Sensors and 'Apps' For Community-Based Atmospheric Monitoring

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Recent advances in both sensors and wireless communication provide opportunities for improved exposure assessment and increasing community involvement in reducing levels of human exposure to airborne contaminants. These new technologies can enhance data collection to answer science and policy questions related to the health and environmental effects of air pollution[1]. In recent years, wireless sensor networks (WSNs) have matured and greatly lowered the cost of collecting data by eliminating the wiring that was once necessary. A DOE cost-benefit analysis of changing from wired to wireless automation systems indicated a three-fold reduction in the initial investment and a five-fold reduction in annual operating costs[2]. Here we describe a PM monitor made by microfabrication techniques, derived from the manufacture of integrated circuits[3], and show how sensor data can be accessed by existing cell phone technology. Today the environmental monitoring community can select from digital applications ('apps') for recording, processing, and sharing sensor data. Integrating air pollution and individual physiological data collected simultaneously from networked sensors and suitable 'apps' will empower individuals and communities with information useful in reducing exposures to air pollutants.

PRESENT SENSOR LANDSCAPE

At the heart of all sensor systems lie the elements that respond to nearby changes in physical or chemical characteristics and the transducers that convert the responses to electrical signals. Commercially available gas sensors are based on two main principles. Chemical gas sensors depend on reactions between the target gases and the sensing material as used for O_3, NO_2 and

CO and sometimes for CO_2 and volatile organic compounds. Optical gas sensors measure absorption of light by species of interest, such as O_3 and CO_2 or chemiluminescence for NO_2. Infrared absorption is widely used for CO_2 in both small sensors. Sensors for respirable particles [below 2.5 μm aerodynamic diameter (AD)] typically rely on light scattering, a widely used method to monitor PM in near real-time, although not a direct mass measurement. Table S1 (in the online Supplemental Information, SI) provides additional details on sensors.

NEW TECHNOLOGIES

WSNs incorporate recent advances in several areas of electrical engineering:

a) Microfabrication techniques now make possible smaller, mass-produced sensors that are lightweight and ultimately inexpensive. In addition to MEMS (micro-electro-mechanical system) sensors with tiny (mm-scale or smaller) moving parts, sensors incorporating microfluidic, optical, and nanotube elements are also being developed;

b) The costs of monitoring over large geographical areas are decreasing because signals from widely dispersed sensors can travel over existing secure WSNs; and

c) Energy efficient radios and sensor circuits now allow for low-maintenance operation without the need for plug-in power or direct operator access.

Case Study: Microfabricated Portable Particulate Matter Monitor

Figure 1 shows a microfabricated portable air quality PM mass monitor designed to link with a cellphone for data collection, processing, and transmission[4]. Microfabrication techniques, such as photolithography, evaporation, and etching form the structures, conductors, and the resistive heater. They permit the PM monitor and its aluminum housing to weigh just 27 g, with a volume of only 8 cm^3. A small fan at the outlet draws PM-laden air through a microfluidic structure and a virtual impactor that separates particles based on a mean cutoff diameter of 2.5 μm AD. Larger particles exit through the pump, while smaller particles pass through a 100-μm high channel between a resistive heater and a mass-sensing oscillator. The sensor is a microfabricated piezoelectric FBAR (film bulk acoustic resonator, a common component of cell phones) connected to a CMOS (complementary metal-oxide-semiconductor) oscillator circuit. The thermal gradient between the heater and the FBAR causes particles to deposit by thermophoresis. As the mass of particles collected on the FBAR increases the oscillator frequency falls from its nominal frequency, 600 MHz, at a rate proportional to the rate of change of the mass of collected particles. At a flow rate of 1 mL/min, the estimated limit of detection for PM in ambient air is 2 ± 1 μg/m^3 for 10 minute sampling. Measuring PM mass based on the rate of change in oscillating frequency is a well-established direct mass measurement method, e.g., in the tapered element oscillating microbalance (TEOM) that has achieved equivalency as a continuous mass monitor for $PM_{2.5}$[5].

