor (such as a R-Pi), it is more problematic with MCU, and even more if a real-time processing is required.

3.2.4 Noise Floor Enhancement

Residual noise is one of the elements of the measurement chain that can limit a sensor ability to perform measurements at low levels, as in quiet spaces. The observed residual background noise levels are generally much higher than the value indicated by the manufacturer for the microphone and are caused, for example, by interference on analog electronic circuits or by the limited performance of some ADCs. The solution to reduce the residual noise is to optimize the electronic components of the sensors. Another way, proposed for example in [11], is to combine several microphones on a same sensor and to reduce the residual noise by applying a noise reduction method based on cross-correlation techniques.

3.2.5 Mass Storage

Sensors can also have mass storage capacities to store various information, for sensor maintenance, but also to temporarily store the collected data when the connection to the gateway or data server is interrupted. The sizing of this memory must take into account the duration of temporary data backup, and potentially the ability of the sensor to transmit a large amount of data once the connection is established, while simultaneously collecting and processing new data. The type of storage device is the second element to be considered. The more relevant choice is to use a flash memory (memory card, USB flash device, SSD), offering lower power consumption, easier maintenance, higher transfer speed, no operating noise, but at the expense of less mass storage than a traditional hard disk (HD), but also shorter lifetime due to a limited number of write cycles and higher cost.

3.2.6 Additional Sensors

The knowledge of the air temperature can be sometimes useful to calibrate noise sensors. More generally, knowledge of atmospheric and meteorological conditions can be interesting for a better use of data. For example, the presence of rain or a strong wind can cause disturbances to the measured acoustic signal, which, if not identified, can lead to misinterpretation of the collected data. The measurement of these atmospheric conditions (temperature, humidity, wind speed and direction) at the same time as the

acoustic signal seems relevant, particularly because of the low cost of the components and of the limited additional data it can generate. More generally, the possibility of connecting other types of sensors (traffic, ambient light, air pollution, video...) would make it possible to develop a global and multi-disciplinary environmental approach.

3.3 Sensor Life

One important issue is to determine the expected lifetime of a low-cost sensor. Knowing that the lifetime of a Class-1 sound level meter can extend to more than 10 years under normal conditions of use, a lifetime of a few years (typically 5 years) already seems an ambitious goal considering the overall cost of a low-cost noise sensor and the quality of its internal components. There are several components that can affect the lifetime of a sensor, mainly the measuring microphone, the data storage elements, and, if applicable, the battery. All other electronic components embedded in a sensors are designed most of time to operate for more than 10 years without problems in outdoor conditions, except when experiencing unplanned event, such as mechanical damage, high level of humidity, or really extreme temperature conditions out of the expected $-20/+55$ Celsius degree range. As detailed above, recent microphones and especially MEMS have a fairly good resistance to atmospheric conditions and have a limited drift over time. Newer mass storage devices also have a longer life expectancy given today's permitted read/write cycles. Finally, as far as autonomous sensors are concerned, the most sensitive component is undoubtedly the battery. Either the battery is removable, in which case an on-site intervention is required, or the battery is rechargeable and in this case the life cycle is defined by its ability to recharge, generally by using solar panels, while maintaining optimal properties. Most solar panel lifespan is around 20 years, with a power output decrease of less than 1% per year [21]. The sensor will then be given around 80% of the initial energy after this time. Environmental conditions, will have also an impact on the longevity of lithium batteries (*i.e.*, the type of battery most commonly used in electronic devices): the worst case is for high temperature (above 40 Celsius degree). Most of time, battery packs do not die suddenly, but the runtime gradually shortens as the capacity fades. The capacity of the battery will also decrease during its life, starting from 95% of its nominal capacity it quickly decreases to around 80% in less than a year (with 250 charge/discharge cycles). In addition, the depth of discharge will have also an impact on the battery durability: considering smaller discharges will prolongs the battery life. The lifetime of such batteries can typically range from a few years (typically 5 years) for consumer products to more than 10 years for industrial products.

