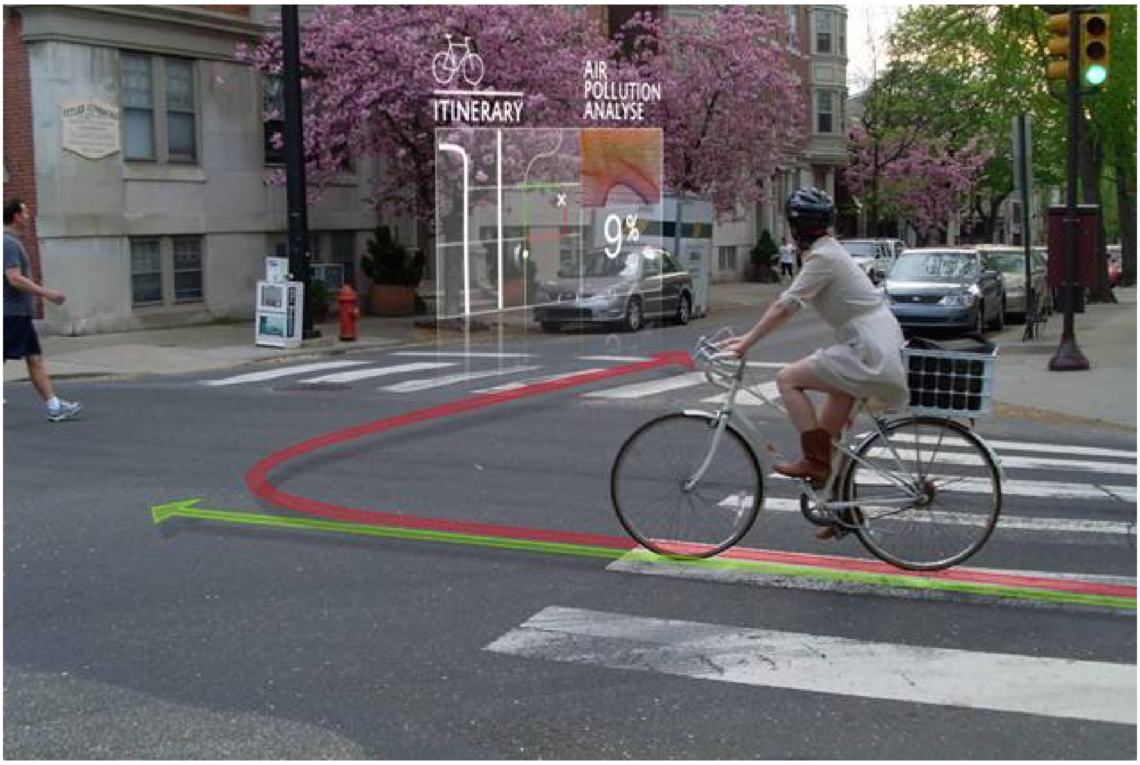
Real-world application of new sensor technologies for air quality monitoring



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Front page picture:
Picture recreating citizens' participation in air quality monitoring by using low-cost sensors during their daily life, such as when commuting by bike. The picture was created by ESN for the EU FP7 project CITI-SENSE.

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1. Introduction: Air quality monitoring with sensor technologies

In Europe, the majority of the population lives in areas where air quality levels frequently exceed WHO's ambient air quality guidelines (EEA, 2013). Current air pollution networks consist on few stations instrumented with costly air quality monitors, which provide accurate data but only in few static locations, and which are further complemented with dispersion models. As a result, data at citizen level are currently scarcer than at station level. The extensive cost of acquiring, operating and maintaining these stations severely limits the number of installations per city or network, and results in a limited spatial resolution of the pollution maps that are available for the citizens. This is especially a limitation when the air quality data is aimed at assessing human exposure to atmospheric pollutants. Moreover, the cost of the stations poses a special threat for developing countries or small cities with low economy.

In this scenario, the appearance of low-cost, easy-to-use, portable air pollution monitors (sensor platforms) allowing high spatial resolution data in real-time provide new opportunities to enhance air quality monitoring and open new possibilities and applications. Sensor devices are currently available to monitor a range of air pollutants and new devices are continually being introduced (Aleixandre & Gerboles, 2012; White et al., 2012; Snyder et al., 2013). Small commercial sensors represent a big opportunity to create sensor networks that monitor gaseous pollutants across large areas without the necessity of interpolation, which is generally inherent to conventional air quality monitoring stations. However, challenges still remain regarding the use of sensors and sensor data, mainly data quality and comparability and derivation of meaningful information from datasets (Snyder et al., 2013). Despite the fact that the performance of sensor platforms has not yet been fully tested under real-world conditions, citizen communities concerned about local air quality have started using these platforms to collect and share data, one of the most recent examples being the Air Quality Egg (http://airqualityegg.com). This situation highlights the need for a review of sensor performance and for a guide on the use of low-cost sensors that may help citizen communities to correctly evaluate sensor data.

Unfortunately, for most purposes, current low-cost sensors do not achieve the level of rigour needed (with regard to data quality, reliability and comparability). However, it must be stated that the technology is advancing rapidly and, even though some currently available sensors are not advanced enough for the most frequent applications (e.g., air quality monitoring), the experts insist that it is only a matter of time (US-EPA, 2013).

There is a clear need for a categorization system that sets reasonable expectations for the application of sensor technologies (whether they are appropriate for e.g., classroom activities, for special purpose monitoring, or for accurate measurement of ambient concentrations). Many sensors that can be commercially acquired have not been evaluated with enough detail to determine their accuracy and the factors it depends on (US-EPA, 2013), especially the "do-it-yourself" (DIY) sensors.

It is already possible to envisage that this new technology will bring new applications and enhance current applications in the field of air quality monitoring. Four main air quality monitoring strategies are proposed for sensor technologies:

1. Supplementing routine ambient air monitoring networks
2. Monitoring at the source
3. Monitoring personal exposure
4. Participatory sensing

1.1. Supplementing routine ambient air quality monitoring networks

This is the clearest application of the new sensor platforms. Supplementing routine networks with sensor platforms would be possible not only due to their lower cost, but also to the fact that sensors are smaller and can be mounted on e.g., street lamps, traffic signs, etc., and to the fact that they are frequently battery-operated. The combination of these factors would allow for a much wider spatial coverage than provided by current air quality monitoring stations. Of course, sensor networks would need to operate in parallel with conventional stations, and the data provided by the sensors would need to be compared and corrected with regard to conventional reference monitors from the stations.

A currently possible use of the sensor technologies for regulated pollutants within the context of the air quality directives (EC, 2004 and EC, 2008) is to use sensors as indicative measurements or in support of "objective estimation" for air quality assessment, as long as they comply with the quality objectives set for these kind of assessment methods in the directives. The assessment and monitoring requirements (with reference methods or equivalents) defined in the directives depend in principle on whether exceedance of the assessment thresholds occurs anywhere within an assessment zone. Consequently, the assessment of pollutant levels should cover the entire zone and not only the spots where fixed stations exist. A way to enlarge the spatial coverage of the assessment is to conduct indicative measurements, which may be less accurate. Micro-sensors may allow to assess the spatial and temporal distribution of pollutant concentrations in a variety of environments where fixed measurement data is not available, in order to identify areas where elevated pollutant concentrations may occur.

Some of the projects currently testing sensor technologies employ platforms located at fixed positions in the city (Mead et al., 2013). However most of the projects make use of the possibility that sensors may be mounted on mobile platforms as bicycles, cars, public transport, etc. or carried by volunteers (see section 4 for examples). The fact that the sensors usually include a GPS receiver to track the sensors facilitates the generation of air quality maps at street level. Mobile platforms cannot trace the temporal variability in the same way as fixed stations, but have a more comprehensive spatial coverage. However with mobile networks it is possible to generate maps of air pollution aggregated over time (for instance, all the mobile platforms which have been traversing one specific street during the last 24 hours), or to compare pollution at different streets or parts of the city at a given moment in time. In this way, both temporal and spatial pollutant variations may be explored (Milton & Steed, 2007). Other examples are better estimations of air pollutant concentrations at interest points such as schools, hospitals or a particular road intersection (when assessing the effectiveness of mitigation strategies, for example).These kinds of assessments might allow for the development of new types of studies of urban pollutants that assess personal exposure while moving through a city, small-scale variations due to street canyon effects and sources and pollutant dispersion at much more detailed scale

(Milton & Steed, 2007). Studies have shown that, for some pollutants associated with traffic such as NO_2 and ultrafine particles, variation within cities may exceed variations between cities (Briggs et al., 1997; Zhu et al., 2002). In general, it is important that sensor data are merged with existing data from models and conventional air quality monitoring networks to provide more accurate air pollution maps that are able to capture air pollutant variations at street and city level.

The main limitation of this monitoring strategy is linked to the quality and treatment of the GPS signal. The quality of the GPS signal can be lower in narrow streets with high buildings than in a residential area with two-story housing and tree-lined streets, as described by classic studies (Melgrad et al., 1994). Therefore, it should be considered that the GPS signal could introduce a certain degree of uncertainty, which should be accounted for.

