Towards Distributed, Low-Cost, Non-Expert Fine Dust Sensing with Smartphones

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Abstract
Air quality and its influence on health and quality of life are one of the important topics of our time. Nevertheless, it is often still very difficult (1) for individuals to assess their personal exposure and (2) for cities and other stakeholders to develop appropriate measures that are both effective and incorporate today's needs regarding mobility, housing and work. The reason is that consistent, fine-granular data is missing. This paper presents an overview of an ongoing doctoral thesis that attempts to address open questions in the field of distributed mobile fine dust sensing. This includes suitable *sensing technology* (sensors/devices; signal processing techniques), *human-computer interaction aspects* (measures that enable non-expert users to conceptualize and correctly execute the measurement process) and questions concerning *participatory sensing systems* (scenarios, calibration, incentivization).

Author Keywords
Environmental Sensing; Citizen Science; Mobile Sensing; Non-Expert Users; Air Quality; Fine Dust; Participatory Sensing; Particulate Matter; IoT 2016 Doctoral Colloquium

ACM Classification Keywords
B.4.m [Input/Output and Data Communication]: Miscellaneous; H.5.m [Information Interfaces and Presentation (e.g., HCI)]: Miscellaneous

Introduction

Atmospheric aerosol particles present a serious problem for human health on the global scale, contributing to cardiovascular disease and early death [17]. Up to now air quality is almost exclusively based on data from relatively few large, static and expensive measuring stations, of which the representativeness for the nationwide exposure of the population remains uncertain [14]. This lack of environmental data conflicts with the need of the citizens for information as well as the need of political decision-makers to take appropriate action. Distributed networks for ambient fine dust monitoring have the potential to deliver readings with a high temporal and spatial resolution and low latency. This enables novel modern environmental sensing, in which traditional fixed stations are augmented by different classes of cheaper, less accurate sensors, potentially carried by citizens or integrated in their personal devices. However, such systems entail a number of challenges that need to be addressed, chief among them the need for suitable instrumentation, appropriate user interfaces and system aspects such as calibration and incentivization.

Field of Research and Methodology

The doctoral thesis is being supervised by Prof. Dr.-Ing. Michael Beigl, who heads the *Chair for Pervasive Computing Systems* and the research lab *TECO* at Karlsruhe Institute of Technology (KIT), Germany. The group has a long tradition in Mobile, Pervasive and Ubiquitous Computing, with research in the intersection of the three areas *Sensing & Analytics*, *Human-Computer-Interaction (HCI)* and *Systems*. The topic of the doctoral thesis – mobile participatory aerosol measurement in citizen science and distributed sensing scenarios – touches these three areas as well.

Research Questions

The questions driving the doctoral research are:

- Which technologies for mobile, distributed measurement of particulate matter exist?
- Which scenarios exist or can be envisioned for this kind of sensing?
- How do the requirements for future end-user measurement of fine dust differ from the ones for current environmental measurement grids?
- Is it possible to create affordable yet still relatively precise sensing systems that ideally integrate closely with personal mobile devices?
- Can many noisy low-cost devices together shape a better understanding of an areas' air pollution that few highly accurate ones?
- Which forms of user interfaces are needed in future participatory environmental sensing scenarios to guide non-expert users to gather high-quality data?
- Which other measures and/or organizational structures and architectures are needed in future distributed sensing to ensure high levels of participation and data quality?

Research Methodology

In order to investigate these questions, a smartphone-based sensing system will be designed (or rather the design will be continued) and implemented to demonstrate the technical feasibility. Also, to investigate the interplay between non-expert users and data quality, a series of user studies (ethnographic/fornmative as well as evaluative/summative) has been conducted to explore the design space of mobile non-expert sensing systems. Overall, contributions are theoretical (scenarios, power requirements, optical system, etc.), empirical (user behavior) as well as practical (citizen science tool development).

Related Research

Since starting the research on low-cost environmental sensing systems, other authors have explored adjacent or partially overlapping fields of research: In 2014, David Holstius published his doctoral dissertation on monitoring particulate matter with commodity hardware [16]. Among other aspects, it explores the capabilities of low-cost dust sensors in measuring $PM2.5$, in a similar way as previous research by the author of this work [4, 3, 6]. The 2015 doctoral thesis of David Hasenfratz deals with large-scale air quality sensing as well, but focuses more on infrastructure- and vehicular-based sensing with low-cost gas sensors and according algorithms for calibration [15]. A clip-on fine dust sensing approach using smartphone cameras was presented in 2014 by Frans Snik et al.: Other than the research of this work's author [1], the *iSPEX* system does not directly measure dust but instead analyzes the spectrum of the daylight under blue sky conditions [20].

