N-SMARTS: Networked Suite of Mobile Atmospheric Real-time Sensors

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Abstract

By attaching sensors to GPS-enabled cell phones, we can gather the raw data necessary to begin understand how urban air pollution impacts both individuals and communities. In this paper we introduce a hardware and software platform for exploring algorithms and data gathered from pollution sensors integrated into cell phones, and discuss our main research agenda going forward.

Categories and subject descriptors

[J.2] Computer Applications, Physical Sciences and Engineering, Earth and atmospheric sciences

General terms

Measurement

Keywords

Sensing, Mobile Phones

1 Towards a societal scale sensor network

While industry analysts predict that cell phones will become the "next PC," we believe that the cell phone has the power to become something much more than a scaled down, connected IO and processing device. In addition to these standard PC traits, a cell phone is situated in an environment, mobile, and typically co-located with a user. These traits make the cell-phone ideally suited to track and understand the impact that the environment has on individuals, communities, cities and on a global scale, as well as understanding how humans effect their environment.

By attaching sensors to GPS-enabled cell phones, we can gather the raw data necessary to begin understand how, for example, urban air pollution impacts both individuals and communities. While integrating a sensor into a phone and transmitting the data that it gathers to a database is not very difficult, doing so at low cost, on a societal scale, with millions of phones providing data from hundreds of networks spread throughout the world makes the problem much more tricky.

On top of the systems challenges, understanding the raw data gathered from a network of cell phone-attached sensors presents significant challenges as well. Cell phone users are mobile, are unlikely to ever explicitly calibrate their sensors, typically put their phone in their pocket or handbag (thus obstructing the sensor from airflow), spend significant time indoors or in cars, and typically charge their phone at most once per day, often much less frequently. Even if users did calibrate their sensors, the very low-cost sensors we intend to use drift over time and environmental conditions anyway. Without knowing the location of a sensing event, automatically calibrating the sensors in the phone, detecting the environment of the phone, and intelligently managing power (by sampling at the right times) the data gathered by the phones will be next to useless.

Integrating sensors into mobile phones, however, has several practical advantages. For many applications, the most significant challenges that face tradition wireless sensor networks are power management and network formation and maintenance. Obviously these problems are both already solved for mobile phones. Also, a dearth of real-world, practical applications has limited the number of "motes" (wireless sensor network nodes) which get manufactured, and thus the price of a mote remains relatively high. With the number of mobile phones sold in 2009 predicted to surpass 1 billion [2], cell phones obviously have enormous economies of scale that will be hard to replicate in the near term. Thus the mobile phone platform has several significant advantages as a sensor that will allow relatively simple, and massive deployments.

The mobility of the phone also provides some important opportunities. At the expense of sampling a given location continuously, a sensor will provide significant geographic coverage. Also, sensors will be heavily biased towards locations in which people congregate, so for human-centric applications, sensing in mobile phones will often provide coverage exactly where it is needed most. In over-sampled locations, the precision of the sensing system can be increased by carefully averaging the readings from several nearby sensors (see Section 4). Also, sensors close to one another can be automatically calibrated, especially if there are some "ground truth" reference sensors also situated in the environment (see Section 4).

1.1 Mobile sensing for developing countries

Integrating sensors into mobile-phones has the potential to significantly benefit people living in developing countries in particular. Air pollution in general, and indoor air pollution in particular, has an enormous health impact on people in developing countries. Outdoor

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air pollution is increasingly becoming a significant health risk as well, with the rapid industrialization that is happening in India and China, and beginning all over Africa [5].

There are several common sources of air pollution in developing countries that are not significant factors in the air pollution in the industrialized world. Besides over-polluting industry (due to dirty generation and manufacturing technologies), open flame cooking with solid fuel (often indoors), poorly tuned diesel engines (due to poor regulation), and burning of trash and brush (due to lack of trash service and for agriculture), all contribute to levels of air pollution that are often many times higher in the less industrialized world.

