AirSense: A Portable Context-sensing Device for Personal Air Quality Monitoring

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ABSTRACT

Health effects attributed to air pollution, especially ambient fine particulate matter (**$PM_{2.5}$**), become a global issue. The central environment monitoring networks provide limited spatial coverage and no contextual information. However, there is no solution to take contextual information, such as environmental and user behavioral factors, into account, which is highly associated to the variability of air quality level and the complex relationship between air quality and human activities. In this paper, we design, implement, and evaluate a new context-sensing device for personal air quality monitoring, namely AirSense. AirSense is a portable and cost-effective platform, which is equipped with a dust sensor, a global position system (GPS) sensor, a temperature and humidity sensor, and an accelerometer sensor. The development of such a user-centered and geographical-information integrated platform enables us to collect fine-grained air quality along with contextual information. We evaluate the platform across a set of focused settings, such as the indoor vs outdoor, walking vs in-vehicle, moving vs stationary, and an environment with various levels of dust. Meanwhile, a user study is conducted to verify that AirSense is capatable of performing the ambient air quality monitoring in daily life. We also discuss several other applications with the new context-sensing platform.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

Keywords

Personal Air Quality Monitoring, Context Sensing, Evaluation.

1. INTRODUCTION

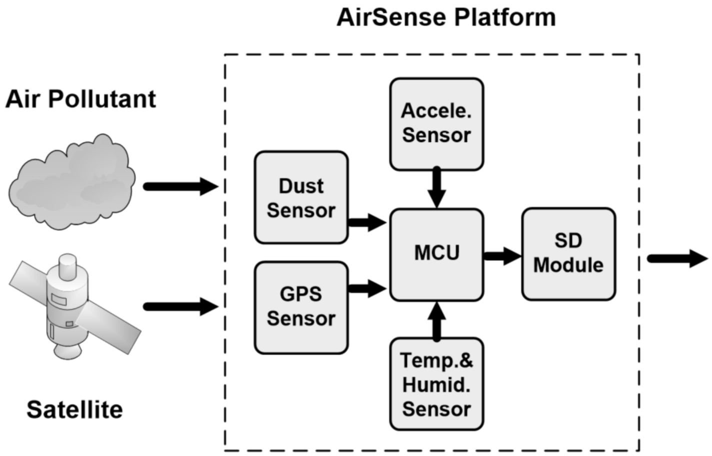
A number of scientific studies have demonstrated the adverse health effects of deteriorated air quality. Air pollution affects various aspects of human health, including the respiratory, cardiovascular, cardiopulmonary and reproductive systems [15]. The World Health Organization (WHO) estimates that three million premature deaths were caused by particulate air pollution worldwide in 2012 [2]. Some recent researches showed that the inhalation of air pollutant has negative influence on human brain activity [5]. Air pollution has become a global challenge and has received widespread concerns. Especially, the $PM_{2.5}$ has gained increasing attention [14] [16].

To date, several commercial products to monitor the air quality are available. Thermo Scientific developed several particulate monitoring stations, such as 1405-F continuous ambient air monitor [17], which can provide accurate ambient air quality monitoring. Dylos DC1100 [7] is a particle counter, which can perform indoor air quality monitoring. The measured particle number counts (PNCs) can be converted into $PM_{2.5}$ mass concentration [15]. Recent researchers proposed several ambient air quality measurement systems. A client-cloud system called AirCloud was designed with two Internet-based $PM_{2.5}$ monitors, AQM and miniAQM at the front-end. The measurements are analysed through an air-quality analytic engine on the cloud-side [6]. Holstius *et al.* [9] developed a portable and affordable nephelometric data acquisition (PANDA) system based on the Shinyei PPD42NS, an off-the-shelf optical sensor. However, these existing platforms are expensive and not necessarily portable (*e.g.* [17]). Furthermore, most of them lack functions to measure contextual information such as geographical information(*e.g.* [9]), temperature, and humidity(*e.g.* [17] [7] [6]).

