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Implementation of wireless IAQ sensing network for real-time monitoring in a university campus in Hong Kong

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SUMMARY

This study develops and implements a low-cost wireless IAQ sensing network in university campus in Hong Kong. An interactive mobile app is developed to display the pollutant levels and the corresponding IAQ index, an easy representation of problematic IAQ. IAQ complaints can be made using the app and the location and environmental condition are recorded for follow-up mitigation actions. Detection and calibration of sensor drift using *k*-mean clustering analysis and Kalman filter are proposed for future development. The proposed IAQ monitoring strategy can provide an economical alternative to proactively manage IAQ.

KEYWORDS

indoor air quality (IAQ), wireless sensing network, real-time monitoring, low-cost sensors, sensor calibration

1 INTRODUCTION

Indoor air quality (IAQ) has been a rising concern in modern society since people spend over 90% of their life indoor (Klepeis et al. 2001; Burroughs and Hansen, 2001). Poor IAQ can lead to negative health effects including short-term respiratory irritation, dizziness, long-term chronical diseases and even cancer (Hoskins, 2003; Joshi, 2008; Kampa and Castanas, 2008). In workplace, prolonged exposure to substandard IAQ lowers productivity and increase absenteeism, as a result raising production cost (Fisk, 2000). Therefore, IAQ management is crucial in maintaining public health and providing a safe and productive indoor workplace.

Currently, on-site IAQ measurement is the most common way to assess the IAQ of an enclosed environment, and it is also undoubtedly the most reliable way. However, conducting a full assessment can be time-consuming, perturbing to occupants and resource intensive, as reported by participants of the scheme (Burnett, 2005; Mui and Wong, 2004; Mui et al. 2006; Hui et al. 2007). In addition to the daunting procedure, annual IAQ assessment is incapable of capturing instantaneous episode of indoor air pollution during a particular human activity (for example smoking) unless complaint is received. Furthermore, addition of furnishing and indoor renovation occur in between annual IAQ assessments can also pose health risks to building users, which cannot be revealed immediately after the alteration. Besides, interpretation of IAQ assessment results often needs professional knowledge and judgement, as a result, IAQ management has yet to be popularized and implemented extensively.

Instead of measuring all IAQ parameters, surrogates indicator approach is adopted to minimize the implementation cost. A health risk-based IAQ index that uses carbon dioxide (CO_2), particulate matter (PM) and total volatile organic compounds (TVOCs) was proposed to predict IAQ dissatisfaction without conducting a full test (Wong *et al.* 2007; Wong *et al.* 2016). IAQ screening test has been proven to be effective and cost-efficient to identify asymptomatic IAQ problems which serves as an economic management tool to maintain IAQ.

Real-time IAQ surveillance is a state-of-art technology to continuously monitor the levels of indoor air pollutant. It reveals the acute exposures to air pollutants which can be harmful to occupants. It also provides spatial characterization and temporal understandings of IAQ of an environment, which aid the identification of emitting sources and the formulation of mitigation strategies. IAQ monitoring campaign also raises the awareness of IAQ among building users and facilitates the understanding of health impacts of poor IAQ (Kumar *et al.* 2016). A study by Marques *et al.* (2018) uses Internet of Things (IoT) system to monitor and display PM levels. IoT enables scalability and flexibility of the system. The database provides chronological history of PM level and therefore assisting the formulation of IAQ mitigation strategies. Continuously measuring IAQ parameters has also been used in some places like Doha and Taiwan to monitor and maintain good IAQ. Unfortunately, no such technology has ever been implemented in Hong Kong so far.

Recently, more and more developers seek ways to monitor IAQ to provide a healthy indoor environment for building users and tenants (NWD, 2018). In order to meet the industry demand, health risks of poor IAQ shall be addressed in daily building operation period. A real-time continuous monitoring of IAQ which reflects the health risk of occupants is therefore deemed important. This study develops and implements a low-cost wireless IAQ sensing network (WSN) in university campus in Hong Kong. Alongside with the sensor module, a software program for data transmission and an interactive mobile app are developed for set-up, diagnosing and monitoring purpose. Future development regarding sensor drift detection for output signal adjustment is also discussed. The proposed IAQ monitoring strategy is believed to provide an economical alternative to proactively manage IAQ.