A combination of public policy and education, however, can have a significant impact on emission levels and human exposure to pollution, however. . Since the cell phone is becoming ubiquitous in the urban areas of developing countries, it is, in many respects, a good means of education and generating awareness .

A preliminary mobile sensing pollution study we conducted in Ghana provides a poignant anecdote for the impact that awareness about our pollution can have on people's behavior. During the course of the study, one of the participants, a taxi driver, became concerned about the alarms that the sensors he was carrying were generating. In response, he had his own car serviced, at his own expense. It is not clear from our survey whether he did this because he believed that his own car was the source of the pollution, or out of more altruistic motives, but regardless, we believe this story speaks to the power of information to influence people's behavior.

One fact that is immediately obvious when visiting many cities in developing countries is that cities in developing countries are generally much more polluted than the developed world. This is due to a combination of less regulation, less enforcement of existing regulations and the lack of viable, clean technologies [5].

Since policy makers are likely to carry mobile phones, we believe that ubiquitous sensing on mobile phones is likely to impact environmental policy. Furthermore, in some cases, people do not change their behavior even when practical and safer alternatives are available, often because of the lack of perceived health risk [4]. We believe that raising people's awareness of their exposure will impact their willingness to adopt new technologies that benefit their health.

Ubiquitous pollution monitoring on mobile phones also has interesting economics. Since mobile phones are manufactured in such large quantities, any sensing in the phones will automatically leverage these economies of scale. Thus, as MEMS sensing technologies mature, the cost of of sensing on a phone becomes marginal.

Also, even the marginal cost of integrating sensors into phones will be borne by the wealthy people of a society, since mobile phones are typically used by wealthy people. Thus, there is an built-in subsidy which will benefit society as a whole. Of course, there will be some bias in sampling towards the environments of wealthy people, but we believe that there is enough overlap between the environments of the wealthy and the poor, that the information will be informative and useful regardless.

Finally, mobile sensing is particularly promising for developing regions because high levels of pollution are easier to detect with low cost sensors. As sensing technology matures, mobile sensing will become more and more relevant to the developed world as well, since cities in the developed world generally have less pollution. For the time, being however, ubiquitous mobile sensing will be most relevant and useful in the developing world.

1.2 Mobile phone network monitoring

Since the algorithms and software we are developing are relatively neutral to the type of sensor being used, one interesting application of the N-SMARTS platform is enabling mobile phone network operators to monitor the coverage of their network. By recording the received signal strength on the phone whenever a sensor reading is taken, we can build a detailed coverage map for a network operator. Since operators typically spend significant resources monitoring the coverage and call quality of their network (Verizon wireless spends millions of dollars annually in capital and engineering costs monitoring their wireless network by driving around in specially equipped cars), and mostly only monitor main routes [**?**, **?**]), this could lead to significant cost savings for network operators.

We believe that network operators, especially budget constrained operators in developing countries, might be willing to subsidize data communication for sensor data transfer in exchange for network coverage information.

1.3 The N-SMARTS and CommonSense Projects

The N-SMARTS (a UC Berkeley project) and the CommonSense (an affiliated Intel Research project) focus on:

- Developing a platform to understand the real-world challenges of sensing on a mobile phone, and to provide other researchers, both within and outside of computer science, with a platform for their own experiments. *(What do the sensor data look like? What are people's movement patterns? How do people's behaviors impact the data? How can the impact of those behaviors be minimized by platform design?)*
- Understanding how information about one's environment can impact one's behavior *(Will people incur personal expense to sense their own environment? Will they invent their own sensing applications given the right tools? What information will induce them to change their behavior?)*
- Building a system architecture that can scale to millions of phones *(What are the system bottlenecks? How can communication costs be minimized? How much computation should occur on the phone?)*
- Designing algorithms to scalably provide accurate estimates of pollution levels and other sensed data *(How can accuracy be increased by super-sampling? How can the phones be automatically calibrated to one another, or other sensors in the environment? How can those inferences be parallelized?)*
- Designing algorithms to detect and account for the user's behaviors *(Can we accurately detect when the phone is a user's pocket or purse, when the user is in a car, indoors, outdoors, etc.? Can we correct our readings? Can we accurately label data with the user's context, so that we can answer questions like "What is the median exposure to CO for bicycle commuters on Shattuck Avenue?")*
- Assembling and building a suite of useful sensors to integrate.