As evidenced in previous studies [15] [16] [19] [18], contextual information associated with air quality plays an important role to better understand personal exposure to air pollutant. When individuals move from one context scene to another, the air pollution in corresponding context is various in time and space [18] [15]. The personal activity patterns can improve our understanding of variability of personal particulate matter exposure. Because of this complex relationship, the approaches to investigate individual particulate matter exposure often integrate contextual information such as environmental and user behavioral factors. The contextual information, such as geographical information, user activities, temperature, and humidity, allows us to estimate the association between the people's particulate matter exposure level and health outcome. Therefore, the development of context-sensing air quality platform is highly demanded to enable the user-centered services, which enables to esti-

MobileHealth'15, June 22, 2015, Hangzhou, China.

http://dx.doi.org/10.1145/2757290.2757293.



(a)

Personal Air Quality Profile

Time Stamp		Lat.	N/S	Lon.	W/E	X	Y	Z	PM2.5	Temp.	Humid.
12_3_15	22:54:04	4300.1	N	7847.16	W	48	14	-12	9.57	3.15	27.69
12_3_15	22:54:07	4300.1	N	7847.16	W	18	-62	-5	11.23	3.1	27.83
12_3_15	22:54:10	4300.09	N	7847.16	W	32	-7	-17	22.85	3.01	27.97
12_3_15	22:54:12	4300.09	N	7847.16	W	41	-13	-35	11.23	2.9	27.97
12_3_15	22:54:16	4300.09	N	7847.16	W	31	0	-39	18.7	2.89	28.04
12_3_15	22:54:19	4300.09	N	7847.16	W	59	8	-55	10.4	2.85	28.12
12_3_15	22:54:22	4300.09	N	7847.16	W	29	6	-13	27.83	2.8	28.19
12_3_15	22:54:24	4300.09	N	7847.15	W	33	-11	-29	18.7	2.77	28.47
12_3_15	22:54:28	4300.09	N	7847.15	W	38	-12	-35	12.89	2.76	29.04
12_3_15	22:54:31	4300.09	N	7847.15	W	32	-6	-29	18.7	2.82	29.54
12_3_15	22:54:34	4300.09	N	7847.15	W	48	-4	-23	20.36	2.78	29.97
12_3_15	22:54:36	4300.09	N	7847.15	W	38	-25	-14	7.91	2.78	30.25
12_3_15	22:54:40	4300.09	N	7847.15	W	10	-17	271	20.36	2.78	30.32
12_3_15	22:54:43	4300.09	N	7847.15	W	29	-6	-35	23.68	2.82	30.47
12_3_15	22:54:46	4300.09	N	7847.15	W	40	-6	-18	10.4	2.77	30.47
12_3_15	22:54:48	4300.09	N	7847.15	W	41	-17	320	14.55	2.78	30.47
12_3_15	22:54:52	4300.09	N	7847.15	W	34	1	-3	21.19	2.86	30.64

(b)

Figure 1: The block diagram of AirSense, which consists of five sensor modules: the GPS sensor, dust sensor, accelerometer sensor, temperature & humidity sensor, and SD socket. The output of AirSense is the personal air quality profile in a specific format.

mate the associations between user activities and air quality levels and minimize the adverse effects on human health.

In this work, we develop a unified portable context-sensing platform for personal air quality monitoring, namely AirSense. AirSense is a cost-effective device integrated with multiple sensors including a dust sensor, a GPS sensor, a temperature and humidity sensor, and an accelerometer sensor. All the sensors are compacted on a printed circuit board (PCB) with a small form factor. This portable device provides fine-grained spatiotemporal air quality measurements and the contextual information, including geographical information, user activities, temperature, and humidity, of the activity space.

The remaining of this paper is organized as follows: Section 2 describes the related work of air quality monitoring. Section 3 introduces the AirSense platform design. The evaluation of the AirSense platform in multiple settings is described in Section 4. Section 5 presents a continuous monitoring using the AirSense platform. Section 6 discusses several potential applications for this platform. Finally, Section 7 concludes our paper and the future work.

