Utilising the Strengths of Different Sound Sensor Networks in Smart CityNoise Management

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Summary
City noise management involves a variety of disciplines such as planning, mapping, action plans, policing, complaint management, abatement and public awareness. With the wide availability of mobile broadband internet access coupled with low cost noise sensors, many authorities and researchers are eager to use sound sensor networks for these tasks. A sensor network can be defined as a group of specialized transducers and processing with a communications infrastructure and is intended to monitor and record conditions at diverse locations, connected to a central software. This definition covers a wide range of different possibilities, designs and components such as MEMS microphones, processing software, type approved instrumentation, smart phones, etc. However, are all networks suitable for all tasks? Many sensors trade off measurement precision to reduce cost and enable an increase in number of measurement points within a budget. This paper describes different sensor classes and implementation strategies. It discusses the relative merits of different sensors and describes what is important to take account of when implementing these networks for application to one or multiple noise management tasks, outlining what each can be used for and what they shouldn't be used for. Aspects covered include architecture, and practical applicability. The paper concludes with recommendations for using different smart networks and for further research.

PACS no. 43.58.+z, 43.50.+y

1. Introduction

New technology such as Microelectromechanical systems (MEMS) [1] microphones, processing software and smart phones offers significant reduction in the cost of noise monitors and challenges the use of traditional instrumentation. This new technology and the increase in access to mobile broadband internet affect the design of noise management solutions. A sound sensor network that is cost-effective enough to be very densely distributed opens new opportunities for noise management through providing live data at more locations. This paper focusses on data collection with different types of sound sensor.

2. Definition and categorisation

The author defines a sensor network as a group of specialized transducers and processing with a communications infrastructure to a system for viewing, analysing and reporting data. It monitors and records conditions at several locations, offering, with today's broadband communication, real-time access to data. Sound sensors cover noise monitoring terminals, sound level meters, smart phones, etc. What makes a network "Smart" is it's intelligence to help users achieve their noise management goals.

First of all, MEMS microphones need outdoor protection but, being very lost cost transducers, still help reduce the cost of a sound sensor. However, they face issues concerning limited linear dynamic range, accuracy (linearity over time, level and frequency), the impact of environmental conditions and reproducibility – i.e. variability of response between individual microphones. MEMS microphone specifications primarily limit sensors meeting IEC 61672 requirements [2]. Although MEMS microphones can now have suitably flat frequency responses, they still have higher noise floors, with even better devices "only" claiming 29 dB(A) [3]. Some of the inferior specifications are acceptable for some monitoring applications. Responses can be compensated for using more frequent and advanced calibration but this increases operational costs. In addition, a major authority currently requires access to the preamplifier input

in order to give IEC 61272 [4] type approval. As a MEMS microphone and preamplifier are integrated, this is currently not possible.
There are 2 sound sensor development approaches:

1. Take a sound sensor and add remote communication/management functionality
2. Add sound sensor technology and functions to ensure long-term remote operation to a communications device

The first approach is traditionally used [5]. The second approach is becoming interesting with the spread of smart phones.
Processing software enables sound sensors that can provide results at significantly lower cost than previous generations of sound sensors on various platforms including smart phones. A complete smart phone is not needed, only the central board comprising data processing and communication functionality, building a sound sensor around it.
Smart phones are designed and built to communicate, a task which has often been the main issue with noise monitoring systems. So the focus can be on developing sound detection/processing and long-term remote operation functions.
Smart phones operate 24/7 and require little maintenance for extended periods. However, smart phones are not geared towards remote long-term operation and maintenance. Typically, unresponsive applications or the operating system are simply closed - restart functions are needed for continuous use. Watchdog functionality must counter system instability (as for traditional professional sound sensors). Remote connection and remote operation functionality needs to be added. Like sound level meters, smart phones are optimised to include direct human interaction during maintenance and upgrading. Therefore, to reduce maintenance costs, additional functionality must be added. Android-based smart phones are best suited to having these functionalities added and may perhaps be the best platform for such specialist applications.
For widespread geographical use, ruggedized smart phones must be used. These use industrial grade components to operate correctly in extended environmental conditions, in particular, temperatures above 50°C caused by direct sunlight.
Smart phones have similar power consumption to other processors and communications hardware such as routers. The more software processes data, the more time spent on-line and the weaker the communications signal, the more power drawn. In practice, for modern sound sensors sensors, the difference in power consumption between the 2 approaches to developing sensors is minimal.
Whatever the microphone, smart phones have some signal processing issues to resolve. Smart phone designers typically aim for high-fidelity audio while reducing the signal bandwidth and bitrate rather than providing a perfectly flat frequency response. Initial testing indicates that generic smartphone SLM apps installed on any device result in a much wider spread of data than IEC 61672 [2].
This, together with variability in the individual MEMS microphones typically used, means that measurement uncertainty appears to be much higher than IEC 61672 [4] instrumentation. Nevertheless, a calibrated, quality smart phone with an app tailored to that specific hardware can be useful.
With these similarities, these 2 basic sensor design approaches are similar. The key issues are the design of remote operation, long-term stability, communication strategy and accuracy. Thus, the important differentiators are the design factors "cost", flexibility, reliability and accuracy. These govern the choice of sensor network. In order to differentiate between various sound sensors and thus help users select a suitable network, this paper use 4 sound sensor categories:
1 Robust NMT (Noise Monitoring Terminal) with data reduction: based on platforms dedicated to measuring sound, type approved as sound level meters, with functionality to reduce the amount of data transfer for archiving, processing and reporting. These are designed for outdoor monitoring and engineered for low maintenance
2 Robust NMT without data reduction: as above without the functionality to reduce data for transfer
3 High-maintenance NMTs: devices built around sound level meters with no functionality for remote, automated operation and servicing to ensure long-term use without human interaction
4 Smart Devices: based on smart phones with a sound measurement application. These are not type-approved according to IEC 61672 and are less accurate for the reasons described above

