DEVELOPMENT OF PORTABLE ELECTRONIC NOSE FOR MONITORING THE ATMOSPHERIC HAZARDS IN CONFINED SPACE

by

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LIST OF ABBREVIATIONS

AD	Anderson-Darling
ADC	Analogue-to-Digital Converter
ANN	Artificial Neural Network
CB	Catalytic Bead
CFD	Computational Fluid Dynamic
CH_4	Methane
CO	Carbon Monoxide
CP	Conducting Polymer
DOSH	Department of Safety and Health
EC	Electrochemical
GCMS	Gas Chromatography–Mass Spectrometry
GUI	Graphical User Interface
H_2S	Hydrogen Sulphide
HS	Headspace
HSB	Sultanah Bahiyah Hospital
IC	Integrated Circuits
IDLH	Immediately Dangerous to Life and Death
I/O	Input and output
KS	Kolmogorov-Smirnov
LCD	Liquid Crystal Display
L.E.L	Lower Explosive Limit
LPF	Low Pass Filter
MLP	Multilayer Perceptron
MOS	Metal Oxide Semiconductor
MOSFET	Catalytic Field-Effect
NIOSH	National Institute of Occupational Safety and Health
O_2	Oxygen
OCM	Odour Capturing Module
OSHA	Occupational Safety and Health Administration
PC	Principal Component
PCA	Principal Component Analysis
PCB	Printed Circuit Board

PNN	Probabilistic Neural Network
ppm	parts per million
QMB	Quartz Crystal Microbalance
RBF	Radial Basis Function
Re	Reynolds number
RF	Radio Frequency
SAW	Surface Acoustic Wave
SMT	Surface Mounted Technology
SNR	Signal to Noise Ratio
SPI	Serial Peripheral interface
SOMs	Self-Organizing Maps
SVM	Support Vector Machine
SW	Shapiro-Wilk
U.FL	Ultra Miniature Coaxial
U.E.L	Upper Explosive Limit

LIST OF SYMBOLS

α	Significance level in statistics
d	Hydraulic diameter (m)
m	Gradient of sensor response versus concentration of gas
k	Constant value of sensor response versus concentration of gas
p-value	Probability value between 0 to 1
ρ	Density of the fluid (kgm^3)
u	Fluid mean velocity (m/s)
μ	Dynamic viscosity of the fluid ($kg\ ms^{-1}$ or $Ns\ m^{-2}$)
x_{ppm}	Air sample concentrations in parts per million data
$x_{\%}$	Air sample concentrations in percentage data
Y	Sensor responses (Ω)
$\%_E$	Percentage error

Pembangunan Hidung Elektronik Mudah Alih Untuk Memantau Bahaya Atmosfera Di Dalam Ruang Terkurung

ABSTRAK

Tesis ini membincangkan pembangunan hidung elektronik (e-hidung) untuk memantau bahaya atmosfera di dalam ruang terkurung. Ruang terkurung merupakan ruang yang cukup bagi pekerja untuk memasuki dan melakukan kerja. Ia mempunyai cara masuk atau keluar yang terhad dan tidak direka untuk pekerjaan yang berterusan. Ia boleh menyumbang kepada kemalangan atmosfera yang akan mengancam keselamatan pekerja dan kemajuan industri. Keadaan atmosfera paling kritikal apabila mengandungi oksigen terlalu tinggi atau terlalu kurang dalam atmosfera atau atmosfera mengandungi gas mudah terbakar atau toksik. Teknologi terkini bagi memantau atmosfera dialakukan semasa pra-kemasukan dalam ruang terkurung menggunakan pengesan gas. Kajian ini bertujuan untuk membangunkan instrumen mudah alih bagi membantu pekerja semasa pra-kemasukan dijalankan untuk memantau atmosfera. E-hidung ialah integrasi daripada perkakasan dan perisian yang dapat mengesan serta mengklasifikasikan sampel udara yang berbeza menggunakan teknik pengecaman corak. Instrumen yang dibangunkan ini menggunakan penderia jujukan yang telah dikenal pasti berdasarkan nilai efektif gas utama pada kadar bacaan yang merbahaya. Kadar bacaan suhu dan kelembapan sekitar juga diukur. Instrumen ini menggunakan analisis statistik multivariat iaitu Analisis Komponen Utama (PCA) untuk mendiskriminasi kepekatan gas yang berbeza. Mesin Vektor Sokongan (SVM) dan Rangkaian Saraf Tiruan (ANN) iaitu Rangkaian Fungsi Asas Radial (RBF) digunakan untuk mengkelasifikasikan data daripada sampel udara. Kaedah ini akan meningkatkan keupayaan instrumen tersebut manakala sifat mudahalihnya akan mengurangkan saiz dan kesukaran pengendalian sebagai instrumen mesra pengguna. Instrumen ini berjaya dibangunkan, diuji dan ditentukur dengan menggunakan sampel gas kepekatan tetap. Hasilnya membuktikan bahawa instrumen yang dibangunkan dapat mendiskriminasi sampel udara menggunakan PCA dengan jumlah variasi 99.42%, manakala kadar kejayaan pengelas untuk SVM dan Rangkaian RBF menunjukkan 99.28% untuk prestasi latihan dan 98.33% untuk prestasi ujian. Ini akan menyumbang kepada satu kaedah dan alternatif yang boleh digunakan dalam pengujian keadaan sebenar untuk memantau bahaya atmosfera di dalam ruang terkurung. Keselamatan pekerja juga lebih terjamin semasa melakukan kerja sepanjang berada di dalam ruang terkurung.