1.2. Monitoring at the source or within industrial areas

Another potential use of low-cost sensors is monitoring at the source, given that concentrations are much higher and thus sensor responses improve. For instance, sensors can help industries monitor emissions, and also enhance worker safety. New sensing technologies can be used to build dense surveillance networks for industries, both at the sources level, within industrial halls, as well as outdoors in the vicinity of the industrial plants. Although the sensitivity and accuracy is still not at the level of the required for regulatory emissions or ambient monitoring, the data can supplement the existing networks and provide ubiquitous monitoring to better capture, e.g., industrial incidents as chemical releases, fugitive emissions, worker exposure, etc. (Snyder et al., 2013) To our knowledge sensor platforms are still not employed for this purpose, but they are under consideration for refineries (Fujita & Campbell, 2013) and also for natural gas pipeline monitoring (Wan et al., 2012).

The EU Joint Research Centre (JRC) has employed sensors mounted on an unmanned aerial vehicle (oktokopter) to monitor emissions from ships. The system successfully measured the exhaust plume concentration at the stack (Gerboles, 2012a).

1.3. Monitoring personal exposure

Personal exposure to air pollution links air quality with health effects. The protection of human health is one of the main reasons why air quality monitoring is regulated by European legislation (EU 2004 , EU 2008). However, estimating personal exposures and attributing exposure to sources presents significant challenges because of the spatial and temporal variability and the difficulty in estimating time-activity patterns, i.e., the time individuals spend in different environments (office, commuting, working out outdoors, etc.) (Jerret et al., 2005; Snyder et al., 2013).

Using only the sensors embedded in smartphones, researchers have tried to solve the gap in data availability at citizen level by relying on individual location tracers to estimate personal exposure to pollutants based on information collected by the monitoring stations (Mun et al., 2009). One of the advantages of this type of indirect sensing is that it reduces costs, and that it is not necessary for the user to carry additional sensors to the ones already integrated nowadays in cell phones (Demirbas et al., 2009). Indirect sensing uses the location data from the phone and merges it with exposure models making possible to estimate exposures at multiple locations per person rather than only at the residence location (Demirbas et al., 2009).

Another way to provide citizens with an estimation of their exposure is based on body-worn sensor nodes carried by users during their everyday activities (AIR, 2006; Nikzad et al., 2011, 2012; Zappi et al., 2012). Sensor nodes provide information about air pollution in the surroundings of the user, and it is also possible to evaluate personal exposure along a route. Additionally, data can be combined in the backend server to create a detailed understanding of the pollutant distributions (Zappi et al., 2012). Some projects have developed their own sensors (AIR, 2006; Common Sense Project, 2009; Nikzad et al., 2012; Dutta et al., 2009) for personalized air quality monitoring.

Recently, integrative USB pluggable sensors are built for mobile phones to obtain air quality information (Hasenfratz et al., 2012). Other technology employed is the communication sensor-phone using Bluetooth (Honicky et al., 2008; Dutta et al., 2009; Fahrni et al., 2011; Jiang et al., 2011). These authors report that the most accurate way of tracking an individual's exposure to environmental factors is to directly and continuously monitor the individual's personal space. However, this may of course conflict with the individual's privacy.

Sensors integrated into mobile phones have the advantage of mobility, co-location with people, pre-built network and power infrastructure, and potentially, ubiquity. These characteristics, however, also present significant challenges. Mobility means non-uniform sampling in space, and also constrains the size and weight of the sensors (Honicky et al., 2008). These authors conclude that mobile sensing has the potential to provide the platform for building the largest scientific instrument ever made, to construct an accurate image of the impact that humans have on their environment at a societal scale while also being able to examine an individual's exposure at a specific place and time.

For sectors of the population with special sensitivity to air pollution (children, asthmatics, elderly, etc.) or individuals particularly concerned with health issues, carrying sensors may be considered acceptable. However, for the major part of the population, carrying sensors or employing methods which may be considered invasive with regard to privacy (e.g., continuous location tracking) could be less attractive. Therefore, the coexistence of different methods that not only rely on personal monitors to provide information to the citizens (e.g., conventional networks) still remains highly relevant.

Despite the challenges of personal monitoring, improving estimates of personal exposure may prove an asset for epidemiological studies, which often rely on limited ambient air monitoring data as input (Snyder et al., 2013). Additionally, air pollution sensors can be linked with physiological sensors, thus providing a better estimate of human exposure (Brook et al., 2011; Bigazzi et al., 2013). Examples of these are low-cost, portable sensors for health monitoring which have been under development in the last years, such as iCalm (a skin conductance sensor to monitor heart rate, Eydgahi, 2008) or Portland ACE that combines trajectory, local traffic, air quality, meteorology and physiological data (Bigazzi et al., 2013).

1.4. Participatory sensing

Participatory air quality monitoring is taking place in several cities around the word (see section 4 below). Other terms such as crowdsourcing, urban participatory monitoring, citizen science, or citizen observatory, also refer to the new concept based on citizens generating data (in this case, air quality data).

Participatory sensing refers to the vision of distributed data collection and analysis at the personal, urban, and global scale, in which participants make key decisions about what, when and where to sense. It emphasizes the involvement of individuals and community groups (Burke et al., 2006). A revolutionary aspect of this new monitoring strategy is the change in who is measuring air pollution and the purpose for which it is being measured. Until now, air pollution measurement has primarily been in the hands of trained scientists, experts and technicians employing reference instruments. New low-cost easy-to-use sensors are making it possible for any individual to measure air pollution and share the data (US-EPA, 2013). This, however, presents strong limitations regarding data quality and comparability as will be discussed below.

In some of the cases, participatory sensing has not been promoted under specific research projects or by governmental organizations, but instead has surged from a sector of the population concerned by air quality. Currently, there is a growing number of “Do It Yourself” (DIY) projects which allow citizens to easily build air quality sensors. One of the most well-known is the Air Quality Egg[1], but there are also other DIY projects related to air quality monitoring in urban areas (e.g., the AirCasting project[2]). Indeed, the attraction toward low-cost sensors is sufficiently great that, even before sensor performance has been characterized, widespread data collection and data sharing using new sensors is already occurring (Snyder et al., 2013). It must be stressed that this is, by far, the largest risk of participatory sensing given that data are in no way quality-checked before they are shared. Thus, these projects raise the question about the importance of quality data and assessing uncertainty levels. Poor quality data or unknown uncertainty levels lead to data misinterpretation and erroneous conclusions. Administrations have already expressed their concerns as to how to respond to citizens reporting data from sensors while information on data quality is unavailable (US-EPA, 2013). Guidance documents and advice on sensor use and data interpretation are essential to help communities and individuals to effectively take advantage of this new technology (Snyder et al., 2013).

There is also a growing interest in the scientific community about the use of citizen collected data for scientific purposes. Examples are the recently funded projects by the European Commission under the call FP7-ENV.2012.6.5-1 "Developing community-based environmental monitoring and information systems using innovative and novel earth observation applications". A description of the projects can be found in section 4 below. However, once again, one of the main challenges is interpreting data from sensors, especially when sensors are used by non-expert communities (US-EPA, 2013).

Given the broad availability of personal GPS-equipped smartphones and the increasing number of air quality low-cost sensors available on the market, it is envisaged that large-scale sensor networks of mobile devices for participatory air pollution monitoring will be increasingly more present in the cities in the future. The availability of mobile apps and sensors for pollution monitoring is expected to increase the awareness and interest of citizens and community groups on environmental issues. However, turning such awareness into practical community action and societal change requires more than just collecting and presenting data (Aoki, 2009).

[1] www.airqualityegg.com

[2] http://aircasting.org

In the last few years there has been an increasing interest in using internet tools to create, assemble and disseminate geographic information provided voluntarily by individuals (VGI). Sites such as Wikimapia[3] and OpenStreetMap[4] are empowering citizens to create a global network of geographic information, while Google Earth and other virtual globes are encouraging volunteers to develop interesting applications using their own data (Goodchild, 2007). Also notable is the creation of web spaces to facilitate discussion, sharing, interactions and understanding among all the stakeholders involved in air quality issues, from authorities to the public including scientists. One example is CitizenAir.net. The aim of this website is to provide a space for people of various backgrounds and interests to discuss and exchange ideas related to air sensors, instruments, and applications.

Another challenge in participatory sensing, aside from data quality (which is an issue in all of the monitoring strategies with sensor technologies), is user privacy (see also 1.3). Capturing the user location is critical for these projects, but it is potentially invasive. Shared or stolen data on individuals' routes and routines could compromise their safety and privacy. Techniques as selective hiding, which attempts to return the capability for plausible deniability, as well as selective deletion and retention rule sets can be applied to ensure individual's privacy (Huang et al., 2010; Delphine et al., 2011).

Finally, mobile phones and low-cost sensors have also been employed to monitor indoor air quality (Kim & Paulos, 2009; Jiang et al., 2011). In the inAir project (Kim & Paulos, 2009) a particulate matter (PM) sensor is combined with a tool for sharing measurements and visualizations of indoor air quality within a social network. The idea is that sharing the indoor air quality information across a social network will improve awareness of indoor air quality and persuade people to change their indoor behaviours and activities and strive for better health and domestic well-being. Other applications of crowdsourcing data are also noise pollution monitoring (Maisonneuve et al., 2009), visibility monitoring (Miluzzo et al., 2008), traffic conditions surveillance (Mohan et al., 2008), temperature mapping (Overeem et al., 2013) or rainfall mapping (Overeem et al., 2012).