2 METHODS

Construction of the IAQ sensing module

An IAQ sensing module is developed in this study. To minimize production cost while maintaining measurement quality, some low-cost sensors available in the market are chosen as shown in Table 1. IAQ parameters including CO_2, $PM_{2.5}$, PM_{10}, VOCs and carbon monoxide (CO) are selected – the former three are used to compute IAQ index, while CO has acute harmful effect on human and therefore is also incorporated. Temperature and humidity represent the general environmental condition.

The structural diagram of the sensor module is shown in figure 1 below. Sensors are connected to the motherboard which is programmed using C language. Sampling rate is programmed to be 1 data point every 10s, and the data collected are transmitted wirelessly to the cloud database via a built-in 2.4GHz WiFi module immediately after each sampling. After 10min of sampling, the sensing module enters sleep mode for 4min in order to conserve power. The sensing module is powered (input voltage: 4V; current 1–1.5A) by AC power supply or 11 rechargeable battery (363000mAh), which can support normal use of sensing module for 6 consecutive days without recharging. The whole module is enclosed in a Poly(methyl methacrylate) (PMMA) case with an aluminum cover, with air holes to ensure good airflow and heat dissipation.

Table 1. Specification of IAQ sensors adopted in the IAQ sensing module

IAQ parameter	Accuracy	Resolution	Range	Operating principle	Cost (USD)
Temperature Humidity	±0.2-0.4°C ±2%	0.1°C 0.1%	-40–125 °C -0–100%	Digital	3.21

CO	25±10nA/ppm	0.1ppm	2–100ppm	Amperometric	19.26
CO_2	50ppm±3% reading	50ppm	0–5000ppm	non-dispersive infrared (NDIR)	25.68
$PM_{2.5}$ and PM_{10}	±15%	1μg/m^3	1–999μg/m^3	Optical sensing	25.68
VOCs	NA	0.15–0.5 change ratio of Rs	1–30ppm of EtOH	MOS type	25.68

IAQ index

IAQ screening protocols provide an alternative way to identify unsatisfied IAQ with minimum resource and manpower (Wong *et al.* 2006, 2007; Wong *et al.* 2016). Surrogate IAQ parameters, namely CO_2, VOCs and PM_{10}, are selected to preliminarily assess the IAQ of an environment based on the post-test probability (P'_d) of the occurrence of unsatisfied IAQ for screening test. Equation 1 shows the IAQ index, where λ_j^* is the fractional dose of an assessment parameter with j = 1,2 and 3 is determined by dividing the exposure level of the j-th parameter λ_j by the exposure limit $\lambda_{j,\varphi}$ over an exposure period.

$$\theta_3 = \frac{1}{3}\sum_{j=1}^{3} \lambda_j^{*};\ \lambda_j^{*} = \frac{\lambda_j}{\lambda_{j,\phi}} \qquad (1)$$

Table 2. IAQ index and the assessment result based on previous study (Wong *et al.* 2007)

IAQ index	Likelihood ratio	Screening test (Pre-test probability=0.15)		
		Post-test odd	Post-test failure probability	Assessment result
< 0.32	0.1	0.02	0.02	Very improbable
0.32-0.42	0.4	0.07	0.07	Improbable
0.43-0.53	0.8	0.14	0.12	Improbable
0.54-0.64	1.7	0.30	0.23	Possible
≥ 0.65	25	4.41	0.82	Very probable

To make it easier for public use, P'_d is explicated into verbal expression. A pre-test failure rate of 0.15, which is compatible to current IAQ situation in Hong Kong, is chosen. Table 2 above exhibits the IAQ index levels and the corresponding verbal expression of the probability of having unsatisfactory IAQ.

Development of user interface and mobile app

All data collected by the module are first transmitted to cloud platform for storage. Structured Query Language (SQL) is used to retrieve and organize the data in the management studio panel. Target users like facility management can view the device ID, timestamp and location (pre-input into the management studio) of the measurement and the 1-min average of environmental parameter levels. Data can also be exported out for further analysis to identify problematic IAQ and formulate strategies to enhanced IAQ standard.

