Investigating the Use of Commodity Dust Sensors for the Embedded Measurement of Particulate Matter

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Abstract—**A variety of studies in the past decades have shown that fine particulate matter can be a serious health hazard, contributing to respiratory and cardiovascular disease. Due to this, more and more regulations defining certain permissible concentration limits have been set by governments around the world. However, current standard measurement equipment is large, expensive and sparsely deployed. Additionally, both the exposure to hazardous conditions and the susceptibility to negative health effects vary from person to person. As a result, we see the need for fine-grained, mobile and distributed measurements, e.g. to identify hot spots or monitor people at risk. Our research investigates the feasibility of particulate matter measurements using cheap, commodity dust sensors which are small enough to be incorporated into mobile devices. This paper first discusses application scenarios which would benefit from inexpensive methods to assess the particulate matter load. Subsequently, commercial-off-the-shelf (COTS) sensors are compared and their general suitability for the application scenarios is examined. Finally, an experimental setup for the evaluation of one of the sensors is presented along with preliminary results.**

I. Introduction

The effects of particulate matter on human health have been extensively studied in the past decades. The results are that fine dust can be a serious health hazard, contributing to or even causing respiratory and cardiovascular diseases. Due to this, more and more regulations regarding the reduction of man-made particulate matter have been set by governments around the world. Such standards usually define limits for particle matter concentrations which may not be exceeded. Today, there are usually several of such maximum permissible values for different particle size classes and observation periods. Different classes of particulate matter have successively been defined by the *U.S. Environmental Protection Agency (EPA)*. The most important ones are PM_{10} and $PM_{2.5}$. These are commonly assumed to be the total mass of particles with aerodynamic diameter less than 10 (respectively 2.5) µm. This is not 100% correct. PM_{10} is actually defined as “particulate matter which passes through a size-selective inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter” [1]. [1]

[1]However, the exact measurement of particulate matter according to this definition is not trivial. [2] discusses some issues regarding the precision.

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TABLE I
Maximum permissible values for particulate matter as suggested by the WHO [4], the EU [1], and EPA (USA) [5].

	Class	Maximum permitted	Tolerated exceedings
WHO	$PM_{2.5}$	10 $\frac{\mu g}{m^3}$ (annual mean)	–
		25 $\frac{\mu g}{m^3}$ (24-hour mean)	–
	PM_{10}	20 $\frac{\mu g}{m^3}$ (annual mean)	–
		50 $\frac{\mu g}{m^3}$ (24-hour mean)	–
EU	PM_{10}	40 $\frac{\mu g}{m^3}$ (annual mean)	
		50 $\frac{\mu g}{m^3}$ (24-hour mean)	max. 35 days per year
USA	$PM_{2.5}$	15 $\frac{\mu g}{m^3}$ (annual mean)	
		35 $\frac{\mu g}{m^3}$ (24-hour mean)	
	PM_{10}	150 $\frac{\mu g}{m^3}$ (24-hour mean)	max. 1 day in 3 years

Table I shows different limits for the two classes (PM_{10} and $PM_{2.5}$), as defined by the World Health Organization (WHO), the European Commission, and the EPA. While the values provided by the WHO are mere recommendations, the limits of the EU as well as the EPA are supposed to be binding. However, violations of these standards are tolerated to a certain extent (see Table I), but also these tolerances are exceeded frequently. In Germany for example, 54 of 354 listed measuring stations exceeded the maximum permissible values on more than 35 days in the year 2011. The station with the largest number of violations exceeded the threshold on 79 days, more than double of what is allowed. The year before that, in 2010, even more stations (63) exceeded the 35-day-limit [3]. In addition to the slack enforcement of the thresholds, the denseness of monitoring networks could be improved: Often, only a single measurement station is used to determine the particulate matter load for a large urban area. Also, both the individual exposure to potentially hazardous conditions as well as the susceptibility to negative health effects vary from person to person [4]. As a result, we see the need for more fine-grained, distributed and/or mobile measurements, e.g in order to identify hot spots or monitor people at risk.

In this work, we focus on applications that emphasize the *mobile* and/or *distributed* measurement of fine dust. Standard stationary measurement equipment usually uses gravimetric measurement to determine the particulate matter concentration. Such stations are typically large and expensive and thus not suitable for the described scenarios. In order to be practical for truly mobile, unobtrusive ways to measure particulate matter, the measurement equipment should ideally be embeddable into mobile phones. However, since the available sensors are currently still too large for this, the next best thing would be the incorporation into small handheld sensor devices that can be docked to, or wirelessly communicate with, a smartphone or handheld computer.