2. RELATED WORK

Many research studies have been conducted in this area with different measurement scenes, where the contextual information are various. Wheeler *et al*. [19] continuously measured both indoor and outdoor concentrations of air pollutant over 5 days in winter and summer. Ryswyk *et al*. [18] characterized the effect of personal activity patterns on asthmatic children's personal $PM_{2.5}$ exposure. Mölter *et al*. [10] developed a new micro-environmental exposure model (MEEM) to combine time-activity data with outdoor and indoor air pollutant. Sullivan *et al*. [16] quantified spatiotemporal variability of fine particle concentrations using a combination of the fixed and mobile air pollutant measurements. These studies indicate that the contextual information, such as location, human activities, and environmental factors, are highly related to the variation of air quality level.

3. PLATFORM DESIGN

Our proposed AirSense platform is a unified portable context-sensing platform for personal air quality monitoring. Fig. 1(a) shows the prototype of the AirSense architecture. The platform consists of several sensor modules: a dust sensor, which monitors the air quality; a GPS sensor, which records the geographical location information; a temperature and humidity sensor, which measures the temperature and humidity in the contextual environment; and an accelerometer sensor, which is used for user activities detection. The GPS location information, acceleration information, temperature, and humidity, can work together to recognize various contextual scenes. To enhance its portability, AirSense assembled these sensors into a compact PCB. The platform can measure the personal air quality profile that is stored in a secure digital card (SD card). The personal profile is organized in a specific format as shown in Fig. 1(b). The time stamp indicates the timing of measurement. The geographical information such as latitude (*Lat.* in the profile) and longitude (*Lon.* in the profile) are arranged after the time stamp, being followed by the accelerometer X-axis, Y-axis, and Z-axis count (X, Y, Z in the profile, respectively). The environmental information including dust particles concentration ($PM_{2.5}$ in the profile), temperature ($Temp.$ in the profile), and humidity ($Humid.$ in the profile) are recorded as shown at the end of the profile.

Dust Sensor.

The dust sensor monitors the ambient air quality in the contextual scenes. We select the Sharp $GP2Y1010AU0F$ because of its cost-effective and compacted features. This sensor is an optical sensing based dust sensor. To be specific, a LED emits the light beam in the measurement cavity, and a phototransistor captures the reflected light. When the dust enters the measurement cavity and scatters the reflected light, the voltage over the phototransistor changes because of the blocked light by the dust. The sensitivity of this sensor is $0.5V/0.1mg/m_3$ with the low-power consumption (20mA max, 11mA typical) and compact size (46.0 x 30.0 x 17.6 mm) [13].

GPS Sensor.

The AirSense platform employs a GPS sensor to track user's location. The geographical information is critical for the particle concentration analysis and contextual scenes recognition for the user-centered air quality monitoring system. The GPS sensor is built on the MTK3339 chipset. By tracking up to 22 satellites on 66 channels, the GPS sensor [4] provides precise geographical information, whose error is typically less than 3 meters. With the built in antenna and the high-sensitivity characteristic (-165 dB), the receiver can work in a reduced size (15mm x 15mm x 4mm) with low power consumption (20 mA during navigation) [4].

Accelerometer Sensor.

The accelerometer sensor can detect the users' activity. When the user is moving, the X-axis, Y-axis, and Z-axis count of accelerometer change correspondingly. When the user is stationary, on the other hand, the three axies count are unchanged. The ADXL345 chip is selected in our platform, since it is a high-resolution 3-axis accelerometer with the ultra low power consumption, only 40 uA in the measurement mode [3]. Moreover, due to its small form factor (1.5cm X 1.5cm), the ADXL345 can be mounted on the platform flexibly.

Temperature and Humidity Sensor.

The low-cost temperature and humidity module, SHT15, is used to collect the information on temperature and humidity, because the measurements in indoor and outdoor environment are substantially different. The SHT15, which is characterized by the high precision and long stability, can output the temperature and humidity data directly. The range of the measured temperature is between -20 to 100 Celsius degree. The range of the relative humidity is from 0 to 90 percentage [12].

These environmental sensors are compacted on a PCB board with a micro-controller. All components are placed into a 10 x 10 x 5 cm package, as shown in Fig. 2.

