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5aNSa1. The internet of sound observatories
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With the advance of electronics, sound level meters have become more powerful when it comes to analyzing and storing huge amount of measurements. In recent years, these devices have been hooked up to the internet and stream life data. In the IDEA project, the whole concept of a sound observatory is turned upside down by stripping the sensor nodes to their bare essential, and by migrating all logic and data storage to computing centers. This opens new opportunities in particular for long-term environmental sound monitoring and analysis. As unlimited computing power is available, more advanced analysis such as auditory scene analysis can be incorporated. In addition new analysis methods and indicators can be deployed on the whole network of sound observatories using up-to-date software agent technology. As each observatory is a cheap plug-and-measure device without any buttons or display, participatory sensing becomes easy: citizens plug in their device and data streams to central servers and is displayed on a website of choice for the community. During the presentation, application cases in urban tranquil area, building site noise, wind turbine noise, and train noise monitoring, as well as noise mapping validation will be shown.

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INTRODUCTION

With the advance of electronics, sound level meters have become more powerful when it comes to analyzing and storing huge amounts of measurements. The internet now allows streaming measurement data almost in real time to the investigator's desktop. In contrast, developments of sensor network technology drive the emergence of smart city initiatives where almost anything imaginable is monitored, at least conceptually. In these applications, the number of sensors generally outweighs their individual quality. Since consumer microphones are extremely cheap, environmental noise has become a popular factor to sense. Examples of such initiatives are the MESSAGE project in the UK (Bell et al. 2013), SensorCity initiative in Assen, The Netherlands (www.sensorcity.nl), Libelium in Spain (www.libelium.com), Senseable in the United States (senseable.mit.edu), … These projects mostly use general purpose sensor nodes in combination with consumer grade microphones, either electrets or MEMS (NLP, …). Such microphones are indeed accurate and reliability enough, even in harsh outdoor conditions, for many environmental noise applications (Van Renterghem et al.). The Dutch “geluidsnet” (www.geluidsnet.nl) in contrast combines the sensor network concept with professional measurement microphones.

This paper explores the new opportunities created by flipping the whole concept of a sound observatory upside down: the sensor nodes are stripped to their bare essential, which means devices that collect the sound signal and have no switch or display; all logic and data storage is migrated to computing centers. This paper discusses three lines of opportunities: (1) the opportunities created by the computational power and data storage that is available at the server such as the possibility to do a full auditory scene analysis resulting in a human-like sound description; (2) the chance to update analysis for new indicators that can be applied retroactively, a methodology also applied in the HARMONICA project (Mietlicki et al., 2012); (3) the advantages for participatory sensing.

The examples shown in this paper are taken from the IDEA-project (www.idea-project.be) that was conducted in Flanders over the last four years. The architecture of this project is discussed in a first section.

THE IDEA-PROJECT ARCHITECTURE

The “internet of sound observatories” concept is implemented in the IDEA-project as illustrated in Figure 1. Sensor gateway nodes (Alix single board computer) read the sensor data (microphone, GPS, air quality, temperature, …) and perform essential preprocessing for reducing the data stream. These gateway nodes are connected directly to the internet without any ad hoc chaining using, for example, the Zigbee protocol. The reason for this choice is that the nodes are in general distributed over a wide geographical area and that bandwidth needs to be guaranteed. For flexible installation and reliability, protocols for discovery of newly deployed nodes and data caching for bridging instantaneous poor connection are added.

![Diagram of IDEA-project architecture](image-url)

**FIGURE 1.** Architecture of the internet of sound observatories implementation in the IDEA-project.
At the server side, data storage is managed. This includes a virtualization layer that allows managing the sensor nodes and access data without direct interaction with these remote nodes. An important aspect in the deployed architecture is the multi-agent data processing. Agents are autonomous software modules that run continuously on several compute servers and perform some basic analysis on the data. Examples of such agents are the quality control agents, statistical processing agents with different time intervals (1 minute, 15 minute, 1 hour), feature extraction agents (see next section), sound fragment managers, long term Lden agent, etc. These multitudes of processes, that are sometimes interdependent, have to be managed with care. Therefore a task distribution layer is added that handles resource allocation, task planning, and task monitoring. Tasks that fail because of lack of data or resources are automatically rescheduled. This creates a balance between bringing validated and processed results to the user as soon as possible and robustness against interrupted or temporary slow data flow. Since some agents can be quite time consuming tasks have to be distributed amongst available resources efficiently. More details on load balancing can be found in (Dauwe et al., 2012).

