FAULT-TOLERANT GAS SENSOR ARRAY ARCHITECTURE FOR ARTIFICIAL OLFACTORY SYSTEMS

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

To my beloved wife and my parents for their love

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chair: Assoc. Prof. Mohd. Nizar b. Hamidon, PhD
Faculty: Institute of Advanced Technology

During the past two decades, artificial olfactory system has received considerable attention, mainly because of the findings in wide range of applications arising from research in various areas of applied sciences. Artificial olfactory system has been employed in a broad range of industries, including the food, agricultural, biomedical, pharmaceutical, and diverse scientific fields. Most of the efforts to develop artificial olfaction have been in sensor fabrication, sensor structure, and signal processing techniques. However, major problem in the reported investigations is that the classic structure of the artificial olfactory system is not suitable for critical applications such as medical diagnosis and environment air quality monitoring where reliability and precision are important.

In this thesis, development of the artificial olfactory system based on the fault tolerant architecture was investigated. The proposed architecture can resistant or tolerant failures in the sensor array of artificial olfactory system, that is, fault tolerant. The system is able to continue to function in spite of failures in the sensors of array. The result is a system that can suffer from failure and damage but this harm is not effect on its performance and system is capable to recover faults without direct human intervention. In the proposed architecture, by applying a novel technique which is called 'virtual sensor' the occurred faults are masked and generation of erroneous results is prevented.

In this thesis, the ability of the developed architecture based on the virtual sensor to discriminate complex odors and also, the performance of system in faulty situation was studied. For this purpose, from different evaluation experiments various datasets with large number of data from 26,400 to 108,000 were generated. The results demonstrated that the performance of the system based on the proposed architecture in healthy mode, is similar to the classic structure of artificial olfaction. However, in faulty mode, the classifier based on the proposed architecture in comparison with the

generic architecture presents 70.77%, 64.47%, 64.45% enhancement in precision, sensitivity, and accuracy rates, respectively. Thus, the proposed architecture can be seen as a considerable improvement in artificial olfactory system.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKABENTUK TOLENRASI-KESALAHAN SUSUNAN PENDERIA GAS PADA SISTEM PEMBAU TIRUAN

Oleh

NASSER LOTFIVANDVAHED

November 2013

Pengerusi: Prof. Madya Mohd. Nizar b. Hamidon, PhD
Fakulti: Institut Teknologi Maju

Sepanjang dua dekad yang lalu, sistem pembau tiruan telah diberi perhatian sewajarnya, kebanyakannya adalah kerana penemuan di dalam pelbagai aplikasi yang timbul daripada penyelidikan pelbagai bidang sains gunaan. Sistem pembau tiruan telah diguna pakai secara meluas di dalam pelbagai industri termasuk makanan, pertanian, bio-perubatan, farmaseutikal dan pelbagai bidang saintifik lain. Kebanyakan usaha untuk membangunkan prestasi pembau tiruan ini telah dilakukan terhadap fabrikasi penderiaan, struktur penderiaan dan teknik pemprosesan isyarat. Walau bagaimanapun, masalah utama yang telah dilaporkan di dalam siri-siri penyelidikan adalah struktur klasik sistem pembau tiruan iaitu ianya tidak sesuai untuk aplikasi kritikal seperti diagnosis perubatan dan pemantauan kualiti udara di mana kebolehpercayaan dan ketepatan adalah amat penting.

Di dalam tesis ini, kajian pembangunan sistem pembau tiruan berdasarkan kepada rekabentuk tolenrasi kesalahan telah dijalankan. Cadangan rekabentuk boleh menolak atau bertoleransi terhadap kegagalan dalam susunan deria sistem pembau tiruan iaitu kegagalan toleransi. Sistem in berupaya untuk meneruskan fungsi walaupun kegagalan fungsi di dalam susunan penderiaan. Keputusan kajian ini mendapati sistem ini boleh mengalami masalah akibat daripada kegagalan dan kerosakan tetapi kerosakan ini tidak menjejaskan prestasi dan sistem ini berupaya untuk mengatasi kerosakan tanpa campurtangan manusia. Di dalam cadangan rekabentuk ini, dengan mengguna pakai teknik terkini di mana boleh dipanggil sebagai penderiaan maya, kegagalan yang terjadi diperbaiki dan keputusan tidak tepat yang dikeluarkan dapat diatasi.