Development of Portable Electronic Nose for Monitoring the Atmospheric Hazards in Confined Space

ABSTRACT

This thesis discussed the development of electronic nose (e-nose) for monitoring the atmospheric hazards in a confined space. A confined space is large enough for workers to enter and perform work. It has a limited means of entry or exit and is not designed for continuous occupancy. It can contribute towards atmospheric hazards accidents that threaten the worker safety and industry progress. The most critical atmospheric hazards are too high or low oxygen in the atmosphere or atmospheres that contain flammable or toxic gases. Current technology to monitor the atmospheric hazards is applied before entering confined spaces called pre-entry by using a gas detector. This study aims to develop an instrument to assist workers during pre-entry for atmosphere testing. E-nose is the integration between hardware and software that can identify and classify different concentrations of gases in an air sample using pattern recognition techniques. The developed instrument using specific sensor arrays which were identified based on main hazardous gasses effective value. The temperature and humidity rates are also measured. The instrument utilizes multivariate statistical analysis that is Principal Component Analysis (PCA) for discriminate the different concentrations of gases. The Support Vector Machine (SVM) and Artificial Neural Network (ANN) that is Radial Basis Function (RBF) Network are used to classify the acquired data from the air sample. This will increase the instrument capability while the portability will minimize the size and operational complexity as well as increase user friendliness. The instrument was successfully developed, tested and calibrated using fixed concentrations of gases samples. The results proved that the developed instrument is able to discriminate an air sample using PCA with total variation for 99.42%, while the classifier success rate for SVM and RBF Network indicates at 99.28% for train performance and 98.33% for test performance. This will contribute significantly to acquiring a new and alternative method of using the instrument for monitoring the atmospheric hazards in confined space. This will ensure the safety of workers during work progress in a confined space.

CHAPTER 1: INTRODUCTION

1.1 Background

Most places in the industrial sector, such as steel mills, paper mills, shipyards and public utilities involve activities in confined spaces. Some types of confined spaces in these environments are chambers, tanks, manholes, vats, silos, pits and pipe. A confined space is large enough for workers to enter and perform work. It has a limited means of entry or exit and is not designed for continuous occupancy because it's could contribute towards atmospheric hazard accidents (Workplace Safety and Health Council, 2010). Accidents do happen sometime in these areas and usually involve human fatalities or death. The Occupational Safety and Health Administration (OSHA) and National Institute of Occupational Safety and Health (NIOSH) state that the presence of atmospheric hazards in confined space are serious environmental problem that threatens the industry operation and safety of the workers (Suruda, Pettit, Noonan, & Ronk, 1994).

The hazards in confined spaces can be classified into two categories which are physical hazards and atmospheric hazards (WorkSafeBC, 2008). The physical hazards which can be visualized can be avoided by taking initial safety precautions. The example of physical hazards includes unstable materials, moving parts of machinery, falling objects, a slippery surface and noise. Atmospheric hazards are more dangerous compared to physical hazards as they are unseen and come from oxygen deficiencies, hazardous gases, dust and welding fumes. The hazardous gases can interfere with the human body's ability to transport and utilize oxygen as well as cause negative toxicological effects.