This is why in this paper we investigate the feasibility of particulate matter measurements using cheap, commodity dust sensors, that are low-power and small enough to be incorporated into mobile devices. The remainder of this section presents some application scenarios which could benefit from the use of such sensors for the measurement of particulate matter. Classical applications for these sensors, such as air quality control (e.g. in air purifiers or air monitors) or stationary smoke alarms, are not considered here.

1) Urban/Participatory Sensing: Urban City Sensing approaches have been proposed in the past to create noise pollution maps of urban areas [6], [7]. Similar to the creation of such maps, mobile particulate matter measurements could be used in order to map hazardous areas and mark pollution hot spots. While it is expected that the accuracy using simple devices is lower than that of expensive stationary equipment, mobile measurements would allow for a much higher spatial and temporal resolution. Also, cheap measurement equipment could e.g. allow developing countries to erect inexpensive measurement grids for air quality monitoring purposes.

2) Personal/Life Log: Similar to the kind of devices which people carry in nuclear facilities in order to measure and record their occupational exposure to radioactivity, mobile dust sensors could be applied in potentially hazardous environments such as coal mines or woodworking shops. However, since such scenarios are highly health relevant, a sufficient accuracy needs to be reached.

3) Personal Information: Since the effects of both long-term and short-term exposure may vary greatly between individuals, any standard or guideline cannot completely protect each individual [4]. People may want to be sure on an informal level that they are not overexposed to high concentrations of particulate matter. This application scenario is similar to the one that was described before. However, the focus lies more on coarse information rather than precise measurements here, much as it is the case with cheap commodity UV-meters or thermometers anyone can buy for a few dollars.

II. Related Work

Not a lot of research has been done that specifically addresses embedded mobile measurement of particulate matter, neither in general, nor specifically for participatory sensing applications. Mobile-phone-based urban sensing is done in the UCLA project *peir* (*personal environmental impact report*) [8], [9]. This project aims at sharing "how you impact the environment and how the environment impacts you". Among other things, the smog exposure ($PM_{2.5}$ particulate exposure) and sensitive site impact ($PM_{2.5}$ particulate impact on sensitive sites such as schools and hospitals) are included in the logged data. However, the exposure is not directly measured, but calculated based on a variety of parameters such as the closeness to known hazardous conditions or areas, as for example a freeway.

In [10], a distributed network of nodes was introduced, which was made out of smart sensors in order to monitor dust, particularly in urban areas. The nodes used the *Sharp GP2Y1010* optical dust sensor. Several measurements were made and the accuracy was analyzed against that of a gravimetric measuring device. However, the paper focused on network aspects and the measurement of dust in general, not so much on particulate matter measurements. In addition to that, the paper does not contain detailed information on the evaluation, just that the results were "calculated based on 20 measurements". Unfortunately, there is no information on the sampling frequencies or the duration of those measurements.

III. Experiments

For our experiments, we took a series of measurements with cheap commodity dust sensors in order to investigate the general suitability of such sensors for the measurement of particulate matter. We did not expect the results to be perfect in terms of accuracy, since we did not use any filters to keep our samples clean from coarse dust. Our goal was to observe and quantify the margin of error between our cheap sensors and a calibrated reference device and to assess for which kind of application cheap COTS dust sensors can be used, if any.

1) Sensor selection: While there is a variety of stationary and handheld dust monitors commercially available, there are not many of small sensors to choose from (see Table II): The Japanese company *Shinyei* [11] carries several relatively sophisticated particle sensing modules in the upper price range. Their availability is fair, since Shinyei's sensor portfolio is only available through the company itself as well as few selected distributors. Two Korean sensors – the *SYhitech DSM501* and the *NIDS PS02C-PWM* – are both very close to the design of the *Shinyei PPD42*. However, while information on the *NIDS* sensors is available online [16], [17], our

TABLE II
Specs of candidate dust sensors according to the data sheets.

Sensor		**Size** (mm^3)	**Range**	**Power**	**Retail Price**
Sharp GP2Y1010	[12]	46×30×18	0 – 0.5 $\frac{mg}{m^3}$	0.1 W	~ 10 $
SYhitech DSM501	[13]	59×45×20	0 – 1.4 $\frac{mg}{m^3}$	0.45 W	~ 10 $
Shinyei PPD42NS	[14]	59×45×22	0 – 800,000 $\frac{pcs}{ft^3}$	0.45 W	~ 200 $
Shinyei PPD60PV	[11]	88×60×22	0 – 2,000,000 $\frac{pcs}{ft^3}$	0.7 W	~ 420 $
Shinyei AES-1	[15]	90×90×23	300 – 300,000 $\frac{pcs}{ft^3}$	3.6 W	~ 1,100 $
NIDS PSX-01E	[16]	59×45×20	0 – 2.0 $\frac{mg}{m^3}$	0.15 W	*n/a*
NIDS PS02C-PWM	[17]	*n/a*	0 – 2.0 $\frac{mg}{m^3}$	*n/a*	*n/a*

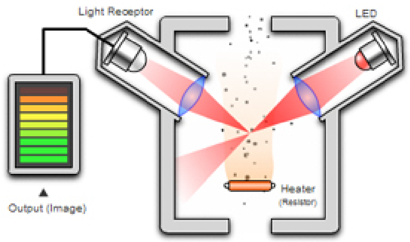

Fig. 1. Many of the sensors use a heating resistor to create an updraft. [11] This limits the possible operation conditions.