Doctoral Thesis: Preliminary Results

Research so far covers several general areas: scenarios for low-cost fine dust sensing, affordable technology, obtaining high-quality data from non-expert users, and incentivization.

Low-Cost Air Quality Sensing with Commodity Sensors
In early work, we showed that commercial off-the-shelf (COTS) dust sensors can be used to collect meaningful data on particulate matter pollution levels [4]. We designed and built a handheld multi-sensor platform equipped with one of these low-cost sensors, the *Envboard* [3]. Subsequently, this platform and the sensor performance was evaluated in the field. Based on data from a one-week co-location measurement with an official state-operated measurement station we showed that with frequent re-calibration, meaningful distributed fine dust measurements are in principle possible at a price at least one order of magnitude lower than that of semi-professional hand-held solutions [6]. In continuation of this work, we compiled scenarios, challenges and approaches for distributed low-cost dust sensing [13]. As a result, we concluded that a holistic approach seems promising, in which current high-quality measurement architectures are augmented by motivated citizens, who operate cheap mobile instrumentation, traverse the city they live in, and feed their readings into a system that centrally combines them with other sources and ensures stable re-calibration as well as high data quality and coverage.

Clip-on Approach for Camera Smartphones
As the sketched participatory sensing scenario requires a certain number of nodes to be feasible, widely available low-cost instrumentation is paramount as an enabler. Ideally, this could e.g. mean fine dust sensors that are integrated into smartphones. Since miniaturization of existing measurement approaches entails some problems (chief among them the reduction of the air volume that is being sampled) we developed an approach which combines the previously shown performance of cheap light-scattering dust sensors and the advantages of the smartphone integration. We retrofitted camera phones with a clip-on module that uses the measurement chamber and light-trap design of an optical dust sensor and replaces the active components (photodiode and LED) with the smartphone's camera and LED flash respectively [1]. The presented design was tested and showed the principle soundness of the approach. However, the sensitivity was not sufficient to measure typical fine dust levels in ambient air at the time.

Dealing with Noise and Non-Expert Users
Before, we had observed the need for relatively frequent calibration of low-cost COTS sensors. Since in the underlying scenarios, non-expert users collect sensor readings

Figure 1: The 3rd generation prototype features a mirror instead of optical fibres and a changed light trap layout [8]. A prototype was designed for a Galaxy S6 smartphone.

to an increasing degree, performing this calibration is intricate and correct execution of the measurement process is not guaranteed. In [9], we presented an elegant signal reconstruction scheme to compensate for dynamic and systematic errors in environmental sensing of phenomena, which can be modeled as Poisson process (e.g. aerosol particles, gases, etc.). The idea is to derive the true signal solely from the Poisson noise of the recorded data, which increases with concentration levels. Our technique is robust to a variety of error sources, including classes of errors caused by low-cost sensors, limited parameter control and untrained, non-expert users. While addressing user errors on a signal-processing level is certainly interesting, there are many ways in which users can negatively affect the quality of the collected data. Further work therefore includes systematically addressing common user errors in the system and especially interaction (see below).

Other open research questions related to user behavior includes proper incentivization of users to achieve sufficient participation. Pursuing this, we recently presented the notion of *Sensified Gaming*, which proposes to embed Participatory Sensing tasks into pervasive games that can support them [11]. Further related research during the doctoral studies includes interactive systems and automatic filtering of reports in participatory sensing systems [5], as well as private distributed sensor calibration [18].

Side Projects and Other Research

Unrelated research conducted during the PhD studies include using a 2DST sheet [10] and audio [19] for usable out-of-band Wi-Fi authentication and studying their usability [12], as well contributions to work on interaction in intelligent environments [2]. Aside from working on concrete research questions, efforts to better integrate research and university teaching at KIT have been made [7].

Ongoing and Future Work

Currently, the clip-on sensor approach for smartphones is further developed [8] and an evaluation both against gold standard equipment in the lab, as well as in an actual participatory sensing setting is pursued. Furthermore, a series of ethnographic studies has been conducted to explore the design space of mobile citizen science sensing tools and applications and to develop a taxonomy of common user errors and technical measures that can be implemented to counteract them. This research is currently undergoing review.

REFERENCES

1. Matthias Budde, Pierre Barbera, Rayan El Masri, Till Riedel, and Michael Beigl. 2013a. Retrofitting Smartphones to be Used as Particulate Matter Dosimeters. In *ISWC'13*.

2. Matthias Budde, Matthias Berning, Christopher Baumgärtner, Florian Kinn, Timo Kopf, Sven Ochs, Frederik Reiche, Till Riedel, and Michael Beigl. 2013b. Point & Control – Interaction in Smart Environments: You Only Click Twice. In *UbiComp '13 Adjunct*.