To enhance the IAQ awareness and the involvement of building end-users, a mobile app is developed for Android operating system. The app allows users to interact by reading the level of each parameter and the corresponding IAQ index, and make complaints to the perceived environmental conditions. After starting up the app, users have to scan the QR code labeled on each device. When the app successfully recognize the device ID, the first question will pop up asking if he/she is satisfied with perceived environment. Answering “Yes” leads to the screen where levels of environmental parameter, IAQ index and assessment result are shown. On the other hand, if the user answers “No”, he/she will be brought to a set of questions regarding thermal comfort, IAQ and allergy issues. Only when all 3 questions are answered, the levels and index will be disclosed. Such arrangement is to avoid pre-judgement if the data are displayed before the questions are answered. Figure 2 gives the flowchart of the mobile app.

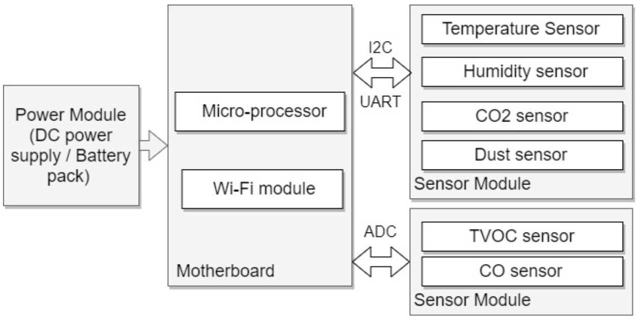

Figure 1. The structural diagram of the IAQ sensing module

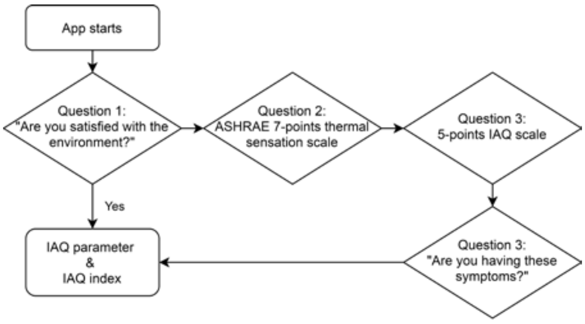

Figure 2. Flowchart of mobile app

3 RESULTS, DISCUSSION AND FUTURE DEVELOPMENT

A preliminary test trial is currently conducting in four different locations in a university campus to identify problems with sensor usage over time. 4 devices were placed in 2 private offices and 2 general offices. Figure 3 shows the variations of environmental parameter for one day from one of the sample locations. It can be seen that the levels of environmental parameter change accordingly with time and human activity. However, extensive longitudinal study will be needed to draw conclusions on the performance of the sensing module.