3.4 Power Resources

As pointed out in [13, 22], autonomous nodes, made with a battery and a solar panel, should present enough storage capacity to store the energy that is required over the

duration of the measurement. For low cost sensors, the dimensions of the solar panel as well as the dimensions of the battery are a tradeoff between the energy consumption of the sensor and the overall price of the sensor. Considering an average power consumption of the sensor around 75 mWh, which seems sufficient for a MCU based noise sensor already offering significant computing power, the solar panel should be able to provide enough energy to power 24 hours of energy request, even during the worst month of the year (not in extreme conditions). If during this period, only 3 hours of sun are available, a solar panel should provide $24 \times 0.075 = 1.8$ W, which seems very reasonable in terms of cost and space requirements. To be able to power the sensor during a few days without sun, the battery should have the biggest possible capacity. A 2600 mAh battery will be able to provide enough energy to a sensor during a few days, even if there is no sun available to recharge the battery.

It is also essential to consider the progressive degradation of the properties of the solar panels and batteries in order to ensure the correct operation of the sensor over the envisaged lifetime. From the initial design stage, this means overestimating the capacities of the panels and batteries to ensure trouble-free operation of the sensors over the expected service life. Lastly, one can also mention that the technical improvement of the energy system must also be accompanied by the development of algorithms and procedures to optimize or reduce energy consumption [23].

3.5 Acoustic Calibration

Regardless of the intrinsic performance of the sensors, calibration is an essential operation for any "controlled" acoustic measurement. At a minimum, the sensor calibration should be performed, using a Class-2 acoustic calibrator, for example, 94 dB at 1000 Hz. The use of a multi-frequency calibrator can be useful in determining a frequency correction, unless the frequency response has been corrected using an equalization filter within the sensor. As pointed out in [9], it is important to regularly check this sensitivity correction throughout the period of use in order, if necessary, to take into account the variations in sensitivity of the measuring microphone. Because of the variability between low-cost microphones, particularly in terms of frequency response, it seems more appropriate to estimate a correction value on a sample of sensors, then calculate an average correction that will be applied to all sensors, as proposed in [14]. The question of the calibration of a very large number of sensors, particularly *in situ*, is still a very hot subject of research [24].

3.6 Additional Challenges

The development of a low-cost acoustic sensor for long-term acoustic measurement is only the first step in a comprehensive approach to the development of a sensor network for noise monitoring. Many other aspects, such as the development of an optimal technical and IT infrastructure for network and data management, anomaly detection, optimization of sensor positions, spatial and temporal data

sampling, and the management of hybrid networks, are important challenges, which are still relatively open in the field of noise monitoring as of today.

3.6.1 Detecting Network Defaults

It cannot be expected from a low-cost sensor the same performance as a professional sensor in terms of reliability and durability. Therefore the probability of malfunctioning of a low-cost sensor must be carefully considered [11, 25, 26]. The implementation of advanced algorithms for dysfunction detection is therefore essential [7, 11]. The subject of automatic fault and anomalies detection is particularly developed in the literature about wireless SN, but unfortunately only little for noise monitoring.

3.6.2 Temporal Sparse Sampling Strategies

The question of the duration and frequency of acoustic measurement is crucial since it concerns different aspects of the definition of sensor characteristics, such as memory space for data storage, computing capacities for real-time processing and data transmission rate. Reducing the measurement time therefore makes it possible to be less demanding on the characteristics of the sensor, and thus to reduce its cost and to increase its lifetime. Thus, it may be particularly interesting to study the temporal structures of noise levels in the environment as well as their spatial dependencies [27, 28], in order to potentially reduce the sampling duration.

3.6.3 Optimizing Sensor Locations and Network Deployment

Even if the very low intrinsic cost of individual sensors may encourage to not limit the number of measurement points to be integrated into the network, in practice, it must be limited to reduce the overall cost of the networks, mainly in terms of maintenance. Thus, dealing with a limited number of sensors, the choice of the 'best' location of each sensor may be of major importance.