Dalam tesis ini, kebolehan untuk membentuk rekabentuk berdasarkan penderiaan maya untuk mengasingkan gabungan aroma dan juga prestasi sistem di dalam situasi kegagalan dikaji. Untuk tujuan ini, satu penilaian ke atas pelbagai set data yang meliputi jumlah yang besar iaitu antara 26,400 hingga 108,000 set data telah dikeluarkan. Keputusan mendapati prestasi sistem berdasarkan kepada cadangan rekabentuk adalah di dalam keadaan mod baik, di mana ianya sama dengan stuktur

klasik pembau tiruan. Tetapi, di dalam keadaan mod gagal, prestasi rekabentuk yang dibangunkan berbanding rekabentuk generik didapati menunjukkan penambahan sebanyak 70.77%, 64.47%, 64.45% masing-masing dalam kepersisan, kepekaan dan kadar ketepatan. Dengan ini, cadangan rekabentuk boleh dilihat sebagai system pembau tiruan yang boleh diambilkira untuk penambahbaikkan.

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LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
AOS	Artificial Olfactory System
BP	Back Propagation
FN	False Negative
FP	False Positive
GC	Gas Chromatography
k-NN	K Nearest Neighbor
MLP	Multi-Layer Perceptron
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MS	Mass Spectrometry
PC	Principal Component
PCA	Principal Component Analysis
ppm	Parts Per Million
QMB	Quartz Micro Balances
TGS	Taguchi Gas Sensor
TN	True Negative
TP	True Positive
VOC	Volatile Organic Compound

CHAPTER 1

INTRODUCTION

1.1 Artificial Olfaction Demands

Vertebrates' olfactory systems detect and discriminate various odorants with high precision. From an evolutionary standpoint sense of smell is one of the early senses in vertebrates. The mammalian olfactory system is able to identify volatile compounds at very low concentrations in parts per trillion [1].

The human nose can detect around 10,000 different odors [2]. The sense of smell can provide sensual pleasure, such as the aroma of flowers, and threats, such as spoiled food or drink. Spices are applied to enhance the taste and smell of foods. Human nose has been used as a primary instrument in a wide diversity of applications, such as quality assessment of food, drink, perfume and cosmetic, environmental air control, agriculture, or even sickness detection [3].

In spite of the significance of olfaction to human, this sense has less refined than that of other mankind senses such as vision and hearing. In comparing with other animals the human olfaction have low perception. The human nose have about one million smell receptors while some animals such as dogs have about 100 million receptors that discriminate aromas more effectively than the human [4]. Infections, mental state, fatigue, sensitivity decreasing through prolong exposure and many other factors effect on the human sense of smell.

Low sensitivity and discriminability of the human olfactory system, jointed with the common appearance of olfactory fatigue, has directed to the requirement for artificial intelligent electronic systems capable of performing repeated identifications with high precision [4].

1.2 Brief Description of the Artificial Olfaction

The concept of odor detecting by an electrical measurement was presented in 1919 [5]. First implementation of an electrical instrument for odor detecting was reported in 1964 [6, 7]. In 1982 the concept of an artificial odor-sensing system was offered [8]. The term 'artificial nose' or 'electronic nose' was presented at the early of the 1990s and, some commercial instruments introduced [7]. Generally, artificial nose system comprises of three principal parts that work sequentially: an array of sensors, a signal processing unit, and a pattern recognition unit [9]. A typical block diagram of the artificial olfactory system for odor classification is presented in Figure 1.1.

The output of the artificial olfactory system can be used for:

- Gas detection
- Classification of different type gases
- Characteristics analyzing of the odor samples

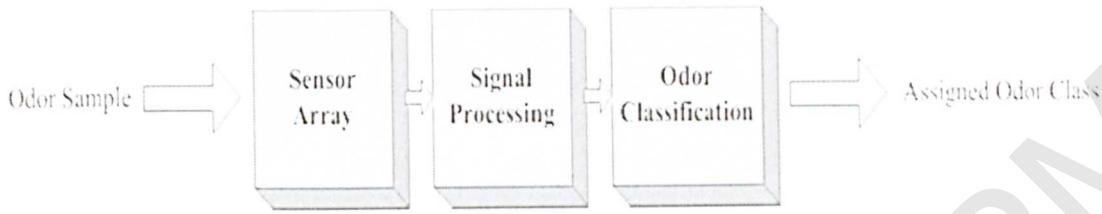

Figure 1.1. General structure of an artificial olfactory system

The sensors in artificial olfaction have a partial sensitivity, and respond to a range of gases. The ideal gas sensor, should respond to a particular gas but, many of gas sensors lack the specificity originally awaited and so they can be applied in artificial olfactory system [7]. The outputs of the sensor array are utilized to the signal processing and odor classification units. For gas identification, diverse methods and techniques could be applied at these phases. In the next stage, the evaluation of classification is done.

1.3 Problem Statement and Motivation

Nowadays, numerous applications of artificial olfaction resulted from research in broad sectors of sciences has been caused a considerable interests and attentions in enhancement of these systems. Most of researches are focused on the gas sensors of the system, and development of signal processing and pattern recognition techniques. Various attempts have been investigated on the gas sensors by applying different type of sensors such as conductive polymers [10-15], metal-oxide [16-31], surface acoustic wave [32-38], quartz crystal microbalance [39, 40] and also, developing the structure of sensor [41-48]. In terms of improving signal processing, various efforts have been reported on signal processing, feature extraction and classification techniques [49-80]. However, reported researches have generally applied the generic structure of artificial olfactory system.