In addition to these four strategies for air quality monitoring with sensor technologies, it should be stated that sensors are also being developed for other urban uses which are indirectly linked to air quality. In this way, sensors are used for urban traffic management, mainly for traffic flow control and for parking-space management. Examples of this kind of work are carried out by private companies, non-profit organisations and research centres such as Cartif (www.cartif.com) or Urbiotica (http://www.urbiotica.com).

[3] http://wikimapia.org

[4] http://www.openstreetmap.org

2. Commercially available sensors for gas measurements

As stated above, the number and type of commercially available sensors is increasing at a rapid pace, despite the absence of scientific data to validate parameters such as their accuracy or precision. The principles of operation are numerous, and the most frequent ones are described in this section (not exhaustively). This section focuses on commercial sensors for ambient gas measurements, given that sensors for particulate pollutants are currently under development. The most common technologies used for commercially available gas sensors are: resistive sensors, electrochemical sensors, dispersive infrared radiation absorption (NDIR) and photo ionization detector sensors (summarized from Aleixandre & Gerboles, 2012).

2.1. Resistive sensors

Resistive sensors are based in a transducer sensor mechanism, which consists in a metal oxide that changes its resistance or conductivity when exposed to different ambient gases. The most common metal oxide used is tin oxide due to its reactivity (to a large number of gases) and its large changes in resistance. The conductivity is dominated by the boundary of the grains formed by the tin oxide. The oxidizing gases react with the tin oxide trapping electrons of the surface. This accumulation of electrons creates a negative charge space that acts as a barrier for the electrons and thus increases conductivity.

Resistive sensors respond to a wide range of gaseous concentrations, from a few ppb (Kida et al., 2009) to several thousand of ppm (Katulski et al., 2009). The NO_2 response of tungstic oxide (WO3) sensors was shown to depend on the WO3 lamellae morphology (Kida et al., 2009). The response time is usually around a few minutes (Katulski et al., 2009). This type of sensor presents poor stability, so that the response changes over time and the sensors need to be recalibrated. Manufactures do no provide much information about the drift, signal-to-noise ratio or stability. These sensors present higher cross sensitivity than the other types of sensors. They react to nearly any volatile compound (reducing or oxidizing), toxic gases like NO_x, or volatile organic compounds.

The temperature and humidity interfere in the responses and have to be controlled or measured to provide a model of their influence. Given that the reactions are favoured at high temperature, a heater is usually incorporated into the sensor. These sensors are usually around a dozen millimeters in size and a few grams in weight.

2.2. Electrochemical sensors

These sensors are based on electrochemical reactions that take place within the sensor between the gas to be monitored and a certain electrolyte. The current produced by these reactions is measured and related to the gas concentration (Jacquinot et al., 1999) by means of the Nerst Law for electrochemical reactions (Kumar and Fray, 1988). The electrolyte used can be liquid, gaseous, gel or solid. The composition determines the selectivity and sensitivity to target gases such as NH_3 (Nagai et al., 2010, 2012), O_3 (Knake and Hauser, 2002), NO_2 (Ono et al., 2001), NO (Miura et al., 1999), NO_x (Miura et al., 1998).

Some of these sensors are developed to be used in emission measurements, hence designed for higher concentrations than those found in the atmosphere (Mothé et al., 2010; Saponara et al., 2011). Examples of concentrations ranges are 6-45 ppmV for ethylene, 109-1231 ppmV for CO, 75-868 ppmV for nitrogen oxides and 3-354 ppmV for SO_2 (Mothé et al., 2010). In addition, new sensors can also achieve low detection limits (Katulski et al., 2009). The usual detection limits for O_3 and NO_2 are 10-20 ppm (reaching down to 2 ppm in some cases), and about 100 ppm for NH_3.

The error tends to be similar in all sensors and they show a deviation from linearity of about 2-5 % (reaching 10% sometimes). The cross sensitivity to other gases can be fine-tuned by the selection of different electrode materials, but cannot be eliminated completely.

The temperature interferes in the response of these sensors, but it can be modelled. The wind speed can also influence the response on ambient applications, due to its influence in the chemical equilibrium on the surface (Gerboles and Buzica, 2009). These sensors present long term stability (from 2% to 15% per year). To avoid stability problems, the sensors need a constant exposure to oxygen, and also ambient humidity in some cases.

Electrochemical sensors are usually around 20 mm in size and have very low power consumption, given that signal generated is a low level electrical current and the main power requirement is its amplification.

2.3. Dispersive infrared radiation absorption sensors

The infrared radiation absorption sensors consist of optical transducing mechanisms, based on the Infrared Gas Absorption Spectra. An infrared light illuminates the gas to be measured, and the asymmetric molecules present on the gas adsorb the radiation at determined narrow bands of adsorption characteristic of each molecule. The intensity of this adsorption follows the Beer-Lambert equation (Pandey and Kim, 2007).

Their detection range goes from 5% volume to 3,000 ppm for hydrocarbon gases and CO_2. Their response is well characterized and follows closely the model equations. The noise is high reaching up to 500 ppm of hydrocarbons or 50 ppm of CO_2 with very fast response times, around tenths of seconds. All the hydrocarbons share a similar absorption band, originating on the carbon hydrogen bond, which makes them all cross sensitive. The CO_2, on the other hand, has a very characteristic absorption band which results in a high sensitivity of these sensors to this gas, thus being very good CO_2 sensor candidates (Kumar et al., 2000). Calibration of NDIR sensors is based on the determination of specific parameters to fit the sensor model with the reference gas.

These sensors have a size of a few millimeters and a power consumption of a few hundred mW.

2.4. Photo ionization detector sensors

In the photo ionization measurement process the molecules of the target gas are illuminated by high energy UV light. The absorption of a photon by a molecule can break this molecule and generate electrical charged ions, which are then exposed to an external electrical field and generate a current. The electrical current obtained is proportional to the gas concentration.

Photo ionization detector sensors are able to detect VOCs with ionization potentials below 10.6 eV, meaning VOCs whose molecules break with energies below 10.6eV. For the benzene, the detection limit is up to 100 ppm, and very low (reaching 3 ppb) f. The responses show a 3% deviation of the linearity on average, while above 10 ppm the linearity of the sensor decreases (in parallel with the noise signal). The sensors are fast with times of response of less than 3 seconds.

Any VOCs with ionization potentials lower than the ionizing potential of the lamp used can be measured with this principle of operation, which results in a decreased selectivity of this type of sensor. Although the sensors are relatively stable they require frequent calibration, and small temperature dependences have been reported. The manufacturers recommend recalibration once a month in clean environments with low particle count and low VOCs present. Because lamps vary from one to another, each lamp replacement requires a new calibration. Sensor responses are calibrated fitting the measurements to linear equations.

The usual size of these sensors is around 20.2 mm x 16.5 mm, with a weight of 8 g and a power consumption of 110 mW. Several companies provide this type of sensors commercially, but all of them seem to share same manufacturer.

3. Comparing sensor technologies and conventional instrumentation

3.1. Literature review

Information regarding new low-cost sensor performance is only beginning to be publicly available. Recent studies have demonstrated promising performances for some low-cost sensors monitoring O_3, NO and NO_2 (Gerboles, 2010; Mead et al., 2013). However, there are more and more sensor platforms in the market and their performance has not been characterized (Snyder et al., 2013). Due to the high sensitivity of this kind of instruments to the electronics, when operating a sensor it is not only necessary to know the sensor specifications, but also how it performs once it is integrated on an electrical board and platform. Additionally, numerous studies show that laboratory characterization is not enough and that it is absolutely essential to test sensor performance under real-world conditions (Gerboles & Buzica, 2009; Gerboles, 2010; Mead et al., 2013). Only recently the performance in real-world conditions is beginning to be assessed but the long-term reliability of low-cost sensors is still unknown. In the course of this work, comparisons between conventional and sensor technologies were only found for gaseous pollutants, thus suggesting that sensor technologies for particulate pollutants are still under development. A review of scientific studies comparing data generated by sensor platforms and by conventional instrumentation was carried out, and the findings from the main studies found are summarized below:

- Kamionka et al (2006) introduced a methodology to automatically calibrate sensor data employing neural networks. The conclusions stressed the necessity of building the calibration model with experimental measurement data and not only with artificial gas mixtures, in the laboratory.

- Lösh et al. (2008) also discussed a technique to improve the stability and reduce cross sensitivity with gas pollutants based on temperature variation and gas prediction. This study was applied to ozone sensors only.

- Gerboles & Buzica (2009) focused on the evaluation of micro-sensors to monitor ozone in ambient air. Their results show a worse performance of ozone sensors than the results presented later in 2012 (Gerboles, 2012a, see below) showing the fast evolution in the field of new sensing technologies. However, issues such as the long-term reliability of sensors still need to be further investigated.