2 N-SMARTS platforms

2.1 The COTS platform

In order to better understand what the pollution data and movement patters of users will be, we need to gather data up front, before we have an integrated sensor/phone platform available. For that reason, we have put together a portable sensor platform that can be carried around, allowing a person to gather data that is roughly similar to the data that will be gathered by the integrated platform. The Commercial, Off-The-Shelf (COTS) platform will allow us to develop and test the algorithms that make up the core of the N-SMART platform.

Figure 1: The automotive and personal version of the data-logging sensor platform

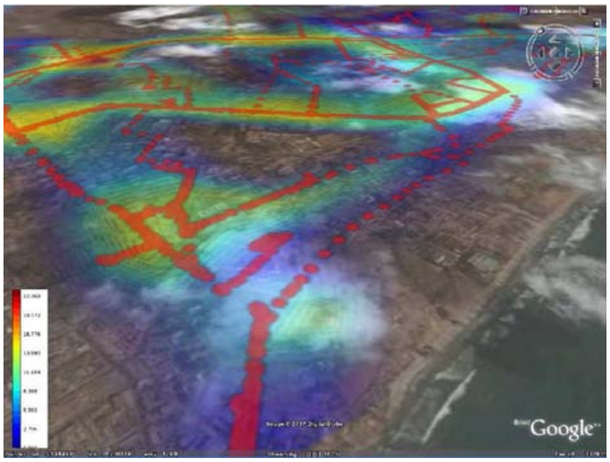

Figure 2: CO data collected from sensors in taxi cabs in Accra, Ghana on March 21st, 2007, overlaid on aerial photography using Google Earth.

The data acquisition platform consists of off-the-shelf pollution sensors, and a GPS. Each unit contains

- A Lascar EL-USB-CO Carbon Monoxide data logger
- A Garmin Qwest GPS (with external antenna)
- A NO2, SO2 or O3 data-logger from BW Technologies

All of the devices log data, and their clocks are synchronized so that the data from each device can be correlated. See our web page for details on the sensors [8].

There are two version of this kit: a "automotive platform" that can be mounted near a car window or externally, and a "personal platform" that can be worn on a user's belt (see Figure 1).

We deployed six automotive platforms on taxis and four personal platforms on students in Accra, Ghana, West Africa, for two weeks in March, 2007. These data were uploaded into a database and can be viewed in a variety of formats, including an overlay on Google Earth (see Figure 2). The database will be publicly available soon.

2.2 The integrated platform

We are also developing an integrated platform that will more closely approximate a phone manufactured with sensors integrated directly into the phone itself. This model will allow significant cost reduction with respect to less complete integrations. Rather than actually manufacturing a new phone and enclosure, however, we simply replace the battery pack of the phone with a module that clips in to the battery well of the phone, and contains both a battery and the sensor module (see Figure 3).

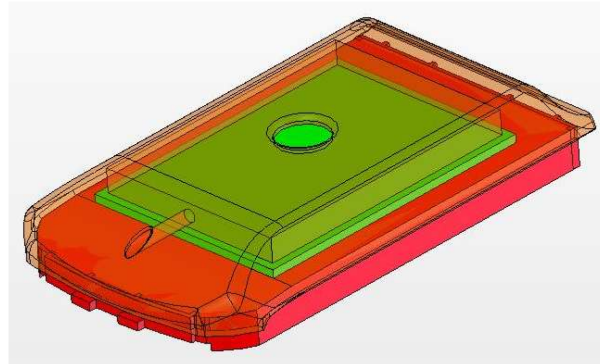

Figure 3: The battery of a LG VX9800 with a PCB mounted on top and covered by a new enclosure (outline shown for the new enclosure only).