Use of transparent materials in the device allows for inclusion of optical approaches, such as particle counting to measure the size distribution and, with the simultaneous mass measurement, to obtain particle effective density (μg/cm^3)[6]. Measuring light absorption and scattering could provide insight into chemical composition and radiative forcing by the aerosol. Another benefit of the PM monitor's small size is that it can be packaged with sensors for temperature, relative humidity, and gases and even sensors for human physiological responses such as blood pressure and heart rate.

STATIONARY AND MOBILE APPLICATIONS

Stationary: Indoors and Outdoors

Limited spatial and temporal information constrains our understanding of the spatial variability of pollutants indoors and outdoors, and obscures the relationship between them. However, most monitoring and research networks include only a few monitors in a given area, often limited to specific time periods, due to the high cost to site and operate samplers.[7,8,9,10]. Indoor sampling is usually limited to a small number of homes, with a small number of samplers in each dwelling and for short time periods, days or weeks, such as in RIOPA as reported by Meng et al.[11]. Even larger indoor/outdoor/personal exposure studies, such as the Detroit Exposure and Aerosol Research Study (DEARS), involving measurements twice per year (winter and summer) over three years was limited to 40 participants during each season in one city, and only 5 days in each measurement period[12].

When sensors are used at stationary monitoring sites, the cost advantages of microfabricated multipollutant sensors (Fig 2) permit the use of a larger number of monitors. The low cost of sensors also allows colocating multiple devices to reduce measurement uncertainty. For example, the CO_2 sensor shown in Fig. 3 is small (33 mm x 33 mm x 14.6 mm) and inexpensive, but the quoted uncertainty is ±30 ppm ±5% of the measured concentration. This is too high for accurately measuring changes in the atmospheric concentration of CO_2 with a single sensor because the standard error is greater than the current 2 ppm increase of CO_2 per year, while the current average is 393 ppm[13]. However, Honicky[14] showed that by colocating N identical sensors that have Gaussian response functions, the standard error decreases by 1/N. Adding transmitters to the stationary sensor packages makes possible two-way communication over a WSN in near real-time, allowing this information to be accessed by community members and used for short-range forecasting of air pollution and alerts. Weather Bug is one example of this approach using standard meteorological sensors (see SI). An example of installing and powering small stationary sensors appears in the Supplemental Information.

Mobile and Personal Applications

The integration of sensors and cell phones begins to provide a new dimension to air quality monitoring. The sensors may be internal or external to the mobile device. Fig. 2 shows a collection of small sensors assembled in one unit, forming a multipollutant sensor that can be worn on the body to measure personal exposure. Coupling multifunctional monitors to cell phones also enables geo-location and data transmission via a cellular network. Dutta's group at the University of Michigan[15] has shown how mobile devices can power sensors via the iPhone™ headset plug, as well as transmit information through the wireless network. Energy to power the sensor is provided by a 22 kHz audio tone produced by the mobile device and then efficiently amplified and rectified externally to yield approximately 14 milliwatts of DC power. The effective data rate is 30 bytes/sec. These methods provide an elegant approach to obtaining data of high spatial and temporal resolution that have the potential to improve exposure estimates significantly[1].

DIGITAL COMPUTER 'APPS'

'Apps' are computer programs for cell phones that users download so they can access, collect and use specific types of information. There are many potential users and contributors of sensor data, from individuals and businesses to organizations and governmental agencies. 'Apps' are emerging as tools for environmental research, as illustrated by recent postings from investigators at the University of Florida[16]. To encourage innovation in this area, in 2011, the US EPA launched the *'Apps' for the Environment Challenge.* This effort led to development of more than one hundred new 'apps' that access existing environmental and health databases in user-friendly interactive formats[17]. Several submissions dealt with air quality, such as the Air Quality Data Explorer for the U.S.[18]

COMMUNITY-BASED PARTICIPATORY MONITORING

Community-based participatory monitoring refers to individuals collecting data within their communities and reporting results in near real-time. This is being made possible through the development and deployment of the sensors and WSN described above. Data collected may be used directly through 'apps' or uploaded to a central database for integration and analysis with other data, followed by downloading summarized results, also via 'apps'. This empowers people to plan their daily lives to avoid significant concentrations of pollutants and allergens. Apps can help decide whether to keep windows open or closed, where to go jogging, and even where to live. Two examples showing enthusiasm for monitoring by the public, although not in real-time, are given by Jones[19] (the first citizen science experiment: simultaneous measurement of rainfall throughout Britain) and Allen[20] (response to earthquakes).