- Aleixandre and Gerboles (2012a) performed a literature review on commercial sensors for ambient gas measurements over a hundred commercial sensors and their performance with the specifications of the AQ Directive (EU, 2008). They concluded that resistive sensors tend to have a higher sensitivity, but have serious problems with reproducibility and stability making them unreliable on most of the applications. The performance of electrochemical sensors is in general not so good regarding sensitivity, but they present better stability characteristics. Infrared gas absorption spectra sensors are less sensitive and are not available for each target gas, but if they are able to detect the target gas in the range of interest, they are a very good option due to their stability and deterministic calibration. Finally, photo ionization sensors are really sensitive, selective and reproducible, but they are only available for few gases and require a higher maintenance.

- Hasenfratz et al. (2012) assessed the calibration of dense networks of sensors with the so called “on-the-fly” calibration technique (i.e., instant calibration). These authors evaluated different algorithms for “on-the-fly” calibration on mobile networks of sensors: forward calibration that uses recent sensor readings to calculate new calibration parameters, backward calibration that re-evaluates the observation by integrating most up-to-date readings and instant calibration that constantly adjusts the calibration parameters. The results show that instant calibration can reduce the measurement error. Other calibration techniques are also discussed in the literature (Bychkovskiy et al., 2003; Maroti et al., 2004; and references there). Calibration and post processing of the data generated by the sensors is important to improve the sensor performance. During calibration, a sensor is exposed to certain gas concentrations and the sensor's calibration parameters are adjusted so that the difference between the applied gas concentration and the sensor's output is minimized. Manual sensor calibration is an elaborate and time-consuming task and other kind of approaches are required for dense networks which aim to combine static, mobile and personal sensor nodes (Hasenfratz et al., 2012).

- Gerboles (2012a) emphasized that, even though laboratory and field comparisons of sensors with reference equipment have been carried out, the results obtained so far are hardly repeatable. In order for the data to be useful from a scientific and technical point of view, it is necessary to develop methods for correcting cross-sensitivities and the effects of temperature and relative humidity. Furthermore, it is also necessary to assess and correct the baseline/span drift of sensors, which are enhanced with aging of the devices. Taking into account these limitations, the results obtained from fixed networks of sensor nodes, when compared to other sensor platform monitoring strategies, are the most encouraging so far (Gerboles, 2010).

- Gerboles et al. (2012b) studied the field performance of ozone microsensors and their calibration. They concluded that the calibration functions determined in a given location could not be directly applied to the microsensor measurements in a different location, given the detection of a bias between calibration at the first site and measurements at the second site. At low ozone concentrations, this bias was about 15 nmol/mol. However, errors of the reference measurement cannot be excluded. The bias could not be simply eliminated by a re-zero calibration of microsensors because its magnitude was concentration-dependent. By calibrating using measurements over the first six days of measurements at the second site, the microsensors were rather successful with daily bias in the range of 1 ± 2.3 nmol/mol and hourly bias in the range of 0.5 ± 4nmol/mol. The magnitude of the bias and its relationship with ozone levels varied depending on the ambient matrix.

- Williams et al. (2013) compared the data gathered by a resistive ozone sensor based on tungstic oxide (WO3) with ambient data measured by reference equipment under real-world conditions. The study demonstrated that, after the correct calibration of the sensor, both the accuracy and the stability of the instrument over periods of months were within a few parts-per-billion by volume. These authors performed a long-term validation of the O_3 sensor in different environments. The results show that the drift in the signal can be compensated. In their study, these authors highlighted the relevance of maintaining the inlet tubes or filters clean. Due to the reactivity of O_3 it is important that the inlets are made of inert materials. The accumulation of dirt on the inlet filters and pump failure can cause a significant loss of ozone presented to the device and consequently a high drift. However, this failure can be avoided with a correct maintenance of the sensor.

- Mead et al. (2013) concluded that electrochemical sensors can have a good performance and measure at parts-per billion level. The results include both high-density, static, dense networks in the wider Cambridge (UK) area, and mobile nodes held by pedestrians and cyclists. It is important to mention that the instrumentation has cross-interferences with temperature and relative humidity as well as with gas pollutants, requiring a post processing of the data before the agreement between sensors and reference equipment can be acceptable. However, once the data is processed the results for NO, NO_2 and CO are encouraging, according to these authors. They conclude that sensors employed in the project, and the low-cost/high-density measurement philosophy which underpins it, have the potential to provide a far more complete assessment of the high-granularity air quality structure generally observed in the urban environment, and could ultimately be used for quantification of human exposure as well as for monitoring and legislative purposes.

- Zaouak et al. (2013) showed the results from a new NO_2 sensor which claims to have no interferences with ozone. In this work, the results are shown for a traffic area, with 24 hour mean values for 14 months without the sensor being maintained. The discrepancies between the sensor and the reference equipment are below 10 ppb, on average.

- US EPA (2013) elaborated a roadmap for the next generation of air monitoring to summarize major findings from literature review, workshops and discussions with experts. With this roadmap EPA aims to support the successful development and use of new monitoring technologies, but also set reasonable expectations for their use, with a list of recommendations and gaps that need to be addressed. A conclusion of the report is that sensor technology is developing rapidly, and it is conceivable that in the future low-cost sensor technology will meet the current requirements of regulatory monitoring.Statistical and geostatistical methods should be applied to evaluate the data quality. One of the topics to investigate is to determine how to reduce the uncertainty when using a dense network of lower quality measurements to ascertain air pollution levels (US EPA, 2013).

3.2. Unpublished data from real-world conditions

In the course of this work, *in-house* tests were carried out with two different types of electrochemical sensors, with the aim to assess their performance under real-world conditions (sensor types undisclosed due to confidentiality issues). Two types of sensors based on different technologies and from different manufacturers were tested for a 1-month period at an urban background location in Barcelona (Spain), where gaseous pollutant data were also generated by conventional instrumentation for the local air quality monitoring network. Two identical units of each type of sensor were tested. The gaseous pollutants tested were SO_2, NO, NO_2, O_3 and CO.

Results from sensors 1 and 2 (two units of the same type of sensor) for O_3 monitoring, in comparison with a reference instrument, are shown in Figure 1. The data evidence a good agreement between the two units (Sensor 1 and Sensor 2), but a divergence in absolute concentrations from the reference monitor. Whereas both types of instruments seem to follow similar daily trends, the concentrations reported by the sensors are on average 39% lower than those reported by the reference monitor. Similar data are also shown in Figure 1 for NO_2, with a similar outcome regarding daily patterns but also with a significant underestimation of NO_2 concentrations (66%) by the sensors with respect to the reference monitor.

The same exercise was carried out with a second type of sensor, for which two units were also available. Data were collected over a 1-month period (15-minute time resolution), also at an urban background location and in ambient air. Results are presented for O_3, NO, NO_2, SO_2 and CO. As can be seen from Figure 2, the Sensors A and B were mostly unable to reproduce the daily cycles of the pollutants analysed. For most of the pollutants (NO, NO_2, CO) the sensors reproduced one of the daily peaks (the typical morning or evening rush hour traffic peaks), but not the entire daily trend. In the case of ozone, a midday maximum was detected by the sensors, although at different times of the day and not coincidental with the reference instrument.

Conversely, the mean monthly values obtained showed a relatively good agreement, although not consistently, between some of the sensors and the reference instruments (Table 1). For NO, O_3 and CO, the mean monthly concentrations reported by sensor A were within 10% of the value reported by the reference instrument, although this was not the case for SO_2 or NO. Agreement was poor between units, with the only exception of NO data.

The results from both types of sensors (1 and 2, and A and B) support the findings by Williams et al. (2013) and Mead et al. (2013), who reported on the relevance of locally calibrating the sensors and of post processing of the data before the agreement between sensors and reference equipment can be acceptable, to correct for interferences with parameters such as temperature and humidity. In the tests presented here, the sensors had not been calibrated locally even though they had been calibrated in the laboratory by the manufacturers. The data were obtained from the manufacturers' online data centres, where it is expected that they had undergone post processing.

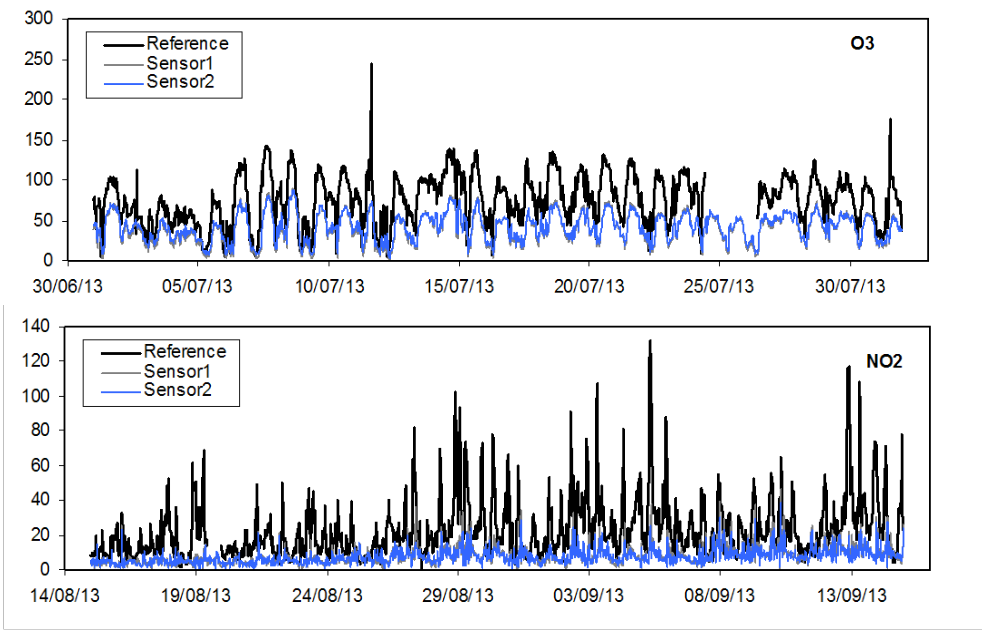

Figure 1. Comparison for O_3 and NO_2 concentrations between two units of one type of sensor and reference instrumentation, monitoring ambient air at an urban background location over a 1-month period.