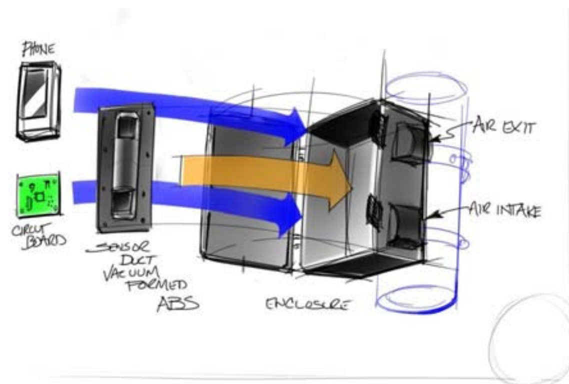

Figure 4: The large enclosure with fan and vent for automotive and stationary deployments (drawing by Christopher Myers) .

The current version of the integrated platform has:

- CO and NOx sensors
- A temperature sensor for calibration
- An accelerometer for activity inferencing
- A Bluetooth radio for communication with the phone
- A flexible power system for use with a variety of power sources

We chose to use Bluetooth to communicate with the phone to avoid mechanical problems with a direct serial link, and to make the design and software more generic.

We have also designed a dual board version that splits the sensors onto a daughterboad. This allows us to mechanically separate the control circuitry from the sensing apparatus. This is convenient in deployments in which the platform is in a larger enclosure attached to a vehicle, for example (see Figure 4).

2.3 Phone platform

We have designed the N-SMARTS board to work with any phone that allows programmatic control of the bluetooth radio. If location sensing is also required, as it is for our application, then the phone

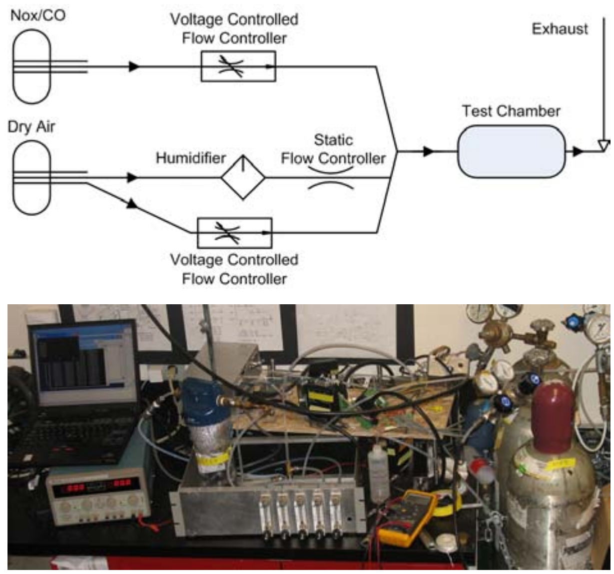

Figure 5: The test chamber we use to calibrate and test response while carefully controlling poisonous gas concentration and humidity.