The operational IDEA-network now contains around 50 permanent measurement nodes. Every month they produce $3 \times 10^9$ data records that are stored in a flexible relational database that is designed according to OGC (open geospatial consortium) Sensor Web Enablement architecture, and more in particular the Sensor Observations Service (SOS). This compliance guarantees that data can be easily exchanged and that existing applications and clients can be reused.

**COMPUTATIONAL POWER FOR CASA**

Computational auditory scene analysis (CASA) (Bregman, 1994) has been a topic of interest for many years and many algorithms have been proposed for identifying and recognizing environmental sounds (Cowling and Sitte, 2003). Yet very little equipment is available that allows to describe how a human listener would break an auditory scene into objects, its basic building blocks. Human mimicking systems for CASA are learning systems. Based on a corpus of data, they learn how to analyze the scene. This knowledge is typically stored in some form of neural network coefficients. If one tries to implement such a system on a classical sound level meter, two problems appear: too low computational power and the difficulty to create a corpus of reference data that could work in all situations where the sound level meter might be used.

Here, a distributed approach is proposed. Raw data is streamed from the measurement nodes with as much detail as possible to the server. A compromise between transmission bandwidth and complexity of the sensor layer data preprocessing has to be made. An additional argument in this choice is the compatibility with existing measurement networks. Initial trials resulted in choosing $1/3$ octave bands collected 8 times per second as the raw data. This spectro-temporal resolution allows identifying most environmental sounds.

A first step in the CASA consists in selecting suitable features and structuring feature space. Compared to most speech recognition systems, we select a very basic feature set based on Gaussian and difference of Gaussian filters in time and frequency. Feature space is structured by unsupervised learning that explores co-occurrence of the basic features using a self organizing map that is extended with continuous learning (Oldoni et al., 2010). Such a system specializes on the sounds that are present during training, which is at a specific location. This has the advantage that the system does not spend valuable resources on sounds that could never be heard at a particular location. Yet overspecialization should be avoided and therefore the network concept is again important. Training could be based on sounds collected from a set of similar measurement locations (e.g. all nodes in a particular city).

The next step in the CASA consists in forming auditory objects. This process could be self-learning based on sequential occurrence of combinations of features; however it seems helpful to include knowledge on the sounds at this step (). A supervised training of a bidirectional artificial neural network is used for this purpose. It connects concepts to areas of the self organized map that spans feature space. In the forward direction microphone input excites particular concepts thus making the corresponding sounds more likely to be identified. In the backward direction, activated concepts bias the excitation of the SOM layer to plausible sounds. It is this backward path that groups over time and thus creates auditory objects. An overview of the complete CASA is given in Figure 2 and more details can be found in (Boes et al., 2012).

The advantage of the proposed distributed sensor network approach is that the corpus of labeled sounds can be dynamically built, system wide. New, unidentified sounds at any of the nodes are recorded and stored for human labeling. For the latter we rely on crowd sourcing. An online game stimulates participants to listen to the sounds and label them while scoring points as they use the same label as a previous player. By banning some trivial words diversity in labeling can be increased. Figure 2b shows the activations of concept neurons related to different labels occurring in the system by this process. It is clear that occasionally there is some confusion and that some concepts
are almost synonyms but introducing context as a and grouping can lead to useful classification as shown in Figure 3c.

![Diagram](image)

**FIGURE 2.** (a) Outline of the model for sound identification; (b) illustration of concept activation and resulting sound identification at a particular node in a backyard close to a school; (c) summary of occurrence of different sounds during one day.

**IMPLEMENTING NEW INDICATORS SYSTEM WIDE**

Scientists interested in deriving new indicators and testing them against for example annoyance or soundscape quality, may want to calculate those new indicators for a large number of locations. This can obviously be done offline on a dataset of detailed observations. The proposed distributed system with centralized post processing allows going one step further. After implementation, a new indicator can immediately be calculated for all nodes where it is relevant on measurements from the past as well as on new observations. For example, for studying quiet areas, the music likeness and the spectral center of gravity indicator proposed in (De Coensel et al., 2006) and
(Botteldooren et al., 2006) were easily implemented for all quiet sides and quiet areas in the IDEA-project sensor network. Another paper presented at ICA 2013 elaborates on this application (De Coensel et al., 2013).

