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The effect of ego-motion on environmental monitoring

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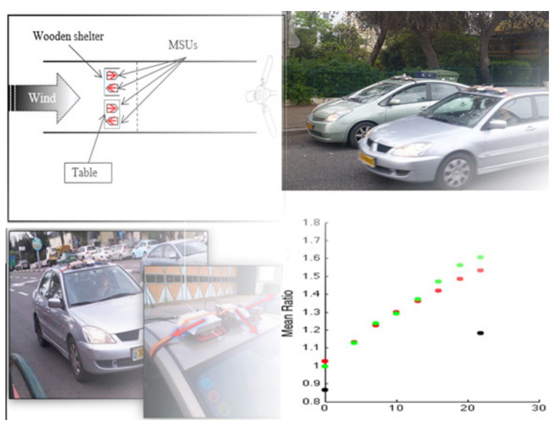
HIGHLIGHTS

- First assessment of the impact of air pollution micro-sensing units' ego-motion on their accuracy in mobile application.
- Evaluation is done through lab experiments and a field campaign.
- Means to cope with ego-motion associated bias are suggested.
- These suggestions present a valuable tool to improve environmental monitoring using MSUs in general or by mobile deployment.

GRAPHICAL ABSTRACT



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ABSTRACT

Air pollution has a proven impact on public health. Currently, pollutant levels are obtained by high-priced, sizeable, stationary Air Quality Monitoring (AQM) stations. Recent developments in sensory and communication technologies have made relatively low-cost, micro-sensing units (MSUs) feasible. Their lower power consumption and small size enable mobile sensing, deploying single or multiple units simultaneously. Recent studies have reported on measurements acquired by mobile MSUs, mounted on cars, bicycles and pedestrians. While these modes of transportation inherently present different velocity and acceleration regimes, the effect of the sensors' varying movement characteristics have not been previously accounted for.

This research assesses the impact of sensor's motion on its functionality through laboratory measurements and a field campaign. The laboratory setup consists of a wind tunnel to assess the effect of air flow on the measurements of nitrogen dioxide and ozone at different velocities in a controlled environment, while the field campaign is based on three cars mounted with MSUs, measuring pollutants and environmental variables at different traveling speeds. In both experimental designs we can regard the MSUs as a moving object in the environment, i.e. having a distinct ego-motion.

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The results show that MSU's behavior is highly affected by variation in speed and sensor placement with respect to direction of movement, mainly due to the physical properties of installed sensors. This strongly suggests that any future design of MSU must account for the speed effect from the design stage all the way through deployment and results analysis. This is the first report examining the influence of airflow variations on MSU's ability to accurately measure pollutant levels.

1. Introduction

Exposure to air pollution is recognized as a contributing factor for various physiological effects and associated risks to public health (International Agency for Research on Cancer (IARC), 2013). The study of air pollution and its exact effects calls for accurate exposure assessments. Air pollution related exposure metrics, typically used in environmental epidemiology studies, are based either on (1) short term surveys using a large number of sensing devices over a short period of time to obtain a high-resolution spatial pollution image (e.g. Crouse et al., 2009); or (2) air pollution measurements acquired from standard Air Quality Monitoring (AQM) stations over extended time periods (e.g. Pope et al., 2002). AQM stations do provide accurate measurements but are large, expensive and require skilled personnel for routine maintenance. Thus, they are few in number and therefore lack the ability to account for the spatial variability of pollution levels in heterogeneous regions (such as urban areas), rendering exposure assessment a very difficult task (Rao et al., 2012).

In an attempt to cope with the isolated nature of the measurements taken by AQM networks, different modeling approaches are used to expand the localized results into high-resolution exposure maps, such as ordinary kriging (Whitworth et al., 2011), or inverse distance weighting and land use regression (Levy et al., 2015). However, these models are more suitable for long-term, chronic exposure studies, due to their aggregative nature, and the possible loss of short-term localized measurements needed for more acute exposure incidents (Karr et al., 2009; Brauer, 2010). A better solution may be to use a denser array of sensing nodes, and thus create a better interpolation, closer to the real-life pollution dispersion scenario (Kanaroglou et al., 2005).

Recent developments in sensory and communication technologies have made the development of small, portable and relatively low-cost sensing units possible. These micro sensing units (MSUs) can be used as a set of individual nodes, interconnected to construct a Wireless Distributed Environmental Sensor Network (WDESN), aimed at measuring air pollution as one unit, gathering high-resolution spatial and temporal data.