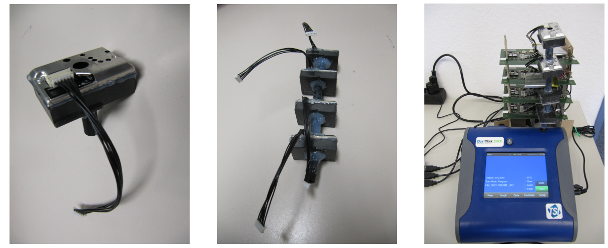

Fig. 2. One of the Sharp GP2Y1010 optical dust sensors with added hose on the air outlet and four sensors bound together, forming a stack.

attempts to receive a quote for them remained unanswered. The *SYhitech* sensor also lacks a distributor in Europe, but is available through a Chinese distributor as *Apollo DSM501*. The sensor that has by far the best availability is the *Sharp GP2Y1010* optical dust sensor. It is mostly used in air quality equipment, such as air purifiers, and can easily be obtained in large quantities from various distributors around the world.

All of the COTS dust sensors we found are principally small enough to be incorporated into a handheld device, though the larger ones could make such a device cumbersome. The sensors are also all based on the same operation principle: A light beam is emitted into a measurement chamber. When dust is present, the light is refracted by particles and the amount of scattered light is detected. All sensors except the *Sharp GP2Y1010* (and possibly the *NIDS PSX-01E*) additionally use a heating resistor to create an updraft (see Figure 1). For the applications outlined above, the use of such a heating has several drawbacks: First, since a current is needed to heat the resistor, the power consumption is generally higher. Second, the response time is higher, since it takes some time – usually around 30 seconds – until the resistor is heated up. Third and most important, the heating imposes strict orientation restrictions during operation. This practically prevents the use for any applications in which the device's orientation can not be controlled. Finally, heated sensors can not be directly ventilated, because this would influence the heating. This may restrict the use in multi-sensor devices together with other environmental sensors that need an airflow.

We opted for the *Sharp GP2Y1010* optical dust sensor, since it best fits our scenarios' general requirements: cheap, small, low-power, and easily available for our tests.

2) Setup: The configuration of our experiments was made up of several *GP2Y1010* dust sensors, single-board AVR-based platforms for sampling [18] and a reference measurement device. All sensors were used as they were delivered, using their factory calibration. As only alteration, a small piece of hose was glued to the sensors so that they could be attached to the reference measurement device. Four of these modified sensors were then bound together in order to be able to sample the same airflow simultaneously (see Figure 2). We prepared two stacks of four sensors each for our measurements. As reference device, the *DustTrak DRX 8533 Aerosol Monitor* from *TSI* was used. This laser photometer is commercially available for ~ 9,000 $ and can detect particulate matter in a range from $1\frac{\mu g}{m^3}$ to $150\frac{mg}{m^3}$. It displays and logs size segregated mass fractions for PM_1, $PM_{2.5}$, *Respirable Particles (Resp)*, PM_{10}, and *Total*. We used a factory-new device that was freshly calibrated by a specialized company. The depicted sensor stacks were then connected to the air inlet of the *DustTrak*, so that all devices measured the exact same air stream. The described setup was placed on a desk in our research facility, close to a doorway. All measurements were taken at that location.

3) Measurements: Before measuring, we calculated a linear calibration-offset for each of the sensors, since the *GP2Y1010* sensors are not shipped exactly calibrated and two devices do not show the exact same measurements. In order to determine the offset values, we took a ten-minute measurement with each sensor and the *TSI* reference device. We found that each of the sensors had a quite different deviation, the extremest ones reaching almost $\pm 100\frac{\mu g}{m^3}$. For the actual measurements that followed, we conducted two 12-hour sampling sessions with a stack of four of the COTS dust sensors each. The sensors were all sampled at 100 Hz. Our reference device, the *DustTrak*, can only be sampled at frequencies up to 1 Hz. Due to this, we averaged the dust sensor measurements to fit this lower sampling interval, giving us a total of ~500,000 data points. Figure 3 shows the sample data from one of the dust sensors and the reference aerosol monitor.