Usually the atmospheric testing in confined space is carried out during pre-entry by authorised person using gas detectors. The atmospheric hazards are rated into three stages; High, Moderate and Low as listed in Table 1.1 which determined by the authorised person (WorkSafeBC, 2008).

Table 1.1: Atmospheric hazards level

Categories	Risk
High	Expose worker to a death risk
Moderate	Atmosphere is not clean and the air is not stable but not likely to impair a worker's ability to escape unaided from a confined space if the ventilation system or respirator fails
Low	Shown by pre-entry atmospheric testing and that is not likely to change during activities

Serious industrial accidents involving fatalities are listed in Table 1.2 (DOSH, 2017). This include accidents that killed three people, while two others were sickened after inhaling toxic gases while working in a confined space in a ship (Schuler, 2015).

Table 1.2: Confined space accidents in Malaysia

Date	Title Case	Location	Summary	Classification
Mar 2010	Found death in confined space	Sabah	Six victims were killed due to **toxic gases** in a confined space (treated water pumping tank)	Fatal
Apr 2011	Died while in confined space	Manhole, Penang	The two victims died during finishing up their work of cleaning sewerage pipes. The **toxic gases** caused them to suffocate and become unconscious	Fatal
Aug 2014	Died falling from height	Factory, Selangor	There were the **flammable gases** that cause an explosive at the top of a short fibre storage tank as a result of the welding process. The explosion caused the workers to be thrown and fall from a height of 8.5 meters	Fatal
Dec 2014	Died due to explosion	Construction site, Johor	The victim died due to explosion due to the existence of **flammable gases**. It is believed that he was carrying welding work in confined space	Fatal
Aug 2016	Two dead in confined space	Petronas Chemical Plant, Sabah	Two dead and three injured in **toxic gases** leak at chemical fertilizer plant	Fatal

An electronic nose (e-nose) is an instrument which comprises an array of electronic chemical sensors with partial sensitivity, an appropriate pattern recognition system and capable of recognising simple or complex odours (Chansongkram & Nimsuk, 2016). Development of the instrument over the past decades is significant for its possible applications and achievements (Rock, Barsan, & Weimar 2008). The application includes food quality assurance, work safety, medical diagnosis, environmental monitoring and plant disease detection (Wilson & Baietto, 2009). An e-nose has good potential for detecting and monitoring atmospheric hazards present in the confined space which could contribute to deadly accidents. A good e-nose must be able to produce the same pattern for a sample on the same array to maintain its repeatability (Mamat & Samad, 2010).

1.2 Problem Statement

The atmospheric hazards workers are exposed to in confined spaces normally involve oxygen (O_2) too low or high or the presence of flammable and toxic gases (Ye, 2011). The main flammable gas is methane (CH_4) while the toxic gases include hydrogen sulphide (H_2S) and carbon monoxide (CO). Before workers enter the confined space, a pre-entry for atmospheric testing is conducted by the authorised person for safety requirement. The atmospheric hazard conditions must be monitored before and while workers perform their activities inside the area. The hazards can cause serious health problems or death to the workers if not monitored properly (DOSH, 2017).

At present, the pre-entry for atmospheric testing is done by using a direct-reading gas detector (WorkSafeBC, 2008). Even do, there are multi gas detector in the market, but the acquired measured data still not reliable due to the purging system that cause low repeatability (Suski, 2005). The detector also shows the real time measurement at specific location only which not represent the whole confined space environment. Therefore, there is a need for a system like e-nose that is able to measure the hazardous gases and predicts the atmospheric hazards in confined space with high accuracy and repeatability (Mamat, Samad, & Hannan, 2011).

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1.3 Research Objectives

The objective of this research is to develop a portable electronic nose (e-nose) to monitor the atmospheric hazards in confined space (i.e. hospital mechanical room) and which address the following:

i. To investigate and identify the atmospheric hazards main hazardous gases.

ii. To design and fabricate e-nose system with multimodal sensor detection.

iii. To integrate the system with optimum self-purging.

iv. To test and validate the functionality of fabricate system in laboratory and field environment.