3. Geo-monitoring

Geo-monitoring is enabled by lower cost sensors and mobile internet availability, and inspired by new concepts such as Google Street View, where mobile units record the situation at a point in time, and mass participation services, like Trip Advisor, where the public provides input for widespread use. It can be based on spot checks using smart phones,

Table I. Cost Analysis of different solutions showing how design issues and reliability can affect (typical) cost

Relative Cost Factor	**Robust NMT w Reduction**	**Robust NMT w/o Reduction**	**High-maint. NMT**	**Smart Device**
Deployment Costs	**15**	**15**	**13**	**8**
Unit cost	10	10	8	4
Initial calibration	2	2	2	2
Deployment	3	3	3	2
Operating Costs	**9,5**	**11,5**	**14,5**	**14,25**
Annual Preventative Maintenance	3	3	3	3
Annual Calibration	3	3	3	3
Unscheduled maintenance (reliability)	1	1	3	3
Communications	1	3	3	3
Power	0,5	0,5	0,5	0,25
Replacement cost p.a.	1	1	2	2
3 year operation	**43,5**	**49,5**	**56,5**	**50,75**
5 year operation	**62,5**	**72,5**	**85,5**	**79,25**

uploading levels and sound recordings, or on mobile sound sensors that correlate measured noise levels with GPS and time data. Both are manual activities and offer additional annotation of the sound and its causes. Although labour intensive for the public, these are, for the city authority, resource free, reducing the operating cost of networks.

However, various issues are yet to be resolved, the key one related to interpretation and usage of results. As most legislation with limits and action plans is related to specific source types, levels at reference locations and, typically, representative levels, geo-monitoring faces concerns about using these levels regarding pollution of measured levels by users and other noise sources, temporal sampling affecting representativity, and correlation of measured levels to reference conditions.

4. The Big Cost Question

A key factor is the cost of the sensor. Many consider this to be the purchase cost of the sensor. However, Brüel & Kjær operates with a comprehensive model based on deployment and operating costs [6]. Experienced people understand that operating costs are significant and, for long term monitoring, they dominate the cost, no matter which sensors are used. Table I analyses the costs of different solutions showing the impact of key design issues. Note that this only covers the sound sensor. IT infrastructure, system and software deployment and operating costs (the manpower requirements to manage the system and, importantly, mine the collected data into useful results for stakeholders) are excluded but can be significant. Intelligent data reduction is critical to reduce those workload and costs. Table I is based on a CAPEX model where systems are purchased. Leasing models [6] affect the cost analysis.

Deployment costs cover the set up of a sensor and are very much dependent on the hardware purchase and installation and configuration of hardware, power, communications networks, software and IT infrastructure. The necessary initial calibration of the sound sensor is also included.

Operating costs cover maintenance of hardware, software and IT infrastructure, power and communications, and operator costs. Preventative maintenance visits include acoustical recalibration and are typically annual. Experience shows that sensor reliability and remote servicing significantly affect costs by reducing the number of visits required to keep the unit operational and ensure up-time. Reliability also decreases component replacement. In Table I, this is done on an annual basis over the lifetime of the system.

This shows that reliability is key to cost and safeguards to restart hardware automatically and/or remotely, identify sensor health and warn of problems optimize operating costs and up-time. Lower reliability gives down time and few users accept sensors with high down time as missing data causes doubt and increases operating costs per unit of data.