Besides guiding individuals' behavior to avoid exposure to air pollution, sensor networks could have a significant role in developing a more robust nationwide environmental surveillance system. From the perspective of environmental health scientists the application of sensors provides new opportunities to improve the spatial and temporal resolution of environmental, physiological, and biological measurements that, when made simultaneously, would greatly enhance exposure assessment and understanding the modes-of-action of airborne pollutants. The Center for Disease Control's (CDC's) BioSense system[21] is a step in this direction (see SI).

CONCLUSIONS

Ongoing miniaturization of sensor technology, the increasing availability of wireless sensor networks, and the development of user-friendly applications for mobile devices, offer opportunities for improved environmental and health monitoring. Government agencies and researchers are starting to apply these advances to address science and policy questions related to the health and environmental impacts of exposure to pollutants. Decreasing costs for environmental sensors and wireless communication equipment are enabling sensor-cellphone linkages and a growing variety of 'apps' for handling two-way data transmission, data compilation and analysis, and sharing the resulting information with the public. Deploying simple inexpensive and multifunctional sensors for routine monitoring and field studies can provide greater data density to better understand the spatial and temporal variations of pollutants and human exposure.

Widespread use of sensor networks could significantly improve our understanding of linkages between air pollutants and adverse health effects. With the addition of sensors for human physiological responses (such as blood pressure and heart rate), the suite of available environmental sensors begins to provide new dimensions for collecting human exposure data useful for epidemiologists to better link pollutants to respiratory and cardiovascular health effects. In addition, tools suitable for community-based participatory atmospheric monitoring are now appearing, and they are expected to generate strong public interest and empower people to better protect their health by being more aware of adverse pollution conditions.

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FIGURE CAPTIONS

Fig 1. Expanded view of the MEMS PM monitor. The labeled elements are (a) microfabricated virtual impactor, (b) a resistive thermophoretic heater, (c) an air inlet, (d) outlet, (e) exposed FBAR die, (f) air sampling fan, and (g) oscillator output RF signal.

Fig. 2. Small environmental sensors and related devices, for use in atmospheric studies in conjunction with cellphones, similar to those used in the Common Sense Project's Handheld Mobile Device that monitors CO, O_3, NO_x, temperature and relative humidity. (a) input/output and/or low power wifi radio; (b) populated printed circuit board [(PCB) based on the Common Sense Badge with Epic Core (http://www.eecs.berkeley.edu/~prabal/projects/epic/sensors)] including the red square with white circle, a gas sensor; (c) and (d) electronics; (e) and (f) electrochemical gas sensors; (g) and (h) an opened 4-inch case that holds the PCB with all the sensors, the radio and associated electronics, as well as inlets for air. (Devices from Prof. Prabal Dutta, University of Michigan.)

Fig. 3. Small carbon dioxide sensor and U.S. 25-cent coin for scale. (Sensor from Edurevo, Inc., Seoul, South Korea.)