3. Matthias Budde, Matthias Berning, Mathias Busse, Takashi Miyaki, and Michael Beigl. 2012a. The TECO Envboard: A mobile sensor platform for accurate urban sensing – and more. In *INSS'12*.

4. Matthias Budde, Mathias Busse, and Michael Beigl. 2012b. Investigating the use of commodity dust sensors for the embedded measurement of particulate matter. In *INSS'12*.

5. Matthias Budde, Julio De Melo Borges, Stefan Tomov, Till Riedel, and Michael Beigl. 2014. Leveraging Spatio-temporal Clustering for Participatory Urban Infrastructure Monitoring. In *Urb-IoT'14*.

6. Matthias Budde, Rayan El Masri, Till Riedel, and Michael Beigl. 2013. Enabling Low-Cost Particulate Matter Measurement for Participatory Sensing Scenarios. In *MUM'13*.

7. Matthias Budde, Sarah Grebing, Erik Burger, Max Kramer, Bernhard Beckert, Michael Beigl, and Ralf Reussner. 2016. Praxis der Forschung: Eine Lehrveranstaltung des forschungsnahen Lehrens und Lernens in der Informatik am KIT. *Neues Handbuch Hochschullehre* 74 (2016), 55–79.

8. Matthias Budde, Marcel Köpke, and Michael Beigl. Design of a Light-Scattering Particle Sensor for Citizen Science Air Quality Monitoring with Smartphones: Tradeoffs and Experiences. In *ProScience*, Vol. 3. (Proc. 2nd Int. Conf. Atmospheric Dust), to appear.

9. Matthias Budde, Marcel Köpke, and Michael Beigl. 2015. Robust in-situ data reconstruction from poisson noise for low-cost, mobile, non-expert environmental sensing. In *ISWC'15*.

10. Matthias Budde, Marcel Köpke, Matthias Berning, Till Riedel, and Michael Beigl. 2013. Using a 2DST Waveguide for Usable, Physically Constrained Out-of-band Wi-Fi Authentication. In *UbiComp '13*.

11. Matthias Budde, Rikard Öxler, Michael Beigl, and Jussi Holopainen. 2016. Sensified Gaming – Design Patterns and Game Design Elements for Gameful Environmental Sensing. In *13th International Conference on Advances in Computer Entertainment Technology (ACE2016)*.

12. Matthias Budde, Till Riedel, Marcel Köpke, Matthias Berning, and Michael Beigl. 2014a. A Comparative Study to Evaluate the Usability of Context-Based Wi-Fi Access Mechanisms. In *HCI International 2014*.

13. Matthias Budde, Lin Zhang, and Michael Beigl. 2014b. Distributed, Low-cost Particulate Matter Sensing: Scenarios, Challenges, Approaches. In *ProScience*, Vol. 1. (Proc. 1st Int. Conf. Atmospheric Dust).

14. Jan Duyzer, Dick van den Hout, Peter Zandveld, and Sjoerd van Ratingen. 2015. Representativeness of air quality monitoring networks. *Atmospheric Environment* 104 (2015), 88–101.

15. David Hasenfratz. 2015. *Enabling Large-Scale Urban Air Quality Monitoring with Mobile Sensor Nodes*. Dissertation (Doctor of Sciences). ETH Zürich.

16. David Holstius. 2014. *Monitoring Particulate Matter with Commodity Hardware*. Dissertation (PhD in Environmental Health Sciences). UC Berkeley.

17. J Lelieveld, JS Evans, M Fnais, D Giannadaki, and A Pozzer. 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525, 7569 (2015), 367–371.

18. Jan-Frederic Markert, Matthias Budde, Gregor Schindler, Markus Klug, and Michael Beigl. 2016. Private Rendezvous-based Calibration of Low-Cost Sensors for Participatory Environmental Sensing. In *Urb-IoT'16*.

19. Stephan Sigg, Matthias Budde, Yusheng Ji, and Michael Beigl. 2011. Entropy of Audio Fingerprints for Unobtrusive Device Authentication. In *Modeling and Using Context (CONTEXT 2011)*. 296–299.

20. Frans Snik, Jeroen HH Rietjens, Arnoud Apituley, Hester Volten, Bas Mijling, Antonio Di Noia, Stephanie Heikamp, Ritse C Heinsbroek, Otto P Hasekamp, J Martijn Smit, and others. 2014. Mapping atmospheric aerosols with a citizen science network of smartphone spectropolarimeters. *Geophysical Research Letters* 41, 20 (2014), 7351–7358.