AN INTEGRATED INDOOR AIR QUALITY MONITORING SYSTEM WITH POLLUTANTS RECOGNITION AND ENHANCED INDOOR AIR QUALITY INDEX

by

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LIST OF ABBREVIATIONS

ADC	Analog-To-Digital Converter
ANN	Artificial Neural Network
ANOVA	Analysis Of Variance
API	Air Pollution Index
AQI	Air Quality Index
ARIMA	Autoregressive Integrated Moving Average
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BRI	Building related illnesses
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPU	Central Processor Unit
DOSH	Department of Occupational Safety and Health
DIFF	Differential
DPM	Data Processing Module
EIAQI	Enhanced Indoor Air Quality Index
ETS	Environmental Tobacco Smoke
ETS	Health effects due to environmental tobacco smoke
FDA	Fisher Discriminant Analysis
MLP	Multilayer Perceptron
FLASH	Procedure Memory
FRACT	Fractional
FTDI	Future Technology Devices International

FTS Fuzzy Time-Series

GN Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places

GUI Graphical User Interface

H_2 Hydrogen

H_2S Hydrogen Sulfate

HKEPD Hong Kong Environmental Protection Department

HVAC Heating, Ventilation, And Conditioning

IAP Indoor Air Pollution

IAQ Indoor Air Quality

IAQI Indoor Air Quality Index

IAQMG Indoor Air Quality Management Group

IAQMS Indoor Air Quality Monitoring System

ICP-IAQ Industry Code of Practice on IAQ

KNN K-Nearest Neighbor

LDA Linear Discriminant Analysis

MCU Microcontroller Unit

MoHR Ministry of Human Resources

MOX Metal Oxide

MVAC Mechanical Ventilating And Air Conditioning

MSE Mean Square Error

NO_2 Nitrogen Dioxide

O_2 Oxygen

O_3 Ozone

OAP Outdoor air pollution

OS	Operating System
OSH	Occupational Safety and Healthy
PC	Principal Component
PC1	First Principal Component
PC2	Second Principal Component
PCA	Principle Component Analysis
PDA	Personal Digital Assistant
PIR	Pyroelectric InfraRed
PM	Particulate Matter
PWM	Pulse Width Modulation
RF	Radio Frequency
RH	Relative Humidity
RW	Raw
REL	Relative
SAW	Surface Acoustic Wave
SBS	Sick Building Syndrome
SD	Standard Deviation
SI	Smell Index
SIAQG	Singapore Indoor Air Quality Guideline
SIDS	Sudden Infant Death Syndrome
SMC	Sensor Module Cloud
SN	Sensor Normalization
SO_2	Tin Dioxide
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory

TCI	Thermal Comfort Index
TCP	Thermal Comfort Problems
Temp	Temperature
UART	Universal Asynchronous Receiver and Transmitter
US EPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
VAN	Vector Array Normalization
WHO	World Health Organization
WSN	Wireless Sensor Networks

Sistem Pemantauan Kualiti Udara Dalaman Bersepadu yang Dapat Mengenalpasti Sumber Pencemaran Serta Indeks Pencemaran Udara Dalaman yang Ditambahbaikkan