In order to quantify the deviation of the measurements of the COTS sensors from the reference device, we computed the *Mean Absolute Error* ($MAE = \frac{1}{n}\sum_{i=1}^{n}|f_i - y_i|$) between the measurement of the *DustTrak* aerosol monitor and the sampled dust sensors. We then examined how the MAE changes when we compare averages of different interval lengths. The averages were computed for interval lengths from ten seconds up to 30 minutes. Figure 4 shows our first results. The graph illustrates that for averaging intervals larger than approximately five minutes, meaningful measurements begin to become possible. For these averaging intervals, the mean absolute error drops below 20 $\frac{\mu g}{m^3}$. When comparing these numbers to the thresholds shown in Table I, it seems that at least coarse statements regarding the particulate load are possible with very simple dust sensors.

IV. Conclusion and Future Work

In this paper, we motivated and examined the use of low-cost, low-power particulate matter sensors for mobile handheld

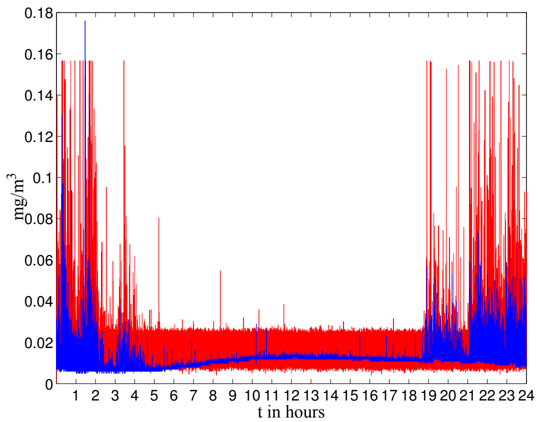

Fig. 3. Data from one of the dust sensors (red curve) and the reference device (blue curve) in $\frac{mg}{m^3}$.

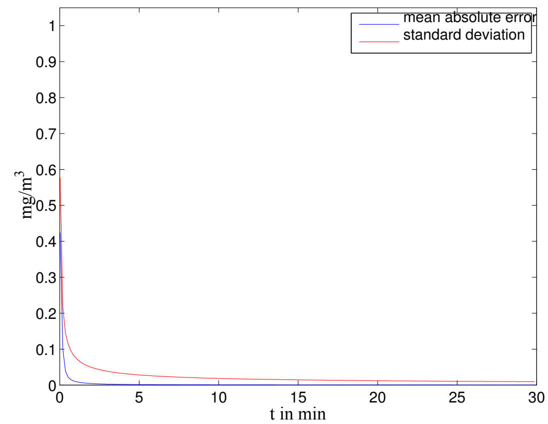

Fig. 4. Mean Absolute Error and Standard Deviation over different averaging intervals.

measurements. Several application scenarios were discussed and various cheap commercial-off-the-shelf (COTS) dust sensors were studied with respect to their general suitability for the outlined scenarios. Finally, one of the sensors was selected and used to make some experiments aiming at assessing in how far COTS sensors are suitable for the measurement of particulate matter. We argue that there are definitely several interesting application scenarios that would benefit from inexpensive sensors that can measure the particulate load. These include *Participatory Sensing* applications, such as creating maps pointing out pollution hot spots or the erection of inexpensive measurement grids, as well as personal appliances, e.g. exposure logs or warning systems. At the same time, only few of the currently available COTS sensors that are available in the market fit the general requirements to be incorporated into mobile handheld measurement devices. With respect to the question of whether or not the accuracy of the COTS sensors is sufficient for fine dust measurements, there is no definite answer: While we found that the measurements of the simple sharp sensor generally correspond with the particulate load which our gauged reference aerosol monitor measured, the margin of error can be considered to be inadequate for some of the application scenarios. However, when observing longer intervals, the advantages (higher spatial and temporal resolution, low price, low-power, relatively compact size) may outweigh the accuracy deficiencies.

In future work, the preliminary results presented in this paper will be deepened. This will include the investigation of methods to automatically calibrate the sensors, since we learned that this compensation is crucial as a basis for meaningful measurements. Other promising steps may be the analysis of the sensor's noise characteristics in order to select appropriate filters for preprocessing or the use of distributed measurements to increase the sensing accuracy. In parallel, we will experiment with modifications of the sensors, such as varying the light intensity or spectra of the diode, applying HEPA filters and/or impactors and studying the effects of further miniaturization. We hope to learn from these future investigations, for which type of application optical COTS dust sensors are suitable, and for which types the need to explore new measurement approaches from other fields – such as e.g. capacitive or microfluidic detection – should be explored.

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