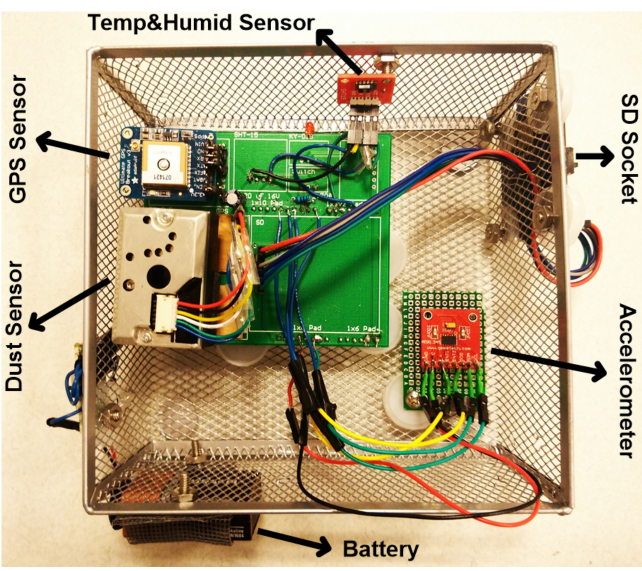


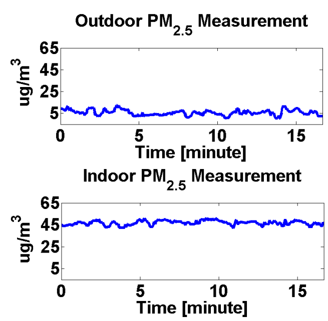
Figure 2: The integrated AirSense platform is compacted into a 10 x 10 x 5 cm package to enhance the portable feature.

4. FOCAL PERFORMANCE EVALUATION

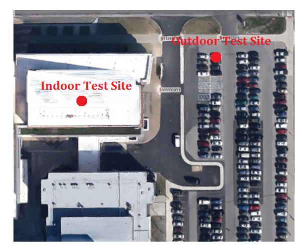
In this section, we evaluate the AirSense across different contextual scenes in real life, including the indoor vs outdoor, moving vs stationary, walking vs in-vehicle, and an environment with various levels of dust. These scenes are the most common environments that people encounter in daily life. In the experiments, AirSense platform not only measures the ambient air quality but also to collects the contextual information such as time, location, temperature, and humidity for each scene, which can be used for the scene recognition. The sets of experiment demonstrate the effectiveness and stability of the AirSense platform.

4.1 Indoor vs Outdoor

In U.S., people on average spend approximately 90 percent of time indoor [1], such as home, office, classroom, and other rooms. The Standard *et. al* [14] showed that indoor air pollutant particle levels are higher than those of outdoor. Similar to their study, we also investigated the differences in $PM_{2.5}$ levels in indoor and outdoor settings. We selected 340 Davis Hall, University at Buffalo as the indoor test site, while a parking lot near the building as the outdoor test site.



(a) The $PM_{2.5}$ measurement for indoor and outdoor environment.



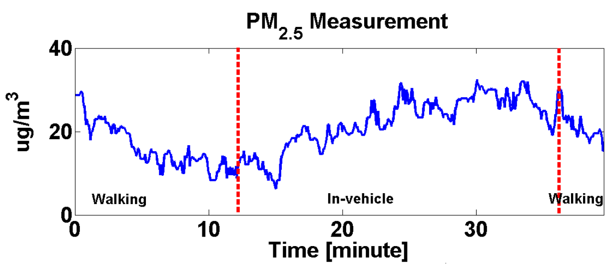
(b) The test sites for the indoor test and outdoor test.

Figure 3: The $PM_{2.5}$ measurement and test location for the indoor vs outdoor test.