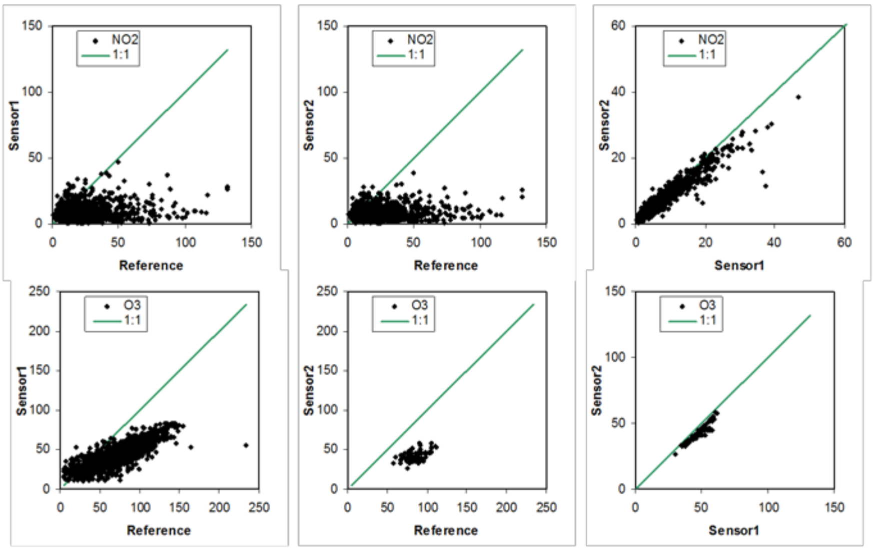

Figure 1. Continued.

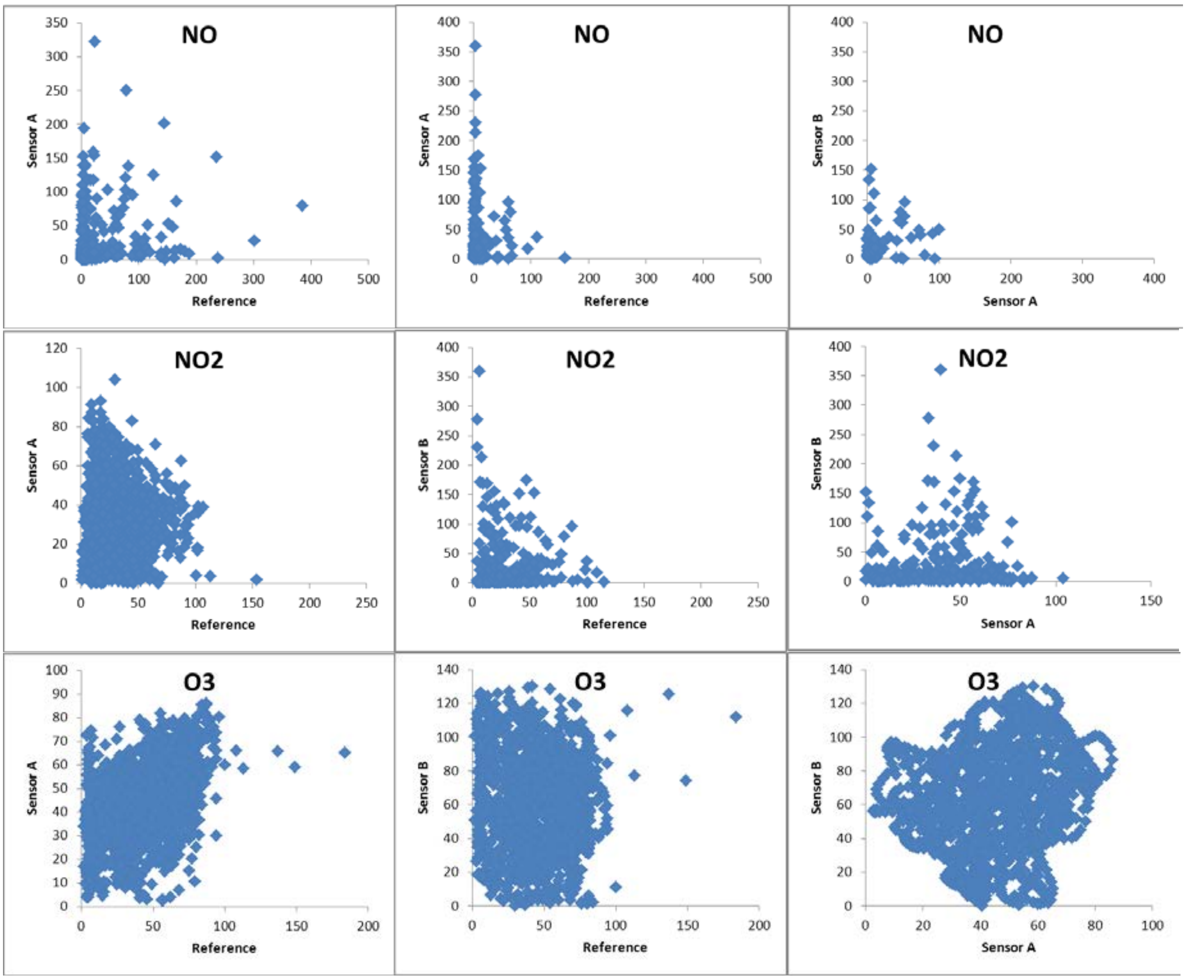

Figure 2. Comparison for O_3, NO_2, CO and NO concentrations between two units of one type of sensor and reference instrumentation, monitoring ambient air at an urban background location over a 1-month period.

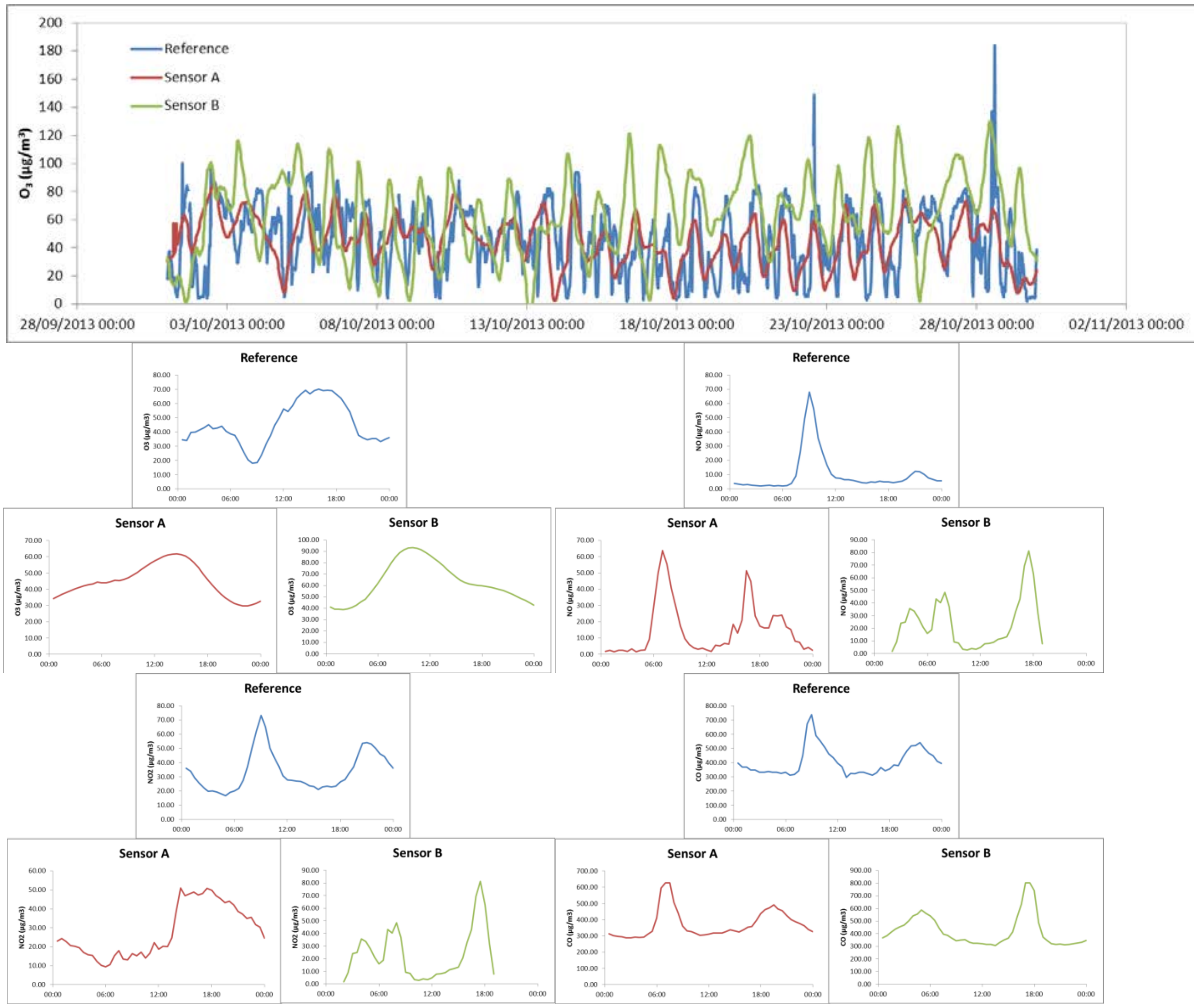

Figure 2. Continued.

