AN OVERVIEW OF SENSOR NETWORKS FOR ENVIRONMENTAL NOISE MONITORING

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The last decade has shown a growing number and wide variety of systems for monitoring environmental noise. This ongoing development is made possible by the availability of cheaper and smaller hardware and innovations in communication networks. The developments are fed by a growing interest in monitoring because it can help in improving noise maps and in getting more insight in complex noise situations. It can also help to take appropriate and cost efficient measures and to assess the effect of these measures. Furthermore, it is a welcome instrument for communication and policy making. In this paper several developments and approaches for acoustic sensor networks are discussed with examples from literature. The systems vary from application of expensive dedicated hardware to low cost sensor nodes and networks based on smartphones. While each system has its own advantages and disadvantages, the various approaches will be compared with respect to several aspects such as costs, scalability, flexibility, reliability and accuracy. One of the considered systems is the acoustic sensor network developed by TNO. This system is based on two types of low cost acoustic sensor nodes, a basic sensor node and an advanced sensor node, in a scalable architecture. The specific benefits of this system will be discussed in more detail. This includes recent developments such as automatic classification and accurate synchronization, which were successfully applied in a field test using seven advanced nodes and twenty-eight basic nodes for monitoring traffic noise in a complex situation.

1. Introduction

There is an increasing awareness for noise pollution and the potential impact on human health. This has resulted in an increased demand for getting insight in complex noise situations, which is stimulated by the European noise directive which states that each member state has to make noise maps. Based on these maps action plans have to be proposed for problem areas. Producing accurate and meaningful noise maps based on only calculations is shown to be a difficult task. Acoustic monitoring can help in improving the accuracy of noise maps and getting more insight in often complex noise situations. It can also help to take appropriate and cost efficient measures and to assess the effect of these measures. Furthermore, it is a good instrument for communication and policy making. However, accurately measuring environmental noise at many locations for long periods under various circumstances is not an easy task.
2. Acoustic sensor networks

Traditional noise measurements in urban areas are mainly carried out by professionals that record and analyse data at a location of interest using a sound level meter or similar device. Such a manual method does not scale well as the demand for more noise measurements in both time (longer periods) and space (more locations) increases. The last decade has shown a growing number and wide variety of systems for monitoring environmental noise. This ongoing development is made possible by the availability of cheaper and smaller hardware and innovations in communication networks. Several developments and architectures for the application of acoustic sensor networks are reported in literature. The networks vary from application of expensive dedicated hardware to very low cost sensor nodes and sensor networks based on smartphones.

2.1 Categories for acoustic sensor networks

The sensor networks for environmental noise monitoring can roughly be distinguished in four different categories. These categories are discussed in the following sections and for each category some examples are given. By giving this overview, it is not the intention to be complete.

2.1.1 Category 1: Networks based on dedicated monitoring equipment

The first category is monitoring equipment built for reliability, accuracy, low noise floor, weather resistance and low power consumption. This equipment is widely accepted for noise monitoring applications. Special sensors and hardware components are used which make the prices typically several thousands of Euros per node. These systems are mostly equipped with IEC class 1 microphones. Examples of this group are monitoring systems from Bruel&Kjaer, 01dB and Larson&Davis. The soft- and hardware of these systems are not easy to adapt, which makes the systems in this category not very flexible to be used for other purposes than the applications envisioned by the manufacturer.

2.1.2 Category 2: Affordable acoustic sensor networks with improved properties for scalability, flexibility, accuracy and reliability

The second category is balancing between the very expensive dedicated monitoring hardware (category 1) and cheap sensors for pervasive use (category 3). In category 2 low price, enabling to set up large networks, is not the only goal. Requirements with respect to accuracy and reliability and the ability for additional processing and flexibility for different use are reasons to use somewhat more dedicated hardware. Most systems in this group are based on commercial sound level meters, such as the system designed and used by Munisense, Wang, Santini et al., Sensornet and Bruitparif. Also the system from TNO with two types of sensors can be attributed to this group. This system will be addressed in more detail in sections 3 and 4.

2.1.3 Category 3: Acoustic sensor networks for pervasive use

The third category of networks which can be distinguished are custom built sensor network solutions designed to be inexpensive, low power and autonomous so that it can be deployed pervasively. Examples are the networks developed by the University of Newcastle in the MESSAGE project and the network of the University of Ghent developed in the IDEA project.

The systems are generally based on a single board computer which is a stripped down version of a computer with more limited computational performance, a cheap sound card and cheap microphones. There is a huge price difference between the cheap hardware which is used for consumer electronics and dedicated logging hardware (category 1). The cheap hardware makes it possible to produce and apply sensors on a large scale with many sensors, enabling monitoring in a wide area. In general, the systems have low memory and low processing capacity which is no problem when the sensors are designed to perform only one task, which is generally measuring sound levels over a period of time and sending the data to a central database on the internet. Additional processing, such
as spectral analysis and automatic classification is hardly possible with the low-end equipment. Also the dynamic range and the accuracy are limited which is partly compensated for by combining the large amount of data monitored from many positions. The long term stability of these systems is often rather poor, which results in a lower availability of the data. Also reconfiguring the sensors can be time consuming.