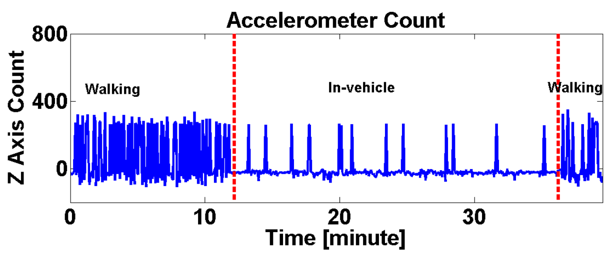
The Fig. 3(a) summarized the testing results. The mean value of indoor and outdoor $PM_{2.5}$ is 46.64 ug/m^3 and 5.61 ug/m^3, with the standard deviation (SD) of 2.01 and of 2.51, respectively. The dust level in the indoor is higher than that of outdoor, and we suspected that it is because the indoor environment is a closed area. Moreover, the human activities and building equipments inside the building produce the air pollutant, causing the high concentration of dust particles. The difference in the SD indicates the indoor air quality is more stable than outdoor site, which might be due to the diverse weather conditions outdoor. Moreover, we also notice that the temperature and relative humidity are various for the indoor and outdoor environment during the recording period. The temperature in indoor environment is higher than that of outdoor but the relative humidity is reverse.

4.2 Walking vs In-vehicle

Air quality in-vehicle is often very higher, compared to other outdoor or indoor micro-environments [8]. We investigate the air quality with different transportation scenarios using the proposed unified portable platform, where the time stamp is obtained form the GPS signal. The test was performed during 6:00 pm to 7:00 pm. The user walks from a local cafeteria to a parking lot, then enters a vehicle. Fig. 4(a) shows the air quality monitoring results. Specifically, the air pollutant mean value outside the car is 17.12 ug/m^3 with SD of 5.79. The mean value of air pollutant inside the car is $21.40 ug/m^3$ with SD of 6.59. The air pollutant outside the car is consistently low. The air pollutant inside the car cabin stays unchanged at first, then increases slowly. It is because the pollutant from the car and human activities accumulates inside car cabin during the driving. The car cabin is a closed room and the dust concentration is not affected by the nature factors such as wind and rain. Therefore, the car cabin has a higher dust level. Fig. 4(b) illusrates the Z-axis count from the accelerometer sensor. When the subject is walking, the Z axis value from accelerometer sensor changes dramatically. Then, when subject drives the car, the accelerometer's Z-axis value changes occasionally because of the car's acceleration and deceleration.



(a) The $PM_{2.5}$ measurement when the user is walking and in-vehicle.



(b) The corresponding Z-axis count from the accelerometer when user is walking and in-vehicle.

Figure 4: The $PM_{2.5}$ measurement and accelerometer information in the walking vs in-vehicle scenes.

4.3 Moving vs Stationary

As most of us go to the public places such as cafe, restaurant, shopping malls, we monitored the air quality in the public places. In this test, the user, who carries the platform, walks from the office to a cafe and stays there for about 10 minutes and comes to a cafeteria and stays there for 15 minutes. Finally, he returns to the office. The test routine is shown in Fig. 5(b). This test was performed during 2:00 pm to 3:00 pm. Fig. 5(a) describes air quality level change as well as the temperature and humidity. In the stationary scene, where is crowded, the dust concentration is much higher and more fluctuating. In the moving scene, the air quality is relatively stable. Specifically, during the walking, the mean air pollutant is 31.94 ug/m^3 with SD of 1.74. However, in the stationary scene, the mean air pollutant is 35.02 ug/m^3 with SD of 3.59. Moreover, we notice that the humidity and temperature are higher in the stationary scene.

4.4 A Scene with Various Levels of Dust

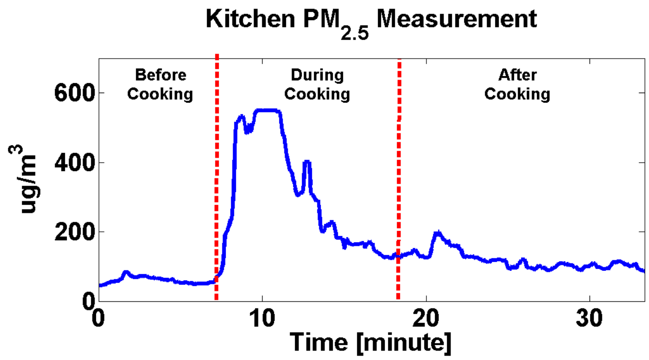


Figure 6: When the cooking begins, the $PM_{2.5}$ measurement increases dramatically. After the cooking, the $PM_{2.5}$ measurement drops slowly.