Scalability is the network's suitability to increase spatial sampling frequency. New technology is resulting in lower cost, power-lean sensors with better communications, enabling more scalable systems. Thus, scalability is also affected by costs.

In addition to use as sound sensors, smart phones can also be used to help setup including the necessary documentation [7, 8]. Implementing supplementary system tools in smart phones enables the user to utilize the smart phone's in-built camera and GPS to correctly locate and professionally document the sound sensor location, enabling the sound sensor to be simpler and thus cheaper and more robust. Real-time setup can also be eased using QR or NFC [7, 8] software in the smart phone to identify and check the status of individual sound sensors.

To conclude, a Robust NMT, properly designed, can be a sensible long-term financial investment.

5. Flexibility

Brüel & Kjær and previous papers [9] define flexibility to cover data acquisition and processing. The more processing that is done in the sensor, the more costly and power hungry the unit, and the less data that needs to be communicated and centrally stored. With faster and cheaper data transfer, less sensor processing is needed, affecting system design. If only simple data without real-time access is needed, this reduces power consumption. Today's high-end NMTs use similar or less power than the connected routers. Developments in solar panels and batteries also contribute to efficient design. With efficient communications available, sensor cost and power usage can be optimized by utilizing central server processing combined with intelligent data reduction in the sensor.

6. Accuracy

A key issue is accuracy – how close the results are to the "truth" – in other words, certainty – and the documentation of achieved uncertainty. Most measurement instrumentation requires independent verification, accredited calibration and, for monitoring, regular, automated system checks. This is important. In environmental noise monitoring, most applications need indications of measurement uncertainty, whether formally, as in the ISO 20906 airport noise monitoring standard [10], or through public demand to believe results. The closer the levels are to policing compliance with legal limits, the more important it is to reduce uncertainty and provide confidence in results.

Thus, the big question is "Is calibration required?" Why? Is it mandated in legislation? If it is not – why not? What can you do with data where you have no idea of the associated uncertainty? Its validity can be drawn into doubt by any party. Perhaps the only application where uncalibrated data can be used is where the mere presence of monitoring is the main driver. Here, indicating an interest in noise levels may be enough and users may be willing to accept levels where, in principle, the uncertainty is 10 dB. However, this is an exception, it is much less likely that limited funds will be spent on gathering data whose validity can be questioned.

However, "calibration" needs definition as, even in electro-acoustic circles, the term is used loosely. Calibration terminology is very clearly defined in ISO 20906 Amd 1. We need to know what the sound sensor product can do – this requires independent testing (type approval to the IEC 61672-1 sound instrumentation standard [4]). Instrumentation must be regularly accredited as calibrated through bi-annual testing and verification. On-site the sensitivity must be verified under suitable conditions using a calibrated acoustic calibrator. The system must provide indications of changes in sensitivity.

ISO 20906 requires Class 1 IEC 61672 and states that, for determining specific noise levels of aircraft flights during events, the combined standard uncertainty of the measurement can be set to 0,74 dB(A), giving 95% confidence for a 3 dB range of results. Being dominated by the measurement instrumentation, if this is not type approved, accredited as calibrated and with verified sensitivity using a calibrated acoustic calibrator, then this value increases. So, for a wide range of applications from limit compliance to noise contour map verification this instrumentation is suitable and non-compliant systems are of doubtful value.

In addition, an important issue is microphone location which has big impact on measured levels and their resulting use. This requires cognizant installation.

Note: General electromagnetic compatibility (EMC) requirements for instrumentation are far stricter in IEC 61672 than in those for general instrumentation. This means that instrumentation that is type approved to IEC 616762 is less susceptible to electromagnetic interference (EMI), affecting results even at moderate levels and resulting in greater uncertainty.

All software on the sensor affects measurement accuracy. All sound sensors are built on a platform of different software, each of which are, in today's world, being regularly updated to combat vira and bugs. Software updates need to be evaluated for impact on results and may demand sensor "recalibration". This further increases the importance of assessing operating costs when setting up a "smart" network.

7. Strengths and weaknesses

A "smart" network provides intelligence to aid the user achieve the goals they have with noise management, for example, in cities. Typically, these goals are two-fold.

- The major one, with the most focus and funding, is the policing of noise limit compliance, typically with legal, operational or financial impact in the event of limit exceedence.
- The second one is the management and potential improvement of the noise environment and includes noise maps, action plans, current situation reporting trend analysis and public awareness, among other tasks.

For both tasks, the question is how should or can the general public be involved in collecting data and information to aid management.