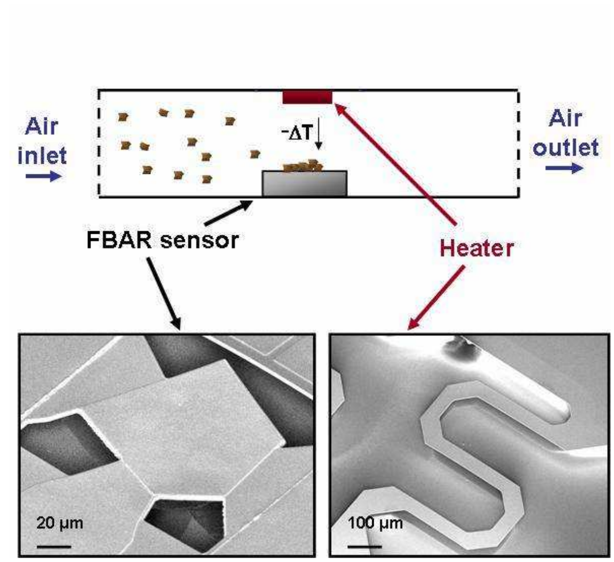

Figure 6: $PM_{2.5}$ particles are deposited on a resonating FBAR via thermal phoresis, changing the resonance frequency of the FBAR.

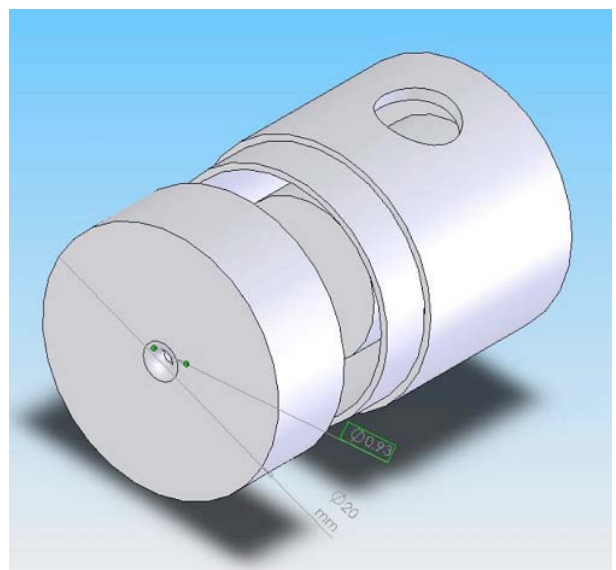

Figure 7: An inertial impaction filter is used for orientation independent, robust particle filtration.

should also have an integrated GPS. For our initial deployment, we are using the relatively expensive but easy to use Nokia N95 smartphone.

The GPS integrated into GSM-based phones, however has a fundamental limitation that Qualcomm MSM chipset-based phones have overcome. Qualcomm's chipset tightly integrates a GPS radio that takes advantage of the tightly synchronized clock that is necessary to make a CDMA radio work. In doing so, it effectively eliminates a dimension in the parameter space that the radio searches when trying to lock on to satellite signals. This allows the radio to dwell on each parameter setting for about 1000 times longer than in a normal GPS, averaging the signal over a significantly longer amount of time, and significantly reducing noise. The effect is a gain over a normal GPS radio, which Qualcomm quantifies as about 16dB. .

Practically speaking, this means that MSM-chipset based phones, when combined with other Assisted-GPS technologies, are capable of getting very fast cold-start fixes as well as indoor fixes. Our experience has found this difference to be very significant, and for passive-sensing (human out of the loop) applications, this capability is doubly important. For this reason, we also are building BREW-based phone software to interact with the N-SMARTS sensor platform.

2.4 Testing

For testing and calibration of our equipment we have designed and built a simple test chamber that allows us to control accurately the chemical concentration, flow rate and humidity in a test chamber. This allows us to calibrate our sensors, as well as perform experiments on the response time, linearity and noise properties of the various sensors we are using.

The test mechanism consists of a pure, dry air source, a dry toxic gas source, a humidifier, a constant rate flow controller, two voltage controlled flow controllers, a test chamber, a DA converter to drive the flow controllers, and an AD converter to take readings from the flow controllers and any analog sensors — such as temperature, or some gas sensors that we have tested (see Figure 5).

This test mechanism has proved invaluable in systematically testing a range of sensor devices under various conditions. It allows us to test for linearity, drift, response time, hysteresis, humidity response and many other factors that would be otherwise very difficult to characterize.

The we will describe calibration and testing of our various devices in follow-up papers.