ABSTRAK

Kualiti udara dalaman (IAQ) yang buruk boleh menjejaskan kesihatan manusia. Udara dalaman yang tercemar mempunyai tahap kepekatan gas yang berbahaya sehingga lima kali lebih tinggi dari udara dalaman biasa. Bagi memastikan kita dapat bernafas dengan udara dalaman yang selamat dan selesa, pemantauan IAQ yang berterusan adalah penting. Objektif utama kajian ini adalah untuk membangunkan sebuah sistem pemantauan udara dalaman (IAQMS) bersepadu yang dapat mengenalpasti sumber pencemaran serta indeks pencemaran udara dalaman yang ditambahbaikkan (EIAQI). Sistem IAQMS tanpa wayar ini menggunakan pelbagai pengesan termasuk pengesan gas, pengesan zarah dan pengesan haba untuk mengesan sumber-sumber pencemaran udara dalaman dan sistem ini adalah lebih murah berbanding sistem pemantauan yang profesional. Secara keseluruhan, kajian ini menggunakan lapan pengesan untuk mengukur sembilan gas dan bahan pencemar udara dalaman seperti Oksigen (O_2), Karbon Dioksida (CO_2), Karbon Monoksida (CO), Ozon (O_3), Nitrogen Dioksida (NO_2), Sebatian Organik Meruap (VOCs), Habuk (PM), Suhu (Temp) dan Kelembapan Relatif (RH). IAQMS ini telah berjaya mengenalpasti lima punca pencemaran udara dalaman dengan kadar pengkelasan 100%. Punca-punca pencemaran tersebut adalah: udara persekitaran, aktiviti manusia, kehadiran bahan kimia, kehadiran wangian dan kehadiran makanan dan minuman, berjaya dikenalpasti menggunakan 'Multilayer Perceptron' (MLP) dan 'K-Nearest Neighbor' (KNN) menggunakan data 'Vector Array Normalization' (VAN) yang tidak melalui 'Principal Component Analysis' (PCA). Akhir sekali, objektif terakhir kajian ini adalah untuk mengintegrasikan IAQMS dengan EIAQI. Kajian ini mencadangkan EIAQI yang terdiri daripada tiga indeks yang berbeza: Indeks Kualiti Udara Dalaman (IAQI), Indeks Keselesaan Terma (TCI) dan Indeks Bau (SI). IAQI menggunapakai tujuh gas dan bahan pencemar udara dalaman untuk mengukur kualiti udara dalaman dan menunjukkan status IAQ sama ada ia adalah "Baik", "Sederhana", "Tidak Sihat" ataupun "Berbahaya". IAQI ini dibangunkan dengan menggunakan index kualiti udara (AQI) yang diterbitkan oleh Agensi Perlindungan Persekitaran Amerika (US EPA) sebagai sumber rujukan utama. TCI menggunakan prinsip yang sama dengan IAQI. TCI menggunakan Temp dan RH untuk menunjukkan tahap keselesaan terma sama ada "Sangat Selesa", "Selesa", "Kurang Selesa" ataupun "Sangat Kurang Selesa". Berbeza dengan IAQI dan TCI yang menjana indeks mereka berdasarkan bahan pencemar tunggal, SI dihasilkan berdasarkan pelbagai parameter pencemar. Sebagai contoh, IAQI ditentukan berdasarkan pencemar tunggal yang memberikan kadar kualiti yang paling rendah. SI sebaliknya, menjana persepsi bau berdasarkan semua sembilan bahan pencemar. SI akan mengelaskan bau tersebut sama ada "Neutral", "Menyenangkan" atau "Tidak Menyenangkan". Akhir sekali, EIAQI dirumuskan dengan menggabungkan ketiga-tiga indeks yang diperolehi sebelum ini. EIAQI memberitahu pengguna mengenai status keselesaan keseluruhan di dalam bilik.

An Integrated Indoor Air Quality Monitoring System with Pollutants Recognition and Enhanced Indoor Air Quality Index