Noise mapping has become very popular in Europe ever since the Environmental Noise Directive (END) (2002/49/EC) was issued. Validating such maps with measurements is not easy since it requires long term observations. At the other hand class 1 equipment might not be needed for this validation since: (1) the validation does not need to be within 1 dB(A); (2) the A-weighted noise spectrum is broadband around 1000 Hz which is a frequency region where the consumer-electronics microphones perform well; (3) very low levels will not occur in urban situations and thus noise floor problems are unlikely. An additional agent was implemented to calculate $L_{day}$ as defined by the END for all locations where at least several months of continuous measurements were available. In Figure 3, measurements at ten locations in one city are compared with the official END map, with the END map with additional background sound energy based on the model developed in the QSIDE project (Wei et al., 2012), and with a final model where turbulence scattering is added as well (Forssen et al., 2013). It can be seen that at highly exposed locations the official noise map matches the measurement or overestimates levels. At shielded locations (6, 8, 9, and 10) the official noise maps underestimate levels and adding the background level and turbulence scattering significantly improves the model prediction. At location 9 the contribution of the schoolchildren playing outside periodically is significant and could be subtracted lowering the measured $L_{day}$ by over 5 dB(A). It should be noted that measurements are continuing and $L_{day}$ and $L_{ten}$ estimates are renewed every week so comparison may improve. Convergence studies have shown that these indicators hardly change anymore after 6 to 8 weeks of measurements, but seasonal affects have not yet been studied.

**FIGURE 3.** Long term measurement of daytime noise level compared to different models: END: official noise map in compliance with environmental noise directive 2002/49/EC; END+Q: QSIDE for background levels based on multiple reflection and long distance sources added; END+Q+QT: same but with additional effect of turbulence-scattering.

In addition to single site indicators, the internet of noise observatories also allows to connect observations at different locations. Figure 4 illustrates the detection of train events. During upward refracting propagation conditions (bottom-right) it becomes difficult to identify the train noise event. Knowledge from the close measurement point is used to define a search window and as a priori knowledge in the sound recognition mechanisms discussed in the previous section.

### PARTICIPATORY SENSING

Participatory sensing of the quality of the environment has become quite popular recently. It is expected to raise awareness with the public but it is also a cheap way to gather large amounts of local data. The sensor box used for participatory sensing has to be plug-and-measure requiring no changes in settings or installation procedures. It is thus advantageous to use the proposed distributed approach and bring all logic to the server side. Measurement equipment has intrinsic accuracy limitations and as consumer grade microphones are used, sensor failure could occur more often. However, in a participatory sensing application, the lay persons performing the measurement can introduce additional loss of quality. Several concepts for detecting quality loss are thus implemented: the operational range observed in lab tests determines the intrinsic quality of the sensor reading ($Q_{intrin}$); observing combinations of features that have never been observed before (see CASA above) at this location indicates that the sound was never encountered before and thus potential sensor malfunction or sensor displacement ($Q_{SOM}$); if readings deviate more than usual from diurnal pattern, the sensor may be drifting ($Q_{diurn}$); a drastic change in signal variability over a one minute period can be considered an efficient heuristic for quality degradation and deliberate manipulation of the
observed level \( (Q_{\text{heur}}) \). An ordered weighted average over all of these quality values is used to obtain a final quality indicator.

**FIGURE 4.** Illustration of the advantage of using a sensor network for detecting noise events related to a train passage. In red a measurement close to the source is shown, green and blue indicate more remote observations. Four train passages under different meteorological conditions are shown.

Tests with 15 volunteers learned that the proposed system is indeed plug-and-play as most participants installed the measurement node within half an hour of receiving it without any training. Via the internet, the participants can check their instantaneous measurement; which is much appreciated and there is really no demand to have a display on the device itself. As the campaign progressed new features were added, for example long term \( L_{\text{den}} \) after one month of measurements. Figure 5 shows two screen shots of the interface provided to the participants in the participatory sensing experiment. Only overall levels are displayed but at different time scales. The last 10 minutes display seems to be used to identify noise events that have just happened. As the time interval progresses, the time resolution is reduced, but features of interest for the participants can still be discovered such as the high noise level at new years eve in Figure 5 or the reduced noise level during week 3 when snow was slowing traffic down and increasing the ground effect. The experiment started on October 15\(^{th}\) and by the end of January none of the participants has withdrawn. In December local television news and newspaper got interested.

**FIGURE 5.** Screenshots of the interface used for the participants in the participatory noise sensing experiment.
CONCLUSIONS

This paper illustrates the opportunities created by a new concept of environmental noise assessment: the internet of noise observatories. It shows how connecting a large number of low-end sensing devices via the internet is beneficial for high-end analysis such as computational auditory scene analysis, combined event detection, and deploying new indicators for amongst others annoyance and soundscape quality. The distributed noise observatories have thus become an interesting living lab for testing new ideas and concepts.

In addition the approach combines well with participatory sensing since all devices settings and analysis choices, that have to be made by the field expert, remain at the server side. Online displays can be tuned to the needs and interests of the participants and their peers, making the platform very well suited for collective awareness raising.

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