Initial studies testing the feasibility of such MSUs in pre-field and field trials showed that these units indeed capture air pollution spatio-temporal variations. Their downfall, however, is their relatively low accuracy compared to AQMs or other benchmark devices (Lee and Lee, 2001; Becker et al., 2000; Mead et al., 2013; Williams et al., 2013; Molchanov et al., 2015). Studies that evaluated MSUs' capabilities in a controlled lab environment emphasized the need for a calibration process (Lee and Lee, 2001; Becker et al., 2000). Field deployments of low-cost air quality sensor networks measuring ambient O_3 levels by metal-oxide micro-sensors (Williams et al., 2013) and CO, NO and NO_2 by electro-chemical (Mead et al., 2013) or metal-oxide (Piedrahita et al., 2014) probes proposed calibration processes that are applicable to a controlled lab environment but fall short in comparison to data collected at a collocated standard AQM station, even after an initial field calibration had been applied (Williams et al., 2013). Molchanov et al. presented an in-field calibration process (Molchanov et al., 2015), however their calibration procedure strongly relies on the sensors being stationary. Tsujita et al. (2005) suggested a field calibration approach where the metal-oxide NO_2 sensor baseline is adjusted to the average value of four surrounding AQM stations during time periods in which the NO_2 concentrations are low ($\ll$10 ppb) and homogeneous meteorological conditions apply. Yet, the method is designed to work with low NO_2 concentrations whereas the MSUs' NO_2 detection limit is typically at or above such low concentrations (10 ppb). This renders the method inapplicable. Spinelle et al. suggested a protocol for evaluation and calibration of low-cost gas sensors (Spinelle et al., 2013), reemphasizing the need to account for the wind conditions that the sensors are expected to work under. Thus, it was acknowledged that wind does have an effect on the measurements, however their protocol does not quantify the nature of this effect.

The small size and low power-consumption of MSUs also allow for mobile measurements. Placing these units on mobile platforms enables the coverage of a wider area with a smaller number of units, while keeping the spatial and temporal resolution high. Few recent studies showed the possibility and advantages of such use, and the relatively easy adaptation of such MSUs to function as mobile sensing units, with the addition of GPS (Al Ali et al., 2010; Devarakonda et al., 2013). These studies based their design on the assumption that mobility itself has no effect on the sensors' functionality. An attempt to consider this issue was done by Levy et al. (2014) in a mobile field-experiment in an urban environment in Montreal, Canada. Their study showed that a correction has to be applied to particulate matter measurements taken while moving, due to the varying flow rate effect on the collection efficiency of the instrument. However, they didn't regard gas-phase pollutants in this correction since the gas measuring instruments had a regulated flow rate, i.e., active sampling, and the sensing apparatus was standard AQM measurement equipment, rather than low-cost, diffusion-only-based gas sensors, i.e. passive sampling.

The gas sensors installed on the Elm™ units used in this study are passive metal-oxide sensors (MOS). When the sensor faces the winds' inflow direction, an increased flow is created on the sensors' face, affecting its behavior (Honicky, 2011). The effect is due to the metal-oxide sensors having a preliminary heating phase of ~300 °C designed to evaporate the sampled air and initiate the proper reaction conditions on the MOS surface. A shift in the surface temperature caused by the increased air flow can divert the sensor from its calibrated status and alter its output. Wang et al. (2010) showed that metal-oxide gas sensors are sensitive both to ambient temperature as well as relative humidity (RH), as later shown, two variables that have been found to be affected by the traveling speed.

As such, this paper focuses on the use of MSUs for urban air-quality monitoring, by means of mobile deployment. The aim was to test the validity of measurements made by sensors traveling at different velocities, through comparing mobile and stationary measurements taken at the same time and location. To this end, laboratory work and a field campaign were performed.

2. Materials and methods

2.1. Sensing equipment

All air quality measurements were taken using Elm™ MSUs (PerkinElmer LTD, USA (PerkinElmer)). Each Elm™ unit is encased in a relatively-small weather-resistant metallic case (sizing 26 × 17 × 7 cm, L W H), and consists of two semiconducting MOS (measuring O_3 and NO_2). Each sensor has an 18 mm inlet which is significantly larger than the sensors' sensing face, electret microphone for noise level measurements and dual semiconductor temperature and RH sensor (See Table S1, in the supporting information, for detailed sensor