2.1.4 Category 4: Acoustic sensor networks based on smartphones

The last category is based on smartphones. The current generation of smartphones have onboard sensors (microphone, GPS), a programmable processor, memory and communication capabilities which makes it possible to perform noise measurements. By distributing application software that users of smartphones can install on their phones, a network of many sensors can be generated. Some examples of such networks are Noisetube\textsuperscript{16}, NoiseSPY\textsuperscript{17} and Widenoise\textsuperscript{18}.

The penetration of smartphones nowadays is very high which makes it very useful for participatory sensing with a high number of sensors. d’Hondt et al\textsuperscript{19} report a successful experiment for noise mapping a 1 km\textsuperscript{2} area in the city of Antwerp. They show that when calibration and placement of sensors is considered seriously, the data generated by a network of smartphones can be used for noise mapping. Issues of using smartphones are the low accuracy of microphones, a non-flat and time varying frequency response requiring (regular) frequency dependent calibration and privacy issues. Also the status and placement of the smartphone is not always known. To interpret the data it is for example needed to know whether the mobile phone is inside or outside a pocket or a building, what is the position above the ground and if there are any other reflecting surfaces in the neighborhood. Another general challenge is how to motivate people to participate in environmental noise monitoring.

2.2 Comparison

While each system has its own advantages and disadvantages, the approaches can be compared with respect to several aspects such as hardware costs, scalability, flexibility, reliability and accuracy. For the four categories mentioned in the previous section these aspects are graphically sketched in Figure 1 and discussed in more depth in the following paragraphs.

![Figure 1. Comparison of the four categories of acoustic sensor networks.](image-url)
Each aspect is given a (subjective) grade between 1 and 10. A high value for the different aspects means low cost, good scalability, good flexibility, high reliability and high accuracy, respectively.

2.2.1 Hardware Costs

The hardware costs decrease from category 1 to category 4. In categories 1 and 2 more dedicated hardware is used, with the most dedicated and expensive hardware in category 1. There is still a large price difference between the hardware used for categories 1 and 2. Category 3 uses very low cost consumer electronics, while category 4 uses relatively cheap smartphones.

Within an application, beside hardware costs also other costs, mainly maintenance costs, must be taken into account. These costs can increase considerably when the availability and accuracy of the data becomes more important. Especially for the category 2 and 3 networks the maintenance costs can become considerably higher than the hardware costs.

2.2.2 Scalability

An important aspect for large scale monitoring is scalability. Especially when a network is used for generating input for noise maps, high granularity in space is necessary. Aspects such as the ease to add new nodes, the robustness for failing nodes, the amount of data transmission and local processing need proper attention. Sensor networks of categories 3 and 4 are especially suited for large scale monitoring of sound levels and are for that purpose highly scalable. Category 1 is generally not designed for large scale networks. The scalability properties for category 2 are generally also good, making it possible to apply these networks for medium to large scale applications.

2.2.3 Flexibility

The requirements for various monitoring applications can differ significantly. To be able to apply the network for different applications a flexible approach is needed. For some cases basic monitoring of noise levels over time and over a large area is required. Other applications require more information, such as the local character of the sound which may be described by the spectral content. It is also possible that special noise metrics need to be determined, like sound exposure levels with different spectral weightings. The ability to record and listen to time signals may be helpful for understanding the nature of the sound source. Local sound classification may be helpful for automatically identifying interesting events. Localising events would provide even more insight and requires accurate synchronisation between the sensors. These different requirements which are not all known beforehand, ask for a flexible approach for an acoustic sensor network which is easily reconfigurable. Finally, the power consumption and power management have influence on the flexibility of a sensor network. If the sensor nodes are completely autonomous with their own power supply, the flexibility for deployment is much better.

2.2.4 Accuracy

An important aspect of sensor networks for environmental noise monitoring is the accuracy of the data. When collecting absolute noise levels, accurate calibration of the measuring devices is essential. Important hardware elements which determine the accuracy are the microphone and the A/D converter. The noise floor and frequency response of the microphone are related to the price of the microphone. When the frequency response is not flat it can be corrected to some extent in the processing, assuming that it is stable over time. When this is not the case regular calibration is needed for each sensor to determine the frequency characteristics, which is time consuming. Besides the sensor itself, also the A/D converter determines the dynamic range. The category 3 and 4 systems have often a relatively high noise floor and limited dynamic range. Additionally, the accuracy of the measured data is dependent on background noise, the effect of wind and the way of deployment. When smartphones are used, there is limited control on the deployment, which makes it
hardly possible to judge the quality of the data. In categories 1 and 2 more dedicated IEC class 1 or 2 microphones are used.