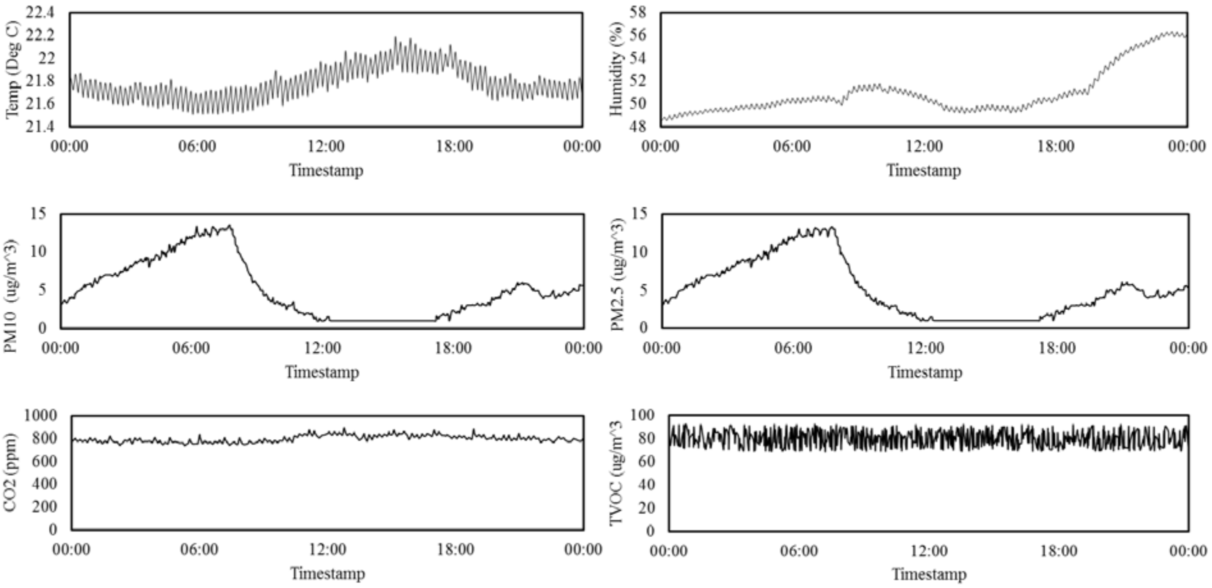

Figure 3. Measurement results of a university departmental office for a day

In the next stage, the WSN IAQ monitoring program will be launched in various locations in campus including conference rooms, classrooms, research offices, laboratories, etc. Public engagement will be expected. With enormous amount of environment data in hand, sensor drift detection for output signal adjustment can be conducted to improve the reliability of the low-cost sensor module. Before drift detection, de-noising of sensor signal shall be conducted by obtaining the wavelet decomposition coefficient W, which can be calculate by $W = \int y_i \omega_{\psi,\tau}(t)\, dt$, with y_i is the measurement data, $\omega_{\psi,\tau}(t)$ is the wave basis given by $\omega_{\psi,\tau}(t) = 1/\psi^{1/2} \times \omega((t-\tau)/\psi)$, τ and ψ is the translation and scale parameter. Threshold ε shall be set such that if $W \geq \varepsilon$, W will be significant and shall be retained.

k-mean clustering is a common unsupervised machine learning algorithms that differentiates data into different clusters. For sensor drift identification, measurement data $Y_s = \{y_{s,1}, y_{s,2}, \ldots, y_{s,m}\}$ will be grouped into two clusters which started with two randomly selected center points c_1 and c_2. The distance between $y_{s,k}$ and c_r can be expressed as $d_{k,r}$, which then $y_{s,k}$ will be assign to the closest cluster. The center mean c_m will change when new value is added until the c_m is stabled, given by $c_m = 1/k \times \sum y_{s,k}$, where k is the number of data point in a cluster. To identify drift, a threshold λ is set to distinct data that have a larger $d_{k,r}$ than when under no drift condition. Threshold λ can be set at the initial stage when sensor is just calibrated using laboratory grade measurement instrument during production process.

Kalman filter is used to calibrate the signal output when noise and/ or sensor drift is identified. It is widely adopted as control algorithm to produce approximations of inaccurate observations by estimating the joint probability distribution. Figure 4 shows the recursive loop of Kalman filter in updating the sensor signal to its assumed ground-true self based on noise and drift estimate described in Lacey (1998). This combined method allows calibration of sensor without a dense deployment of sensing network (Li *et al.* 2015).

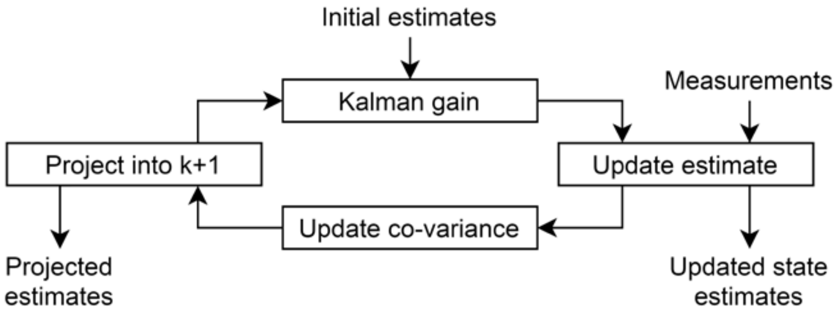

Figure 4. Schematic flowchart of Kalman filter adopted in sensor signal updating and calibration (Lacey, 1998)

4 CONCLUSIONS

Using sensor network for monitoring indoor air quality to protect the health of individuals has not been realized. Mostly because of the complexity and difficulty in both measuring and interpreting the air pollutant levels. This study demonstrate the implementation of WSN in monitoring the IAQ in an indoor environment. By adopting the developed IAQ index, levels of IAQ parameters will be converted into easily understandable benchmark for laymen to comprehend the potential health risks of exposing to a certain environment. In next stage, sensor will be calibrated continuously to maintain the data reliability. It is believe to bring new IAQ monitoring strategies to the industry and improve the IAQ as a whole. With such framework in hand, managing IAQ will be more proactive and economical.

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