We also include a test site whose dust concentrations are directly affected by specific activities, such as cooking in kitchen. The high dust concentration environments pose a threat to the dust-sensitive people. In this test, we investigate the dust concentration changes in the kitchen. The Fig. 6 shows the results: the mean value of dust concentration is 131.86 ug/m^3 and the SD is 121.12. The high mean value indicates the high concentration of dust during the cooking. And the high SD value indicates the air quality variation after the cooking.

5. CONTINUOUS PERFORMANCE EVALUATION

After comprehensively evaluating the AirSense platform, a user study is performed to verify if AirSense is feasible to perform the continually air quality monitoring in daily life. This case study includes multiple senses such as home (cook), in-transit (walk), shopping, cafe, and home (sleep). The time-location data was collected for six hours from $18:00$ to $24:00$ on March 9_{th} 2015. The data are classified base on the type of activities, and the results are visualized in Fig. 7(a). The green, blue, red, and magenta curves present the scenes of home, in-transit, shopping, and cafe, respectively. The level of $PM_{2.5}$ that the individual exposed to during each activity was measured and the distribution is shown in Fig. 7(b). The level of $PM_{2.5}$ is highest in cafe as it is expected due to the number of people and their activities in cafe, but also ambient $PM_{2.5}$ level during in-transit is higher than other indoor (home or shopping). It is also worth noting that the $PM_{2.5}$ level at home is affected by the type of activity that person is engaged in the same microenvironment (home): cooking increased the level (above the six-hour average, denoted by dotted red line), but sleeping at home lowered the $PM_{2.5}$ level below the average.

6. DISCUSSION

We demonstrated that the context-sensing and tracking capabilities of our proposed platform enable various of high-impact applications. Different applications require different context attributes. In this section, we will specifically discuss three applications with distinct requirements.

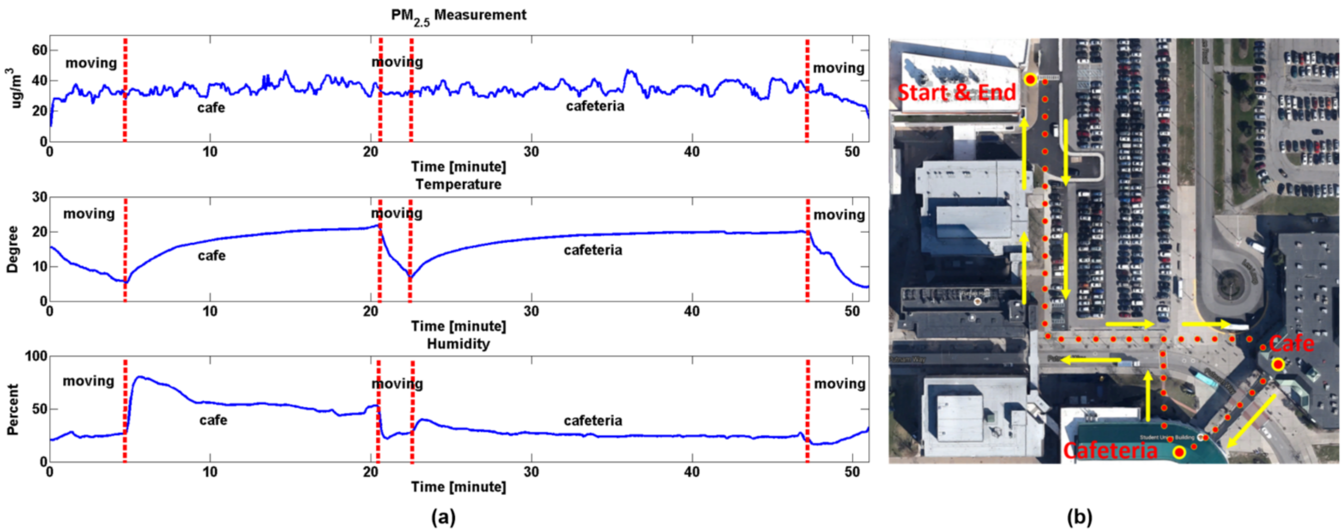
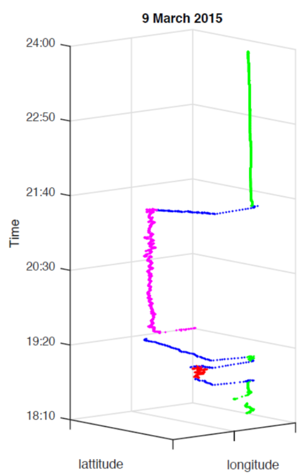
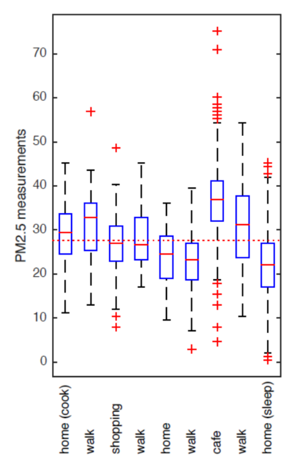


