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Design aspects of acoustic sensor networks for environmental noise monitoring

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ABSTRACT

An increase in public awareness of noise pollution and the impact of noise on human health has led to the need for enhanced insight in complex noise situations. This insight is commonly obtained either by brief measurements or by evaluation of a simplified acoustic model. Both of these approaches however have limitations in complex noise situations. Noise monitoring can be an appropriate and cost efficient measure to obtain more insight, for it allows to measure at many locations for long periods of time. Monitoring can for example be used to improve the accuracy of models or to assess and respond to changes in the acoustic situation. Several monitoring approaches, for various applications, have been developed or are under development. In the first part of this paper an overview is given of current developments in acoustic monitoring networks and their key aspects. Sensor networks for environmental noise monitoring are here divided into four different categories, distinguished by five aspects: hardware costs, scalability, flexibility, reliability and accuracy. These five aspects determine the range of applications for which a network is suited. In the second part of this paper a monitoring network developed in-house is used to further illustrate the relevance of these aspects. This network was designed to facilitate research into the field of acoustic monitoring networks and is used to experiment with and learn from a broad field of applications.

Since the network is not designed for just one application, it has a special focus on flexibility and scalability. This allows the network to cope with the requirement of various applications with different scales. In the third section of this paper three applications of the network are shown to illustrate the five aspects.

1. Introduction

There is an increasing public awareness of noise pollution and its potential impact on human health [1]. This has led to the need for better insight in complex noise situations. Noise mapping is required by the European Noise Directive (END) obliging each member state to provide noise maps for cities with more than 100.000 inhabitants [2]. Based on these maps action plans have to be proposed for problem areas. Producing accurate and meaningful noise maps, based only on calculations, has proven to be a difficult task [3]. Acoustic monitoring can help in improving the accuracy of noise maps and getting more insight in often complex noise situations. Monitoring can also help select appropriate and cost-effective measures and to assess their effect. Furthermore, it is a better instrument for transparent communication of noise related information to the public and for policy making. However, accurately measuring environmental noise at many locations for long periods under various conditions is not an easy task. Several monitoring approaches have been developed or are under development. Section 2 of this paper gives an overview of current developments in acoustic monitoring networks. Here a subdivision of four categories of acoustic sensor networks is made, putting emphasis on five different aspects. In Section 3 an acoustic sensor network developed in-house, designed to facilitate research into the field of acoustic monitoring, is discussed in more detail to further illustrate the five aspects. The design choices and their effects on the five aspects are discussed. Resulting examples of feasible applications are shown in Section 4. Section 5 contains a discussion for further developments and Section 6 summarizes the main conclusions of this paper.

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2. Acoustic sensor networks

Traditional noise measurements in environmental noise monitoring are mainly carried out by professionals that record and analyze 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. In the past decade a growing number and wide variety of environmental noise monitoring systems has appeared. 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 inexpensive sensor nodes and sensor networks based on smartphones. In this paper the sensor networks for environmental noise monitoring are divided into four different categories [4]. These are discussed in the following sections and for each category some examples are given. By giving the examples in this overview, it is not the intention to be complete.

2.1. Categories

Category 1: Networks based on dedicated monitoring equipment

The first category is monitoring equipment built for reliability (e.g. weather resistance and low power consumption) and accuracy (e.g. low noise floor, equipped with IEC class 1 microphones). This equipment is widely accepted for noise monitoring applications. Examples of this group are monitoring systems from Bruel & Kjaer [5], 01 dB [6] and Larson & Davis [7]. The monitoring systems used for airport environmental noise management [8], belong often to this category.

Category 1 monitoring equipment uses high end sensors and custom hardware components, which results in prices of typically several thousands of Euros per node (estimated on basis of commercial information, which is not further discussed in this paper). The soft- and hardware of these systems cannot easily be changed by the user, which makes the systems in this category unsuited to be used for other purposes than the applications envisioned by the manufacturer.

Category 2: Acoustic sensor networks with improved properties for scalability, flexibility, accuracy and reliability with midrange priced components

The second category balances between the expensive dedicated monitoring hardware (category 1) and cheap sensors for pervasive use (category 3). In category 2 a low price, enabling to set up large networks, is not the primary goal. Requirements with respect to accuracy, reliability, 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 [9], Wang et al. [10], Santini et al. [11,12], Sensornet [13] and Bruitparif [14]. These systems are applied for different applications, such as monitoring of construction noise, events, traffic noise and industrial noise. Typical prices are a few thousand euros per node (estimated on basis of a compact computer, a high end sound card and a class 1 outdoor microphone). The example network of Section 3, with two types of sensor nodes can be attributed to this group [15]. This system will be addressed in more detail in Section 3.

Category 3: Low cost 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 Newcastle University in the MESSAGE [16] project and the network of the Ghent University developed in the IDEA project [17,18].

The systems are generally based on a single board computer which is a stripped down version of a computer with limited computational performance, a low cost sound card and low cost (possibly MEMS) microphones. Typical prices, based on the set of components, are estimated at less than a thousand Euros per node. There is a huge price difference between the consumer electronics which are used and the dedicated logging hardware used for of category 1. The low cost hardware makes it possible to produce and apply sensors on a very 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 automatic classification is hardly possible onboard the low-end equipment. The limited dynamic range and accuracy can however be compensated for by combining the large amount of data monitored from many positions. The long term stability of these systems is less compared to category 2, which results in a lower reliability in the availability of all the data. Also reconfiguring the sensors can be time consuming.

Category 4: Acoustic sensor networks based on smartphones

The last category is based on the usage of smartphones. The current generation of smartphones has onboard sensors (microphone, GPS, accelerometer), 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 [19], NoiseSPY [20] and Widenoise [21]. Typical hardware prices are a few hundred Euros per smartphone (node). However, it should be noted that the creator of the application software generally does not supply the smartphones that form the sensor network. The application itself is sold or is given freely to smartphone owners, whom form the network by activating the application.

The penetration of smartphones nowadays is considerable which makes it advantageous for participatory sensing with a high number of sensors. D'Hondt et al. [22] report a successful experiment for noise mapping a 1 km^2 area in the city of Antwerp. They show that when calibration and placement of sensors is done properly, the data generated by a network of smartphones can be used for noise mapping. Issues when 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 the position of the phone is 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

The different approaches can be compared with respect to five aspects such as hardware costs, scalability, flexibility, reliability