For example, Huang et al. [29] proposed a hybrid model, based on a K-means clustering algorithm and an immune technology particle swarm optimization algorithm, to define the best locations for measurements stations. In the more general context of sensor networks for environmental monitoring, Reis et al. [30] suggested that models can also be used to optimize the deployment of sensors by identifying areas of interest according to specific metrics.

Authors have also questioned the spatial representativeness of noise, in order to limit the number of sensors, and then to consider ways to interpolate noise indicators between the measurement locations. For example, Can et al. [31] showed that interpolation methods were defective when the spacing between sensors was too large (about one measurement point every 250 m in the study). In addition, Gozalo et al. [32] showed that a stratification of roads based on their functionality was helpful before interpolating sound levels showed similarly. Liu et al. [33] also analyzed the sound environments of a city in Germany, and

observed that spatial variation of urban soundscape patterns was explained by underlying landscape characteristics, while temporal variation was mainly driven by urban activities. Lastly, Zuo et al. [34] observed in the city of Toronto that noise variability was predominantly spatial in nature, rather than temporal. More recently, two examples of spatial interpolation of noise levels based on a dense sensor network were described. In [35, 36], the authors show the kriging method seems an efficient method to interpolate noise levels.

Beyond the metric itself associated with the measurement, other elements can also be considered in the deployment and of the optimization of the whole network, such as the connectivity between node/relay/sink, the spatial domain coverage or the network life and energy efficiency [37, 38].

4. CONCLUSIONS

Given the major problem of evaluating and controlling sound environments, the development of low-cost sensor networks is today an interesting alternative solution, complementary, to more traditional solutions such as modelling and "professional" observation networks. Numerous researchers have thus focused on the development of low-cost sensors over the last fifteen years, ranging from proof-of-concept to the deployment of operational networks [39].

From a technical point of view, the review illustrates fairly well the evolution of low-cost sensors, from the adaptation of existing sensors (but with limited resources) to the use of mini-PCs and MCUs (with more extensive computing and measurement capabilities). If the sensors can be directly powered by an existing electrical network, mini-PCs are the most relevant solution up-today, especially in view of the modularity and real-time processing capabilities they offer. For stand-alone sensors, most recent MCUs offer interesting performances, but their overall capacities remain very dependent on their power supply and recharging mode. From an acoustic measurement point of view, the use of a digital MEMS with a sampling frequency of 44.1 kHz now seems to be a technically affordable solution, not very sensitive to electrical and electromagnetic interference, that meets the challenges of noise monitoring. Among the possible technical evolution, the development of sensors composed of several microphones would offer new perspectives for the localization and the tracking of sound sources, as well as for measuring 3D audio [12, 40, 41]. Concerning radio data transmission, Zigbee and 6LoWPAN protocols, based on 802.15.4 specification, present both maximum range and data rates that are compatible with noise measurements. Setting aside the problems of sealing against weather and pollutants, as well as the mechanical protection of the sensor, which can be solved by integrating the electronic components in a specially designed container, the service life of the electronic components, including memory and battery, is now potentially fully compatible with long-term acoustic measurement.

The individual cost of a sensor must be put in relation

to the overall cost of an infrastructure consisting of a very large number of sensors [26], potentially requiring a high level of maintenance. The question of the best location of sensors is therefore an important issue for the future. In addition, the automatic detection of anomalies in the network, whether to identify a hardware malfunction or an abnormal set of data, are also subjects that will have to be addressed to improve the database quality. The multitude of such data also raises the question of developing appropriate data infrastructures for their representation and processing [7, 42].

There are many opportunities that enhance the value of these measurement networks and the collected data. Environmental services of cities can, for example, use data to dynamically adapt their policies, since they are able to measure directly the effects of the policies tested. Another example is that local residents associations, with the help of specialized services, can understand the environmental quality of their neighborhood and use it to alert the authorities or become a source of proposals. To do this, it is also important that current networks be enriched with perceptive data, in order to better describe the impacts of noise on citizens.

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