Figure 5: The $PM_{2.5}$ measurement, temperature, humidity, and test routine in the moving vs stationary test.



(a) The visualized time and location information of this user study.



(b) The $\mathrm{PM}_{2.5}$ measurements for several scenes in this user study.

Figure 7: The result of user daily activity study includes the time-location information and $\mathrm{PM}_{2.5}$ measurements.

6.1 Complementary Air Quality Monitoring

The Environmental Protection Agency of U.S. (EPA) provides the air quality data through its air quality monitoring networks, which include different sites across the country. However, the number of the monitoring sites are widely scattered. For instance, in New York State, except for several sites in New York City, the rest sites are only located in metropolitan areas such as Albany, Buffalo, Rochester, *etc.* Most suburban and countryside areas are not covered by current air quality monitoring networks. Besides, the number of monitoring sites are extremely limited. There are only 5 monitoring sites to cover the entire Buffalo area. Therefore, our platform can serve as a complementary air quality monitoring system to the existing EPA sites networks because of the portable and user-centered characteristics. From this perspective, each individual can be treated as a monitoring site, we can collect the air quality data from all the places people traveled.

6.2 Asthma Attack Reduction

The causality of asthma is complex, and many studies show that asthma attack is highly associated with air quality. Our platform can play a key role on human health monitoring. One concrete example is the asthma protection. An asthma patient, who carries a personal air quality monitoring device, will get the information of air quality in real-time. Based on the ambient air quality result, he will be alerted to leave or stay at the current place. When a patient suffers from the asthma attack, AirSense's records can further assist the patient to know in what kind of situation it is prone to suffer form an asthma attack. With this help, an asthma patients can reduce the asthma attacks by avoiding such areas or activities in daily life.

6.3 Routine Suggestion

Air pollution not only affects asthma patients, but also causes chronic diseases for healthy people, especially for senior people and children. It is necessary to bypass the area and the time period with inferior air quality. According to the stored historical air quality data, the air quality fluctuation trend can be predicted as the air quality forecast. In this way, people are able to better arrange their work and plan their daily activities. To be specific, with the huge data obtained from all the areas using AirSense, an air quality density map can be generated to help people to adjust their routines, in order to avoid the contact with severe deteriorated air conditions, *e.g.*, a person can alter his commute route if an area with inferior air quality is overlapped with the current routine.

7. CONCLUSION

In this project, we prototyped a portable and low-cost personal air quality monitoring device which provides user-centered context-sensing information. The platform is designed to integrate multiple sensors, including a dust sensor, a GPS sensor, a temperature and humidity sensor, and an accelerometer sensor. As the personal activities have significant inference on personal exposure to air pollutant, we measured both the ambient air quality and the contextual information in micro-environment where activities occurred. We investigated four typical scenes, *e.g.*, indoor vs outdoor scene, walking vs in-vehicle scene, moving vs stationary scene, and a special high dust level scene.