1.4 Research Scope

This research focused on investigating the atmospheric hazard main gases in a confined space. The developed e-nose multimodal sensor selection is based on the atmospheric hazard main gases. The instrument's embedded control software is programmed using C language and the Graphical User Interface (GUI) for data acquisition also is been programmed. The instrument was tested and calibrated in a laboratory environment. The field or on-site test environment was conducted in a mechanical room at Sultanah Bahiyah Hospital (HSB), Alor Setar, Kedah, Malaysia. The acquired data was analysed using Principal Component Analysis (PCA) for discriminate the hazardous gases concentration. The Support Vector Machine (SVM) and Artificial Neural Network (ANN) using Radial Basis Function (RBF) Network were used to classify the acquired data from the air sample.

1.5 Contribution of this Thesis

The contributions of this research work are:

i. The sensing module development is based on the atmospheric hazards main gases in confined space.

ii. The development of e-nose includes an optimum self-purging system.

iii. The developed e-nose was calibrated and validated with commercial gas detector to make it trusted or reliable for monitoring the atmospheric hazards main gases in a confined space.

iv. The developed e-nose is extended with analysis using PCA for discriminating, SVM and ANN using RBF Network for classification towards different concentrations of gases in the hospital mechanical room application.

1.6 Thesis Outline

This thesis is organised into six chapters and the general outline is summarised as below:

The introduction of this thesis research is presented in Chapter 1. It describes the basic preface regarding the confined space, atmospheric hazards and the confined space accidents in Malaysia. This chapter also explains the problem statement, objectives, scopes and contributions of this thesis as well as thesis outline.

Chapter 2 provides the literature review on confined space, atmospheric hazards and the pre-entry process. The e-nose system architecture, current status and future trends are also discussed in the chapter. In this chapter also describes the data pre-processing technique, the statistical and classification methods to be use in the applications.

Chapter 3 presents the detailed development of the portable e-nose system including hardware and software development. The instrument hardware components include sensor selection, sensor chamber, signal conditioning board, controller board, purging system, power supply and enclosure. This chapter also describes the software development, the embedded control system and sampling techniques. The data acquisition in the form of Analogue-to-Digital Converter (ADC) value is converted into parts per million (ppm) and percentages based on concentrations of hazardous gases.

Chapter 4 explains the methodology for the data acquisition process. It discussed the setup for in-house (laboratory) and field environment testing. The laboratory experiments include purge testing, functionality testing, calibration and validation. The field environment testing is to expose and test the developed instrument in a real confined space.

Chapter 5 discusses the results and discussion. These include e-nose sensor responses, pre-processing, clustering's and classification analysis. It is also evaluates the performance of the developed instrument.

Chapter 6 concludes the entire research finding. Some future works that extend this research are proposed at the end of the chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Confined Space

Many industrial operations involve activities in spaces of an enclosed nature with limited space to perform work activity, which are known as confined spaces. The United States Occupational Safety and Health Administration (OSHA) defined confines space as a space large enough so that an employee can bodily enter and perform work, it has limited means of entry and is not designed for continuous employee occupancy (Burlet-vienney, Chinniah, Bahloul, & Roberge, 2015).

The example of a confined space includes tank, boiler, silo, pipeline, sewer, manure pit, pumping station and manhole that has limited space or is an enclosed area in which workers work only occasionally (WorkSafeBC, 2008). The enclosed area could fill with hazardous gases that pose danger to the workers while they perform their activity. These atmospheric hazards may results in death or serious injury to the workers.

In order to avoid any serious accident, an authorised person with adequate knowledge, training and experience must perform a written hazard assessment before workers enter the confined space (Burlet-vienney, et al., 2015). The name and signature of the authorised person must appear on the assessment and the employer must keep record of this activities. The authorised person's assessment includes: (a) the hazards that may exist in the confined space, (b) the hazards that may develop while work is performed inside the confined space and (c) general safety hazards in the confined space.

2.2 Atmospheric Hazards

The atmospheric hazards can only be detected by sense of smell. The main atmospheric hazards in confined space are oxygen (too much or too little), flammable and toxic atmosphere (Ye, 2011).

2.2.1 Oxygen Atmosphere

The normal air in the atmosphere is approximately composed of 21% oxygen and 79% nitrogen (Ye, 2011). The oxygen deficiency in confined space may happen when metals rust, combustion engines run for a period time is replaced by other gases (i.e. welding gases) or used by micro-organisms (i.e. fermentation vessels). The enriched or over limit of oxygen in confined space is also dangerous in that it increases the risk of fire or explosion. Materials would quickly and easily burn when there is a high level of oxygen. Table 2.1 shows the potential effects of oxygen deficient and enriched atmospheres (RAE Systems Inc., 2006).