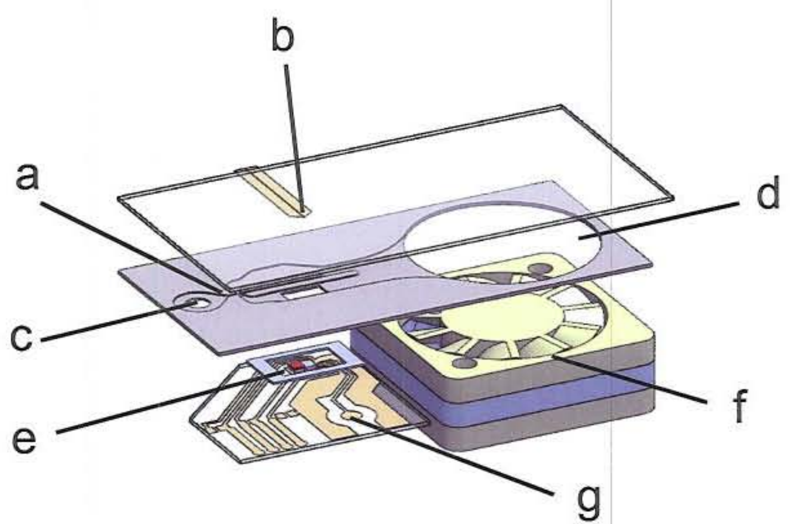

Fig. 1.

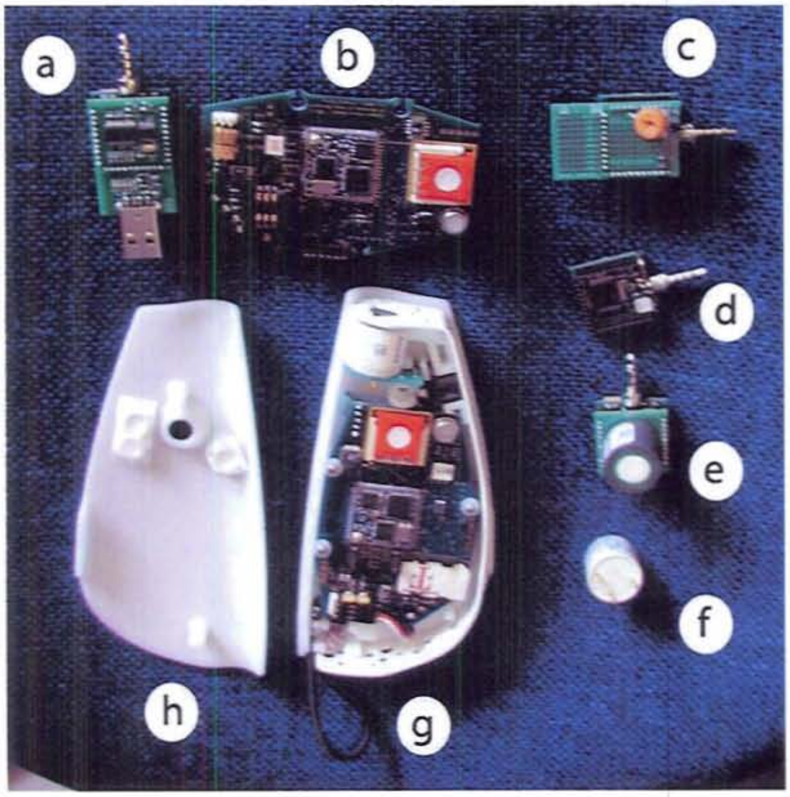

Fig. 2.

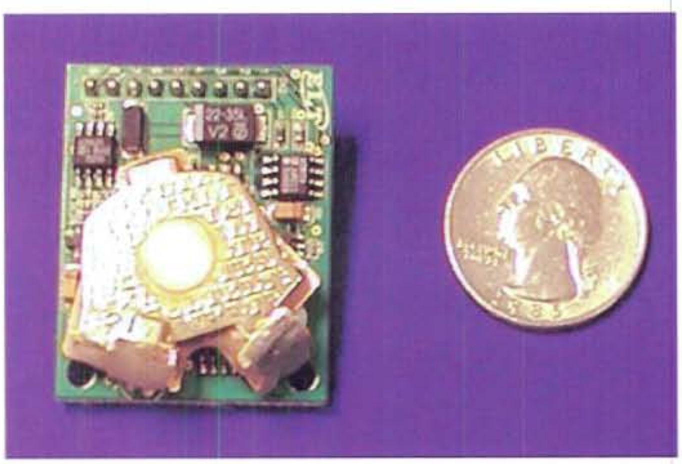

Fig. 3.