For any work required for legal purposes, such as policing of noise limit compliance, you need a system based on type-approved, calibrated sensors (NMTs). This requires professional staffing and, thus, public involvement on collecting data should be limited to collecting ancillary data, something which can be very useful, as indicated by the range of interactive complaint management systems to help identify sources of breaches or concern. Utilising less accurate systems can easily, and has for several operators, create more problems for stakeholders when levels differ from legal systems with documented accuracy.

For example, the Sensornet system in Amsterdam was set up by local residents because they didn't trust the noise levels reported from the official noise monitoring system at Schiphol Airport. Sensornet was built around low-cost sound level meters installed wherever anyone wanted without regard to location. The different results collected further reinforced the public's view that the airport's system was incorrect. In order to address this, Schiphol Airport funded an independent audit of both systems. This resulted in a declaration that Schiphol Airport's official noise monitoring system was declared accurate [11], reinstating the community's trust in the airport and the cessation of their own noise monitoring. A positive result for all but one which involved significant additional investment from the airport and the community in addition to operating each of the monitoring systems.

For the management and potential improvement of the noise environment accurate, highly reliable sensors (such as Robust NMTs) are beneficial for getting good data at low operational cost. They are key where reliable data is important. However, for some applications, accuracy can be relaxed. The key area here is public awareness where the actual presence of noise monitoring is more important than results. Here, smart sensors can be integrated in systems as public indicators and to engage the public in building awareness. It may be advantageous to be able to combine different types of sensors with different accuracies in one system. Here, simpler, less costly sound sensors, operated by the general public for shorter periods may enable more data to be collected, together with additional information to aid management. Again, this should be evaluated against the complexity of explaining results with differing accuracy.

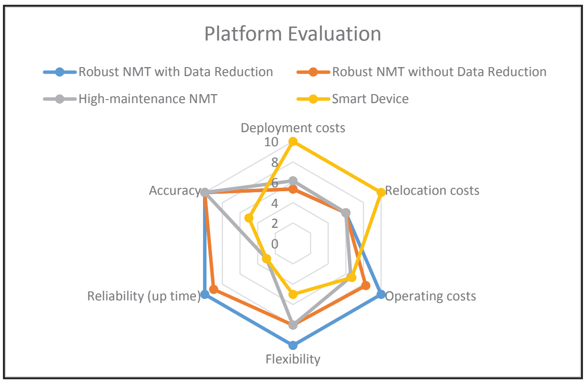

Figure 2. Evaluation of different sound sensors.

An evaluation of sensor types is shown in Figure 2. Different applications place different importance on the various aspects, weighting each parameter differently. Multi-year, permanent sensors for compliance monitoring are assessed differently than short-term public awareness driven indicators.
Lower cost sound sensors, despite lower accuracy and robustness, can provide additional input, even when operated by the public. This lower cost can make it easier for the public to independently check official levels. However, use together with official data may incur significant additional work.

8. Recommendations and conclusions

In the author's opinion, the selection of network and sensor depends on an analysis of fit with the following aspects: deployment costs, operating costs, flexibility, reliability (up time) and accuracy. The more time a noise monitoring network is expected to operate, the more important operating costs become in relation to deployment costs. Several aspects of deployment costs can be avoided when units are relocated, changing the result of the overall assessment.
For long-term monitoring, operating costs are now the key factor as unit costs are dropping. Accuracy is required to ensure that levels can be understood and the investment defended. Thus, in the vast majority of cases, a robust, type-approved NMT with data reduction is preferable. However, for applications where the actual presence of noise monitoring is more important than results, and where the duration of the monitoring is relatively short, smart devices have their validity and are useful supplements to newer, more traditional NMTs, correctly designed with operating cost and accuracy in mind.
So, choose the right network for the right purpose. If measurements are open to scrutiny then they need to be accurate and defendable and they need to be optimized regarding operating cost – here, Robust NMTs are recommended. Any work for legal purposes requires a NMT-based system. Smart sensors may be useful as public indicators and to engage the public in building awareness, including giving the ability for the public to investigate noise levels themselves, but may create more work for the authority, noise "polluter" and the community explaining the difference in accuracy of levels from more precise NMTs.
So, carefully compare budgets, requirements and applications before deciding on a suitable smart network, potentially with a mix of sensor types and data gathering techniques.
Recommendations for further research include:

- further testing of smart phone sound sensors regarding measurement uncertainty in practical scenaria, e.g. as defined by IEC 61672, aiming to provide statistically confident results, determine causes of uncertainty and recommend improvements
- investigation into how to address the key geo-monitoring issue of the interpretation and usage of results, considering aspects such as relation to legislation, specific source levels and residual sound, representative levels including temporal sampling, and how to correlate results to reference locations
- How to practically re-verify sound sensors in a world driven by software and online, remote systems

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