Table 1. Comparison of monthly mean O_3, NO_2, CO and NO concentrations between two units of one type of sensor (A and B) and reference instrumentation, monitoring ambient air at an urban background location over a 1-month period. Low data availability is highlighted in italics. n: number of data points.

	SO_2			NO			NO_2			O_3			CO		
	Ref	**A**	**B**	**Ref**	**A**	**B**	**Ref**	**A**	**B**	**Ref**	**A**	**B**	**Ref**	**A**	**B**
Mean	2	12	41	10	21	24	34	32	24	46	45	63	404	373	423
n	1387	*114*	1324	1387	*418*	*385*	1390	1083	*385*	1389	1392	1386	1390	1392	1392
Max	15	61	161	385	322	359	200	104	359	228	86	130	2600	1853	2618

4. Review of air quality projects based on new sensing technologies

This section provides an overview and description of some of the current projects based on air quality monitoring using new sensor technologies. Note that this is not meant to be an exhaustive review and that some projects do not focus only on ambient air quality.

4.1. EuNetAir: European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability

EuNetAir is a European COST Action focused on new sensing technologies for air quality control. It consists on working groups on (i) sensor materials and nanotechnologies; (ii) sensors, devices and systems for air quality control; (iii) environmental measurements and air pollution modelling; (iv) protocols and standardization methods.

One of the main aims of the COST Action is to establish a pan-European multidisciplinary R&D platform on new sensing based on micro- and nano-sensors, as well as to disseminate R&D results towards industry community and policy makers, and to create collaborative research teams on new sensing technologies. More information about the EuNetAir Action can be found in: http://www.eunetair.it

4.2. Citizens's Observatories EU FP7 Projects

The Citizens' Observatories Projects are five FP7 current projects funded under the topic ENV.2012.6.5-1 "Developing community-based environmental monitoring and information systems using innovative and novel earth observation applications" which started in autumn 2012. They all aim to develop novel technologies and applications in the domain of Earth Observation, trying to exploit the capabilities offered by portable devices (smartphones, tablets, etc.), to enable an effective participation by citizens in environmental stewardship based on broad stakeholder and user involvement in support of both community and policy priorities.

These 'citizens' observatories' will include community-based environmental monitoring, data collection, interpretation and information delivery systems. Each project will include suitable pilot case studies to test, demonstrate and validate the concept of citizens' observatories – the infrastructure, the technology and the methodologies coming from research undertaken under these projects-, the direct transfer of environmental knowledge for policy, industries, research and societal use and the possibilities for a comprehensive implementation and application of the technology.

The expected impact of these projects is the empowerment of citizens allowing them to influence in the environmental governance processes, providing as well models for decision-makers that facilitate connections between environmental governance, global policy objectives and citizens' needs. The projects are:

- CITI-SENSE: Development of Sensor-based Citizens' Observatory Community for Improving Quality of Life in Cities
- WeSenseIt: Citizen Observatory of Water
- COBWEB: Citizen Observatory Web
- Citclops: Citizens' Observatory for Coast and Ocean Optical Monitoring
- Omniscientis: Odour Monitoring and Information System based on Citizen and Technology Innovative Sensors

4.3. CITI-SENSE: Development of Sensor-based Citizens' Observatory Community for Improving Quality of Life in Cities

CITI-SENSE aims to develop and test an environmental monitoring and information system focused on atmospheric pollution in cities and agglomerations, which will enable citizens to contribute to and participate in environmental governance by using novel technological solutions. The three pilot case studies envisaged will focus on a range of environmental issues of societal concern such as combined environmental exposure and health associated with air quality, noise and development of public spaces, and indoor air at schools. More information at the project's website: www.citisense.eu.

4.4. Citi-Sense-MOB: Mobile services for Environment and Health Citizen's Observatory

The aim of CITI-SENSE-MOB is to create and use innovative technology to continuously measure, share and communicate environmental data. By the use of mobile sensing platforms it will contribute to create a dynamic city infrastructure for real-time city management and sustainable progress.

The air quality measuring system is composed of numerous sensors mounted on buses and bikes. The continuously gathered data is then transmitted to a server which combines it with already existing data (models, monitoring stations, etc.) to give back to the user added-value personalised data (alerts, exposure, etc.) presented in a user-friendly and visually informative layout using web services and mobile phone apps. The system will be tested in the city of Oslo in 2014. More information can be found in the webpage: www.citi-sense-mob.eu.

4.5. MACPoll: Metrology for Chemical Pollutants in Air

MACPoll is a 3-year Joint Research Project launched on 1st June 2011. The overall goal is to improve the traceability and comparability of measurement results in current air monitoring techniques and to set-up the metrological bases for sensor technology used in air quality applications. More information about the project can be consulted here: www.macpoll.eu

4.6. SmartSantander: Future Internet Research and Experimentation

SmartSantander proposes a unique in the world city-scale experimental research facility in support of typical applications and services for a smart city. The project envisions the deployment of 20,000 sensors in Belgrade, Guildford, Lübeck and Santander, exploiting a large variety of technologies. The project is focused on the validation and development of IoT applications and services. The Belgrade pilot utilizes public transportation vehicles in the city of Belgrade and the city of Pancevo to monitor a set of environmental parameters (CO, CO2, NO2, temperature, humidity) over a large area as well as to provide additional information for the end-user like the location of the buses and estimated arrival times to bus stops. More information in: http://www.smartsantander.eu/

4.7. OpenSense: Open sensor networks for air quality monitoring

OpenSense is an open platform whose major scientific objective is to investigate community-based sensing using wireless and mobile sensors to monitor air pollution. In OpenSense sensing units have been deployed and mounted on mobile vehicles (buses) and stationary monitoring stations around the city of Lausanne, Switzerland. The sensor units monitor atmospheric pollutants: O_3 (e2V), CO (Alphasense), NO_2 (Alphasense), CO_2, and ultrafine particles (Matter Aerosol). The measurement platform is based on the prototype platform developed within the projects Nano-Tera[5] and X-Sense[6] and further extended for monitoring air pollution. The station supports GPRS/UMTS and WLAN for communication and data transfer, a GPS for location tracking, an accelerometer, and receives the door release signal once installed on a tram to assist recognition of halts and tram stops to minimize position uncertainty. The station is supplied with power from the tram.

The deployment consists in 10 stations on top of 10 trams in the city of Zurich and one station at the national air pollution monitoring network in Dübendorf. The data obtained is public and can be accessed online at: http://data.opensense.ethz.ch/. More information about the project can be consulted here: http://www.opensense.ethz.ch/trac/

4.8. Common Sense: participatory urban sensing using a network of handheld air quality monitors

Common Sense is developing participatory sensing systems that allow individuals to measure their personal exposure, groups to aggregate their members' exposure, and activists to mobilize grassroots community action. The project is primarily funded by Intel Labs Berkeley. This participatory sensing approach to collect air quality data makes use of consumer electronics, for instance mobile phones, to capture, process and disseminate sensor data, complementing the current architectures (e.g., classic monitoring networks or wireless sensor networks).