2.5 MEMS $PM_{2.5}$ sensing

Airborne solid (Aerosol) particulate matter smaller than 2.5 microns represents a serious health risk which has traditionally required large devices to detect. We have developed a MEMS based device which measures particulate matter in the air by depositing aerosol particles on a thin-film bulk acoustic resonator (FBAR) oscillating at 1.6GHz. A thermal gradient is induced which causes airborne particles to deposit on the FBAR via thermal phoresis. This deposition changes the resonance frequency of the FBAR, which can be measured. See Figure 6.

We have also designed a small inertial impaction filter [7] capable of long term filtration without replacement, and capable of selecting particles smaller than 2.5 microns. See Figure 7.

3 Challenges for mobile and mobile-phone based sensing

In this section, we discuss important challenges for a mobile sensing system. In Section 4, we discuss how our research relates to these challenges.

Although mobility provides significant advantages, especially for human-centric applications, it also presents some important and significant challenges. User behavior and movement are somewhat unpredictable, so it makes observing a specific point in space-time difficult without an intentional visit to that location. This is especially true for locations which are infrequently traveled by people. This means that mobile sensing is most applicable in situations in which the quantities of interest are often most significant in places where people congregate. This is often the case for pollution sensing, especially when the data are being used for epidemiology.

Also, people put their phones in their pockets and purses, thus obstructing the flow of air to the phone. Similarly, people's behavior and context can introduce local environmental bias. For example, a person's car or home might have a drastically different pollution profile than the immediate surroundings. These local biases introduced by users behavior make it difficult to make observations relevant to people beyond the user of the phone. Activity inferencing and exploiting the multiple sensors in the phone will be an important aspect of mobile sensing.

Finally, if privacy is a critical concern in any application in which people and sensors are involved, especially when GPS or other location sensors are used. Also, authenticity and security will be an important challenge. If the data are being used to make policy decisions, then there will be significant incentive to distort them. Mechanisms for ensuring the integrity of the data will be an important part of any high-impact sensing system.

4 Research Directions

From the above challenges, we have identified several areas in which we are doing research.

- *Social aspects of mobile sensing and "Citizen Science"*: We are investigating how people will change their behavior based on information they obtain from personal pollution sensors, and what kinds of applications they might invent if they are given the right tools [6].

- *Advanced Sensing*: We are developing a MEMS $PM_{2.5}$ sensor that is small enough to be integrated into a cell phone. This includes a micro-pump and impaction filter that will also serve to provide airflow for the other sensors. The sensor will also provide particle discrimination using UV and IR interferometry [1].

- *Super sampling*: We are investigating how to increase the precision of the system by taking advantage of densely sampled areas. Early theoretical and empirical results confirm that the precision of the system can be dramatically improved with properly calibrated sensors.

- *Automatic Calibration*: Early results with Gaussian Process based models suggest that sensors that are in close proximity to one another can be calibrated to one another, and to accurate references situated in the environment [3]. We are developing algorithms to do this in a robust and computationally tractable way on a large scale.

- *Context inference*: Inferring the context of the phone, such as whether and by which types of materials a sensor is obstructed, whether it is indoors or outdoors, in a car, on a bike, walking, etc., will provide important information not only for accurate sensing, but also for labeling data in a way that will add value to the end users of the data. We are exploring how to apply previous research in activity inferencing, especially research focusing on accelerometers, as well as investigating some new techniques based on channel estimation and characterization using the speaker and microphone.

- *Plume detection*: Detecting hazards and indicating locations of safety will provide an important emergency response function. We will adapt existing distributed plume detection algorithms to mobile sensing scenarios.

We are not currently investigating security nor privacy, but encourage others to do so. Although the scale of a system with millions of devices challenges the scalability of many cryptographic algorithms, collusion will be difficult on such a large scale, making the security problem potentially easier in some respects. We believe there are a variety of interesting problems in the security and privacy problems of mobile sensing.

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