ABSTRACT

Poor indoor air quality (IAQ) may pose threats to human's health. The concentration level of harmful gases and contaminants in polluted indoor air is up to five times higher than in normal indoor air. In order to ensure that people breathe-in safe air comfortably in the indoor air environments, continuous IAQ monitoring is deemed important. The main objective of this study is to develop an integrated indoor air quality monitoring system (IAQMS) with pollutants recognition and Enhanced Indoor Air Quality Index (EIAQI). The wireless IAQMS adopts an array of sensors including gas sensors, particle sensors and thermal sensors to detect multiple pollutant parameters at a relatively low cost as compared to the professional sensing devices. Overall, this study uses eight sensors to measure nine indoor air pollutants which are Oxygen (O_2), Carbon Dioxide (CO_2), Carbon Monoxide (CO), Ozone (O_3), Nitrogen Dioxide (NO_2), Volatile Organic Compounds (VOCs), Particulate Matter (PM), Temperature (Temp) and Relative Humidity (RH). This IAQMS has successfully recognized five sources of indoor air pollution with classification rate of 100%. These five sources of indoor air pollution are: ambient air, human activity, presence of chemical, presence of fragrance and presence of food and beverage, are successfully classified by Multilayer Perceptron (MLP) and K-Nearest Neighbour (KNN) using Vector Array Normalization (VAN) before Principle Component Analysis (PCA) feature. Finally, the last objective of this study is to integrate the IAQMS with EIAQI. This study proposes an EIAQI which comprises of three different indices: Indoor Air Quality Index (IAQI), Thermal Comfort Index (TCI) and Smell Index (SI). IAQI utilized the seven air parameters to measure the quality of indoor air and shows the status of IAQ whether it is "Good", "Moderate", "Unhealthy" or "Hazardous". This IAQI is developed using Air Quality Index (AQI) from the United States Environmental Protection Agency (US EPA) as its main reference. TCI applied the same principle with IAQI. The TCI used Temp and RH to indicate the thermal comfort level of a room. Therefore, TCI status is shown either as "Most Comfort", "Comfort", "Less Comfort" or "Least Comfort". In contrast with the IAQI and TCI which generate their index based on single pollutant parameter, SI is generated based on an array of pollutant parameters. For example, IAQI is determined based on single pollutant that gives the lowest rate. SI on the other hand, generates the smell perceptions based on all nine pollutants input. The final result would be classified as either the smell is "Neutral", "Pleasant" or "Unpleasant". After all individual index has been obtained, an EIAQI is formulated which combines all the previous three indices. This EIAQI informs the users about the overall comfort status in the room.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The issue of outdoor air pollution (OAP) such as haze is well known to the public due to the attentions given by the media. On the contrary, the issue of indoor air pollution (IAP) is less known to the public although IAP poses similar threats towards humans' health as compared to OAP. In fact, more attentions should be given to the issue of IAP because people normally spend 90 percent of their time in indoor environments (EPA, 2009). IAP, which undermines indoor air quality (IAQ), is found to contain indoor air pollutants such as harmful gases and contaminants at a concentration level up to five times higher than the concentration of these pollutants in normal air. In severe cases, the concentration level of the pollutants could rise up to 100 times than normal concentration level which lead to hazardous condition for human's health (EPA, 2009).

IAP can be defined as the disturbance of any gases, materials or human activities on the state of ambient air in indoor environment (Reffat & Harkness, 2001). In other words, IAP does not need the presence of disease or infirmity. As long as the concentration in the normal ambient air is disturbed either by gases, other materials or human activity, it is already considered as pollution. The most common sources of IAP is contributed by human activity such as the emission of carbon dioxide through breathing, combustion products from cigarette smoking and emission of volatile organic compounds (VOCs) from excessive usage of cosmetic products such as perfumes and deodorants (Batterman & Burge, 1995). Other materials such as chemical products, building materials and office materials are also major sources of IAP. Chemical products such as air fresheners and cleaning products contribute to IAP by emitting VOCs while building and office materials like printers and carpets also release air contaminants such as dust into indoor air atmosphere (Borkar, 2012; CDC, 2014; Mumyakmaz & Karabacak, 2015; Sait, 2001; & Wasana, 2007). IAP may also emerge as a result of variations of gas concentration in the indoor air as well as from variations in thermal conditions such as temperature and humidity (DOSH, 2010; & Postolache, Pereira, & Girao, 2009). Finally, odour or smell also contributes to IAP (Capelli, Sironi, & Rosso, 2014). Therefore, anything that emits odour such as rotten food and strong smell of coffee are considered as part of sources of IAP. These sources of IAP might not look harmful, but to a certain extent (based on the concentration level) they may be hazardous to human health.