Some sensors are already present in the consumer devices (e.g. accelerometers, geolocation, sound recorder, etc.) but others as meteorological and air quality sensors are still not commonly included. For that reason, handheld air quality monitors have been developed within the project, which are able to work in association with the mobile devices or in a stand-alone configuration. In addition, a vehicular platform has also been developed to be mounted for instance in street sweepers (Aoki, 2009). The platforms monitor CO, O_3, NO_x, temperature and humidity. More information about the project can be found here: http://communitysensing.org/index.php

4.9. CitySense: An Open, City-Wide Wireless Sensor Network

The goal of CitySense is to deploy an outdoor, open wireless sensor network tested across the city of Cambridge, providing a blueprint for future sensor network designs and deployments. The deployment consists in 100 sensors throughout the city mounted on buildings and streetlights for air quality and weather monitoring. The parameters recorded are CO_2 (Vaisala), CO, NOx (Siemens GasFET) and PM_{10} (TSI SidePak) for air quality studies and temperature, humidity, pressure, precipitation and wind speed and direction for weather. Additionally noise pollution is recorded. The data is visualized in real-time employing the Microsoft SensorMap infrastructure: http://atom.research.microsoft.com/sensewebv3/sensormap/

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[5] http://www.nano-tera.ch/

[6] http://www.nano-tera.ch/projects/414.php

4.10. CitiSense: Adaptive Services for Community-Driven Behavioral and Environmental Monitoring to Induce Change

CitiSense is a scientific project funded by NSF to monitor pollution and environmental conditions that users are exposed to in their daily lives in San Diego County (USA) employing new sensing technologies. CitiSense aims to bridge the gap between personal sensing and regional measurement to provide micro-level detail at a regional scale. The system includes mobile phones and affordable, small sensors placed in the environment and carried by users, to collect data about pollutants (O_3 and CO). The data is then used to provide real-time feedback to users and allow them to change their behavior for increased health and life quality. The data can also be shared for further processing and modeling, helping stakeholders to improve the environmental conditions. The CitiSense project includes the design of a complete system that addresses issues of mobile power management, data security and privacy. More information about the project can be found here: https://sosa.ucsd.edu/confluence/display/CitiSensePublic/CitiSense+Overview. Zappi et al. (2012); Nikzad et al., (2012), https://sosa.ucsd.edu/confluence/download/attachments/10355005/WH2012_Camera_Ready.pdf?version=1&modificationDate=1356038467000

4.11. EveryAware: Enhance Environmental Awareness through Social Information Technologies

EveryAware is an FP7 EU project intending to integrate environmental monitoring, awareness enhancement and behavioural change by creating a new technological platform combining sensing technologies, networking applications and data-processing tools. A sensor box for measuring air quality has been developed within the project. The data recorded by the sensor box can be visualized in the app AirProbe, also developed in the project. The sensor box records the concentration of pollutants in the surrounding environment, marks them with GPS coordinates and sends them continuously to AirProbe. AirProbe actuates as an intermediate point between the data collected from sensor box and the server that stores them. The application is available for Android phones and it is designed to: (i) show information about the current air quality; (ii) record the user trip; (iii) let the user to annotate his/her journey; (iv) let the user see a real time graph showing pollutants, (v) share data on social networks. The parameters recorded are: BC, CO, NO_2, O_3, VOCs, temperature and humidity. Additionally noise pollution is also targeted in the project. An app has been developed within the project that allows using the phone as a sensor. The app WideNoise samples decibel noise levels, displaying them on an interactive map. With the app it is possible to take a sound reading and share it with the community. It is also possible to check the average sound level in an area. More information about the project can be consulted in: http://www.everyaware.eu/ and http://cs.everyaware.eu/event/overview.

4.12. Aeroflex: Sensor bike.

The Aeroflex sensor bike is a regular bicycle equipped with instruments to measure local air quality including ultrafine particle number counts (TSI P-Trak), particulate matter PM_{10}, $PM_{2.5}$ and PM_1 (GRIMM 1.108), black carbon (AethLabs micro Aeth model AE51) concentrations and CO (Alphasense CO-BF electrochemical cell) at a high temporal resolution. Each measurement is automatically linked to its geographical location and time of acquisition using GPS and Internet time. Furthermore, the Aeroflex is equipped with automated data transmission, data pre-processing and data visualization (Elen et al., 2013). The idea behind Aeroflex is that everybody who is “able to ride a bike” becomes able to successfully conduct mobile air quality measurements. The bike allows covering longer distances and carrying larger weights of measurement equipment than using personal monitoring carried on a back-pack, for instance.

4.13. CamMobSens: Cambridge Mobile Urban Sensing

CamMobSens is an air pollution monitoring initiative by the Cambridge University and it was part of the MESSAGE project (finalized in 2009). The project employs both hand-held units carried by pedestrians and slightly larger units fixed to lamp-posts. CamMobSens conducted a large scale deployment, lasting three months, in the greater Cambridge area in the spring/summer of 2010. Work has now started on a NERC funded project to deploy an improved version of these devices, incorporating a novel particulates/aerosol sensor, at ~60 locations around Heathrow airport. More information about the project can be found in the project website: http://www.escience.cam.ac.uk/mobiledata/?goback=%2Egde_4263048_member_107590732

4.14. AIR: Area's Immediate Reading

AIR is a public, social experiment in which people are invited to use Preemptive Medias' portable air monitoring devices to explore their neighborhoods and urban environments for pollution and fossil fuel burning hotspots. The device employed in the project allows the participants to identify pollution sources serving as an environmental, health and social discussion platform. AIR is a project launched in 2006 in New York City but has also been demonstrated in other cities in USA, Australia and Brazil. The devices are equipped with sensors to detect CO, NOx and O_3. The AIR device has dual modes: a personal reading mode that displays the immediate pollutant levels, and a compass mode that indicates the presence of any heavy, industrial or commercial, polluters along with their annual emissions (based on the National Emissions Inventory). Moreover, it also displays the presence of other devices nearby. More information about the project can be consulted here: http://www.pm-air.net/

4.15. Air Quality Egg: Community-led sensing network

The Air Quality Egg project is not centralized at any institute or university but is instead developed by a community effort, born out of groups from the Internet of Things Meetups in New York City and Amsterdam. Designers, technologist, developers, architects, students and artists form the Air Quality Egg work group, and the community is open and new people can easily join and contribute. The main aim of the Air Quality Egg community is to fill the spatial gap that currently exists in conventional air quality monitoring networks, where the official data is gathered at specific locations in the city, at times not representative of actual population exposure. The Air Quality Egg is a sensor system designed to allow anyone to collect outdoor NO_2 and CO concentrations as well as temperature and humidity. The sensors are commonly placed at homes and also schools. The data collected by the sensor is sent in real-time to Pachube, an open data service that both stores and provides free access to the data. More information about the project can be found here: http://airqualityegg.com

4.16. PEIR, the Personal Environmental Impact Report

PEIR is a participatory sensing application that uses location data sampled from mobile phones to calculate personalized estimates of environmental impact and exposure. PEIR is led by the University of California, and it was created to explore how to make participatory sensing systems relevant at a large scale, through a platform that integrates mobile data collection, other real-time data sources, and models that collect time and location as primary inputs. PEIR operates at the resolution of the individual,

runs continually, and its feedback is available on demand. The PEIR system has been designed around the broader concept that location-traces, with estimates of participant activities and the local air quality context, can be combined with impact and exposure models to create new interpretations of a participant's choices. More information about PEIR can be read here (Mun et al., 2009):
http://www.cs.cornell.edu/~destrin/resources/conferences/2009-jun-Mun-Sheddy-PEIR.pdf

4.17. iMAP: Indirect Measurement of Air Pollution with Cellphones

iMAP is a project run by the University at Buffalo and based on indirect sensing. Participatory sensing aims to monitor a phenomenon by deploying a dense set of sensors carried by individuals, while indirect sensing aims to infer the manifestations of a sparsely monitored phenomenon on individuals. The main advantage of indirect sensing is that, by making use of existing exposure modeling and estimation methods, it provides a more feasible alternative to direct sensing. The feasibility of the direct sensing approach is limited by the cost, size, and bulk of the different sensors required. Indirect sensing decouples the accurate determination of the effects of a phenomenon on an individual (which is done by using the model and the time-location logs) from the construction of the model (which is done by collecting data via direct sensing at several locations). In the project, 50 volunteers were recruited for a three-month observational study. Time-activity data from the volunteers was gathered by using GPS-equipped cellphones. These data was incorporated into a land use regression model to produce cell-phone based $PM_{2.5}$ exposure estimates. An advantage of this approach is that instead of relying on a person's residence to estimate his or her air pollutant exposure, the exposures are based on their changing locations throughout the time period, allowing for instance to capture locations during commuting and traveling, when exposure to air pollutant is usually highest. Reference: Dermirbas, M., Rudra, C., Rudra A., Ali Bayir, M. iMAP: Indirect Measurement of Air Pollution with Cellphones. PERCOM '09 Proceedings of the 2009 IEEE International Conference on Pervasive Computing and Communications.

4.18. GasMobile: Participatory Air Pollution Monitoring Using Smartphones

GasMobile employs low-cost mobile sensing systems for participatory air quality monitoring. A two-month campaign was designed for pollution measurements in an urban area. The sensor was mounted on a bicycle and measurements where performed in the city. An ozone sensor was connected to a mobile phone by USB. The data was employed to create air pollution maps with a high spatial resolution. To ensure the quality of the data, sensors are re-calibrated when they are in the vicinity of a static reference station. Reference: Hasenfratz, D., Saukh, O., Sturzenegger, S. and Thiele, L. Participatory Air Pollution Monitoring Using Smartphones. In Mobile Sensing: From Smartphones and Wearables to Big Data. 2012.