The next step of our work is to optimize the energy efficiency of AirSense. One observation is that the context scenes are limited because of physical constraints. Therefore, the contextual information, *e.g.*, geographical information, user activities, temperature, and humidity, are highly correlated [11]. We consider to reduce the total energy consumption of context-sensing by discovering the correlations among different context scenes. Another direction we plan to pursue is to develop an automatic scheme to recognize the different context scenes. By training the correlated contextual information from the typical context scenes, the platform should be able to automatically recognize the scene without human input.

8. REFERENCES

[1] Report to Congress on indoor air quality: Volume 2. Technical report, U.S. Environmental Protection Agency, 1989.

[2] Ambient (outdoor) air quality and health. Technical report, World Health Organization, 2014.

[3] Analog Device. *Digital Accelerometer Manual*, 2009. Rev. 0.

[4] Ardufruit. *Adafruit Ultimate GPS Breakout Manual*, 8 2014.

[5] A. V. Broich, L. E. Gerharz, and O. Klemm. Personal monitoring of exposure to particulate matter with a high temporal resolution. *Environmental Science and Pollution Research*, 19(7):2959–2972, 2012.

[6] Y. Cheng, X. Li, Z. Li, S. Jiang, Y. Li, J. Jia, and X. Jiang. Aircloud: a cloud-based air-quality monitoring system for everyone. In *Proceedings of the 12th ACM Conference on Embedded Network Sensor Systems*, pages 251–265. ACM, 2014.

[7] Dylos. *DC1100 Air Quality Monitor Manual*, 12 2008.

[8] O. Geiss, S. Tirendi, J. Barrero-Moreno, and D. Kotzias. Investigation of volatile organic compounds and phthalates present in the cabin air of used private cars. *Environment international*, 35(8):1188–1195, 2009.

[9] D. Holstius, A. Pillarisetti, K. Smith, and E. Seto. Field calibrations of a low-cost aerosol sensor at a regulatory monitoring site in california. *Atmospheric Measurement Techniques*, 7(4):1121–1131, 2014.

[10] A. Mölter, S. Lindley, F. de Vocht, R. Agius, G. Kerry, K. Johnson, M. Ashmore, A. Terry, S. Dimitroulopoulou, and A. Simpson. Performance of a microenviromental model for estimating personal no 2 exposure in children. *Atmospheric Environment*, 51:225–233, 2012.

[11] S. Nath. Ace: exploiting correlation for energy-efficient and continuous context sensing. In *Proceedings of the 10th international conference on Mobile systems, applications, and services*, pages 29–42. ACM, 2012.

[12] Sensirion. *Humidity and Temperature Sensor IC Manual*, 12 2011. Version 5.

[13] Sharp. *Compact Optical Dust Sensor Manual*, 12 2006. Rev. 3.

[14] A. Standard. Standard 62-1999, ventilation for acceptable indoor air quality. *American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga*, 1989.

[15] S. Steinle, S. Reis, C. E. Sabel, S. Semple, M. M. Twigg, C. F. Braban, S. R. Leeson, M. R. Heal, D. Harrison, C. Lin, and H. Wu. Personal exposure monitoring of pm2.5 in indoor and outdoor microenvironments. *Science of The Total Environment*, 508(0):383 – 394, 2015.

[16] R. Sullivan and S. Pryor. Quantifying spatiotemporal variability of fine particles in an urban environment using combined fixed and mobile measurements. *Atmospheric Environment*, 89:664–671, 2014.

[17] Thermo Fisher Scientific Inc. *1405-F Continuous Ambient Air Monitor*, 12 2012.

[18] K. Van Ryswyk, A. J. Wheeler, L. Wallace, J. Kearney, H. You, R. Kulka, and X. Xu. Impact of microenvironments and personal activities on personal pm2. 5 exposures among asthmatic children. *Journal of Exposure Science and Environmental Epidemiology*, 24(3):260–268, 2014.

[19] A. J. Wheeler, L. A. Wallace, J. Kearney, K. Van Ryswyk, H. You, R. Kulka, J. R. Brook, and X. Xu. Personal, indoor, and outdoor concentrations of fine and ultrafine particles using continuous monitors in multiple residences. *Aerosol Science and Technology*, 45(9):1078–1089, 2011.