2.2.5 Reliability

For some applications the availability of the data can be very important. Therefore the system has to be reliable. The reliability is determined by the quality of the hardware, the software and the communication. Status checks, restart procedures and automatic reconfigurability can improve the network reliability.

3. TNO approach

The acoustic network developed by TNO is a category 2 network. It is based on two types of low cost acoustic sensor nodes, a basic wireless sensor node and an advanced sensor node. The network is built up of independent subnetworks. Each subnetwork contains several basic nodes with local communication and one advanced sensor node with long range communication enabling the node to send the data to a central database on the internet. The basic nodes are small wireless sensor nodes and are especially developed for cases when noise levels over relatively large areas have to be determined. The node contains an IEC class 2 sound level meter, which is able to measure sound levels (e.g. LAeq). The meter is very compact and the power consumption is relatively low. A small sensor platform is applied for processing and sending the sensor data. This platform contains a low power microcontroller, a radio, some flash memory and a USB plug for programming the chip or for data transmission when connected to a computer. This node reads the sound levels measured by the sound level meter, at configurable intervals. A multi hopping process is used to transmit the data via the radio using a Collection Tree Protocol (CTP). Beside increasing the communication range, the CTP also makes the network ad-hoc and scalable. This means that nodes can be added or removed at any time or at any location to the network. This makes the network flexible and robust for incidental node failure. The basic sensor node can be powered by batteries.

The basic nodes within each subnetwork transmit all the data to the local advanced sensor nodes. This node is also low cost and based on a small pc with Linux operating system and equipped with a radio antenna, UMTS for internet connection, a GPS chip and a database for storing all the data. An IEC class 1 microphone is connected which makes it possible to record high quality time signals with a sampling frequency of 48 kHz. The on-board Linux pc is easily programmable to implement various digital filters, sound level and spectral calculations or classification algorithms. The advanced units can be powered by line power, batteries or a solar panel. The data is regularly sent to a central database on internet and the advanced nodes can be accessed and managed by a remote connection. The advanced nodes are designed for accurate synchronization making it possible to measure small differences in time of arrival and phase difference between various sensor nodes.

4. Recent application

4.1 Goal

In 2013 a large scale monitoring project was initiated by TNO where the TNO sensor network was applied. The goal of the monitoring campaign was to get a better understanding between local noise and local annoyance in a complex environment with various noise sources, dominated by road traffic and railway noise. A network of microphones was applied to monitor the noise. During the monitoring period people were asked to report their annoyance by filling in survey forms. The goal was to relate the outcome of this survey with the sound levels on the façades at the corresponding houses. Because monitoring gives only results at some discrete positions in the area, a model based
approach was applied to interpolate the sparsely sampled sensor data, resulting in a much better estimation of the different traffic noise sources.

4.2 Network layout

In total 35 microphones were applied using 7 advanced nodes and 28 basic nodes. The network was subdivided in 7 subnetworks, each containing one advanced node and four basic nodes. The microphones were placed along the streets and near houses, some examples are given in Figure 2. The monitoring period was more than one week. The network was completely autonomous and every sensor was powered by batteries.

![Network layout showing 7 advanced nodes (in blue) and 28 basic nodes (in red). Examples: an advanced node in front of a house and a basic node connected to a lamp post.](image)

4.3 Results

An example of the measured sound levels is given in Figure 3. In Figure 4 a spectrogram is given. An autonomous classification procedure was applied identifying several sound sources automatically. In Figure 4 also a result of a noise map is given where calculation results of a traffic noise model were updated with measured data to get accurate noise level results at positions without sensors. By using this model based approach it was possible to combine the local survey results with local noise data resulting in local exposure-response relations. Further details about these local relations will be given in a future paper. The experiment showed that the applied network was very useful for this purpose. The low cost aspect made a large number of sensors possible. The scalability properties made it easy to add networks to the area until all major sound sources were covered. The flexibility aspects made it easy to deploy and to add new features such as the automatic classification and accurate synchronization. The accuracy was assured by applying good quality equipment and proper calibration before and after the experiment.
5. Discussion and conclusions

This paper gives an overview of various sensor network solutions for environmental noise monitoring. Four different categories were distinguished and also advantages and disadvantages of the different approaches were given, together with some examples. The various solutions are compared with respect to the aspects hardware costs, scalability, flexibility, reliability and accuracy. The TNO network is an example of a category 2 network, balancing between these aspects, with an emphasis on scalability, enabling experiments on a larger scale and flexibility to cope with requirements of various applications.

In the future the need and application of noise monitoring will undoubtedly increase. The applied networks will be more and more part of city wide sensor networks measuring a multitude of variables, which enables the development of so-called smart cities. The autonomy of the networks will increase such that reliable and accurate data streams and information is generated which will find its way in useful applications for (automatic) city sensing and control. To reach this status not only technical challenges for sensor networks will have to be solved, but also the coupling of measurements with models (data assimilation), data management and measures for noise control will need further attention.
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