4.19. InAir: Sharing indoor air quality measurements and visualizations

InAir is a project which aims to evaluate the changes in awareness and behaviors of individuals due to sharing measurements and visualizations of indoor air quality. Low-cost technologies play a primary role in improving the quality of indoor environment by monitoring, visualizing and helping people to better understand indoor air quality. By providing a mechanism to compare measured air quality across places, it is expected that individuals may be educated and motivated to change their behavior for improving air quality. Particulate matter was measured over a four-week campaign. The InAir platform was placed at the houses of the participants (the air quality monitor DC1100 by Dylos was employed). The study consisted of two modes, a single-user mode and a sharing mode, each of which lasted two weeks. Six groups of 14 people were recruited. The project found that sharing plays a significant role in maintaining engagement in the system by providing emotional, entertaining and comparative aspects to users. An increase in user awareness and direct changes in behavior are observed when the sources of the problem are apparent and solvable. However an increase of concern and powerlessness feelings appear when the source of the problem was unknown or no solutions were provided. Reference: Kim, S., Paulos, E. in Air:Sharing Indoor Air Quality Measurements and Visualizations. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. 2010. ISBN: 978-1-60558-929-9

4.20. MAQS: A Personalized Mobile Sensing System for Indoor Air Quality Monitoring

MAQS project is focused on indoor air quality. Indoor air quality (IAQ) is challenging because indoor air pollutant concentrations and human motion patterns vary spatially and temporally within and across rooms. Stationary sensing has the limitation that it can only measure IAQ near the sensors, not detecting the variation in other rooms. In MAQS the users carry portable, indoor location tracking sensors that provide personalized IAQ information. MAQS estimates human-dependent air quality factors using CO_2 concentrations, and estimates other air quality factors using air exchange rates (e.g. VOC). MAQS integrates smartphones and portable sensing devices to deliver personalized, energy-efficient, IAQ information. The system was tested in a study with 17 participants, including faculty and graduate students, who share some workplaces and classrooms. The system was recording both room information and IAQ data for all the users for 3 weeks. The results demonstrate the feasibility, effectiveness, and efficiency of MAQS for personalized IAQ monitoring.

4.21. TrafficSense: Rich Monitoring of Road and Traffic Conditions using Mobile Smartphones

Although the project aim is not related with air quality monitoring, it is an example of how other crowd source data can be analyzed together with air quality, enhancing the results.
TrafficSense aims to monitor road and traffic conditions in a city using the smartphones which are carried by individuals. Accelerometer, microphone, GSM radio and/or GPS sensors in the phones are employed to detect potholes, bumps, braking and honking. A mobile phone-based approach to traffic monitoring is a good match for developing regions because it avoids the need for expensive and specialized traffic monitoring infrastructure.
The data collected by projects like TrafficSense can be useful when correlated with data from air quality. For instance, some of the information can be helpful to support emission estimation from road traffic. Additionally information on areas with high traffic can be used for cyclist and pedestrians to avoid them and reduce their exposure to pollutants. The link between air quality and traffic was not consider in TrafficSense. Reference: Mohan, P., Padmanabhan,N., Ramjee, R. 2008. TrafficSense: Rich monitoring of road and traffic conditions using mobile smartphones. Microsoft Research, Technical report MSR-TR-2008-59.

4.22. RESCATAME: Pervasive Air-quality Sensors Network for an Environmental Friendly Urban Traffic Management

The RESCATAME Life project (LIFE 08 ENV/E/000107) aims to integrate management needs of mobility and air quality into a single urban traffic management model. The project implementation of the concept "instrumented city" is not only to achieve the goals of reducing pollution levels below the limits imposed by the European Directives, but also because it is essential to organise city traffic in a rational manner without causing excessive disruption to the mobility needs of citizens and achieve in a systematically way sustainable traffic levels at any time of the day. More information may be found in www.rescatame.eu.

4.23. LabCityCar: Inteligent mobility in Gijón (Spain)

LabCityCar is a Living Lab project based on the sustainable mobility of private cars, developed in the city of Gijón. It proposes the fulfilment of a set of actions that begin with the analysis of the impact of the mobility of these vehicles in the different zones of the city and the ideas for improving their impact with benefits for the citizens and therefore for Gijón.

In this project, the citizens are the main source of information thanks to their active participation, and in this way each one becomes a "citizen-researcher". More information in: http://www.labcitycar.info/index-en.html

4.24. Biketastic: Sensing and mapping for better biking

Bikestatic is a project by the University of California (UCLA). The main aim is to empower the biking community by enriching the experimentation and route sharing process making it both easier and more effective. It has created a platform where participants can share theirs routes and experiences. Additionally to the route data the participants can obtain information about road roughness (e.g., indicative of bumps) and noise levels (could be indicative of large vehicles or heavy traffic) using the accelerometer and microphone from the smartphones. Furthermore, the system allows individuals to submit data along the route. The participants can share and compare the information derived from the sensor.

The example of the last three projects shows the link between the use of sensor technologies for direct and indirect air quality monitoring, by applying the sensors to monitor both air quality parameters and traffic flows. In this respect, as stated in section 1 there are numerous other initiatives across Europe which aim to develop sensors for urban traffic management, as a means to indirectly improve urban air quality. Describing these initiatives is not the scope of this report. Another example of projects dealing indirectly with sensor technologies is FP7 CSA AirMonTech (www.airmontech.eu), which included in its final recommendations the deployment of sensor technologies in combination with conventional air quality networks.

5. Summary and conclusions

Sensor technologies are an emerging field of scientific and commercially-oriented research, with a fast increasing potential in the field of air quality monitoring. Several sensors have been developed so far to monitor gaseous pollutant concentrations, mainly O_3, NO_2, NO, SO_2, VOCs, CO and CO_2, based on different principles (resistive sensors, electrochemical sensors, infrared radiation absorption sensors, and photo ionization detector sensors). Research is still underway for sensors to capture dust (particulate matter, PM) concentrations. These technologies are deployed for direct air quality monitoring. Other sensor technologies also exist for urban traffic management (traffic flows, parking-space management), which are indirect means to improve urban air quality. These technologies are proving effective and with a high potential for urban environments, and should thus be considered as valid options for air quality improvement. However, they are out of the scope of this study.

At present, most air quality sensors have been tested under laboratory conditions, where their performances vary but may be considered, overall, successful according to the literature. However, laboratory conditions (e.g., concentrations) do not necessarily represent real-world conditions. The number of real-world studies, in ambient conditions and with real emission sources and meteorological scenarios, is scarcer and their results are so far not as promising as in the case of laboratory tests. Large divergences may be found between sensor and reference data, and even between different units of the same sensor type. Despite these limitations, several projects based on sensor measurements are currently ongoing in Europe. These results highlight the need for further research aimed at reproducing gaseous pollutant concentration measurements in ambient outdoor air, as well as in indoor air, by overcoming the main challenge of the interferences between the gaseous responses in the real-world aerosol mix. There is currently only preliminary evidence of the real-world performance of sensors in terms of, for example, specificity and stability. Results presented in this work and evidenced in the course of this literature review suggest that currently the comparability between sensor and reference data is not optimal for most gaseous pollutants, and that the parameter showing better results is O_3. However, results cannot be considered fully comparable with data from reference instrumentation and their equivalents. Authors highlight the relevance of locally calibrating the sensors and of post processing of the data as pre-requisites before the agreement between sensors and reference equipment can be acceptable.

Once the limitations of sensor technologies are overcomed and appropriate QA/QC procedures may be fulfilled by sensors, low-cost gas sensors have a large potential for enabling high spatial density monitoring which will be beneficial in urban areas. By means of different deployment strategies, sensor technologies respond to changing air quality monitoring priorities, and allow to move away from a strategy of comprehensive monitoring networks for each pollutant, to one of having a combination of permanent monitoring sites measuring a large range of pollutants in carefully-chosen sites, supplemented by sensor technologies and modelling. Low-cost sensors will allow a much greater density of monitoring sites, which will enhance air quality monitoring given that it will enable networks to capture the high spatial inhomogeneity of urban pollutants. It has even been proposed that sensors could be used in short term campaigns, in addition to permanent monitoring. However, it must be clearly stated that the practical operation of such high-density networks will require research and development (AirMonTech, 2013). By achieving the goal of maximizing the spatial coverage of air pollution measurements, and combining it with mobile monitoring (allowing to assess, e.g., time activity patterns), sensor technologies will favour the better integration of air quality assessment and health effects monitoring, by providing detailed information on population exposure.

Low-cost sensors are bringing an important change on who collects the data and also where the data is available. Traditionally, the collection of data was in the hands of trained technicians, but now it is also in the hands of general public. Moreover, the data is no longer only available in official web pages or scientific databases, but shared by concerned citizens through social networks. This brings new challenges, as for instance on how to respond to the citizens' concerns and how to best use this data.

Local and national authorities start showing interest in the use of the new sensor technologies for indicative measures, or supporting modelling and objective estimates, within the frame of the air quality directives (EC, 2004 and EC, 2008). The current directives open already a possibility to employ such technology for air quality assessment, as long as it satisfies the quality objectives set in the directives.

The current developments lead to an emerging need to develop guidance on:

- how to operate, calibrate and evaluate the accuracy of the sensors;
- how to interpret the data generated by these new sensor technologies;
- strengths and limitations, to set reasonable expectations for use of the different technologies;
- how to manage very large sets of data;
- how to use micro-sensors for education and outreach, including how to respond to inquiries from concerned citizens.

Such guidance would be helpful for sensor developers, authorities and citizens.

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