The health effects from IAP may be experienced soon after exposure, or possibly, years later depending on the individuals and type of pollutants they have been exposed to (EPA, 2014). The common health conditions that may show up immediately include irritation of the eyes, nose, and throats, headaches, dizziness, fatigue, asthma and humidifier fever. The health effects of years of exposure to IAP are more dangerous and can be fatal, which include some respiratory-related diseases, heart disease, and cancer (Maroni, Seifert, & Lindwall, 1995; & Mohave, 2000). The health effects relating to poor indoor air quality have been divided into four categories: Environmental Tobacco Smoke (ETS), Sick Building Syndrome (SBS), Building Related Illness (BRI), and Thermal Comfort Problems (TCP) (DOSH, 2010; EPA, 2008; & IAQMG, 2003).

Hence, meticulous attention should be given to make sure the indoor air is safe and comfortable.

In order to ensure that people breathe-in safe air comfortably in the indoor environments, continuous monitoring of IAQ is deemed important. Real-time and continuous IAQ monitoring allows people to be alert of any pollution that might happen in indoor environment right on time when it happens. Furthermore, the concentration level of gases and contaminants in the indoor air easily vary and can be impacted by various situations (J. Kim, Chu, & Shin, 2014). The changes in the indoor air concentration might not be noticeable by humans' senses because most of the gases and contaminants in indoor air are odourless and colourless. By having continuous IAQ monitoring system in real time, any pollution can be detected and users can be notified immediately, thus, necessary actions could be taken to prevent any unwanted events.

1.2 Problem Statement

Many researchers have come out with various versions of indoor air quality monitoring systems (IAQMS) to monitor the quality of air in indoor environment. The early development of IAQMS started with the introduction of electronic nose or e-nose which is composed of an array of sensors for classifications of oils and alcohol odours in 1982 by Persaud and Dodd (Persaud & Dodd, 1982). Since then, there have been numerous attempts to develop a monitoring system to be used in indoor environment, for example Borkar, (2012), Bhattacharya, Sridevi, & Pitchiah (2012), J. Kim et al. (2014), Postolache et al. (2009) and S. Choi, Kim, Cha, & Ha (2009). Their objectives vary from assessment of IAQ in certain targeted indoor spaces, development of index for application in indoor environments, predicting IAQ levels during certain conditions to a more sophisticated objective of recognizing certain types of indoor air pollutants.

Nevertheless, most of these systems are impaired by some flaws, either due to high costs, incomprehensive coverage of gas sensors, problems in collecting data using portable devices, or lacking in data processing application. A comprehensive system which can overcome the flaws in the previous IAQMS and further enhanced with smart application that could process the air quality data quickly and economically is needed for better IAQ monitoring.

The main problem with the existing IAQMS is that the researchers need to choose between comprehensive coverage of gas sensors but very costly and a low cost system with less accurate gas sensors. Sometimes, the researchers need to sacrifice the comprehensiveness of gas sensors by using less gas sensors in order to produce a low cost IAQMS. A professional gas sensor units or devices which cover a wide variety of gases and measure them to a very sensitive concentration are usually very expensive. Hence, not everyone could afford such devices (Borkar, 2012; Cheng, 2014; & Mamat et al., 2011). Normally, these professional gas sensors are used only when a problem of IAQ is reported. This cost constraint has resulted in insufficient data being made available to the researchers in the studies of IAQ and IAP. As a result, many researchers have tried to propose low cost IAQMS such as J. Kim et al. (2014), Borkar (2012) and Bhattacharya et al. (2012). However, this type of IAQMS usually could not detect multiple pollutants; rather they can only detect single pollutant (i.e. carbon dioxide or carbon monoxide alone) as reported by previous research such as Cheng (2014), Yingjie (2012) and Yu et al. (2011). Hence, they cannot give comprehensive result for IAQ assessment. Comprehensive IAQ result usually requires monitoring of more than 8 pollutants including carbon monoxide, ozone, particulates matter and VOCs (DOSH,