A major problem in all the above investigations is that the classic structure of the artificial olfactory system is not suitable for critical applications such as medical diagnosis where reliability and precision are important. A study on the aging of gas sensors demonstrated after ten months, the fractional change in resistance due gas exposure has decreased due to aging issue that limits the operational life of the sensor [81]. Devices for medical applications must have high level of reliability. The fault in medical equipment has been very costly in terms of death and injuries [82]. A report from the US Food and Drug Administration (FDA) documented that about 44% of the quality-related problems were the result of errors that could have been prevented through effective design controls [83]. A study reported that over 15,000

products used in hospitals, about 4% to 6% were sufficiently dangerous to warrant immediate correction [84].

In classic structure, sensor array usually is composed of several different sensors which are chosen based on sensitivity to a particular gas present in environment. However, this architecture of sensor array cannot guarantee to deliver accurate information all the time, if one of these singular sensors is unavoidably failed by an electrical issue, aging, and other uncertainty issues. Parameter uncertainties included in the behavior of many physical processes in the most of practical applications are inevitable and failures of components often occur.

Other technical issues that sensors might be faced is about quality of services that offered by individual sensors. In artificial olfactory systems there is no mechanism to provide Quality of Service (QoS) for data collection from the sensors like as the sensor network field. The services offered by the generic sensor array not provide assurance about their quality [85]. The services need to be aware when the sensor array function falls below a certain level.

As mentioned previously, individual sensors are prone to high rates of failure [81]. Therefore, there is a critical requirement for architecture of sensors which can cope with failure of sensors and also provide acceptable quality of data for artificial olfactory systems.

The purpose of this study is offering a fault tolerant architecture for sensor array of artificial olfactory system. This architecture can resist over failures in the sensors of the array. The system is able to continue to operate in spite of faults in the sensors. The result is a system that can suffer from failure but this damage is not effect on its performance and system is able to recover the failure without direct human intervention. In the proposed architecture, by using a new technique which is called 'virtual sensors' the happened faults is masked and erroneous data is eliminated from the results.

The objectives of this thesis are presented below:

1- To design fault tolerant sensor array architecture for artificial olfactory systems that can mask failures and prevent from producing erroneous results
2- To characterize the proposed architecture in gas identification to investigate, the possibility of applying the virtual sensor as a selective gas sensor in detecting gases.
3- To verify the ability of the proposed architecture in odor identification at artificial olfactory system to evaluate the performance of the system

1.4 Scopes of Research

The scope of this research includes the following:

- In this research, for setup implementation metal oxide semiconductor gas sensors were used as the most available, easy to use, high sensitivity and long life features type of the chemical gas sensors.
- The proposed architecture is able to tolerate any number of faults at sensor array in artificial olfactory system. In this study, the implemented system was designed to tolerate one faulty sensor in the each cluster of sensors. Each cluster composed of three sensors. For correct operation, 2 out of 3 sensors must be in good mode.
- Various types of odor can be used to evaluate the system. In this study, odor databases were limited to the most reported cases in the literature. Short-chain alcohols as simple gases were applied in primary studies of the proposed architecture. In the analysis of the complex odors, fruits flavored drinks and tea beverages that are commonly used were applied to study the identification abilities of the developed artificial olfactory system.

1.5 Thesis Layout

The thesis is organized into five Chapters.

In Chapter 2, a literature review of the natural olfaction system and artificial olfaction instruments is presented. Since modern artificial olfaction instruments are mimicking the mammalian olfactory system, biological olfaction is described. The general structure of the electronic nose is described in detail. Different analyzing techniques applied in artificial olfaction, including preprocessing, feature extraction, classification and evaluation metrics are presented.

The proposed architecture is presented in Chapter 3. Details of design are described. Different levels of system are demonstrated. The fabricated system components are explained. A reliability model for system is also introduced. Experiments to the evaluation of the virtual sensor in gas detection are clarified in details. Also, this Chapter describes how the virtual sensor can be applied as a gas sensor to discriminate a group of gases. Signal processing and the nearest neighbor classification methods are applied for gas detection. Moreover, the ability of the developed structure based on the virtual sensor to discriminate complex odors is explained.

In Chapter 4, the performance of the virtual sensor in healthy mode, facing with sensor failure and, the accuracy of the virtual sensor in gas concentration prediction are studied. The performance of the proposed architecture is compared with generic form of the sensor array. Also, the ability of the developed structure based on the virtual sensor to discriminate complex odors and also, the performance of system in

faulty situation are studied. The performance of system in healthy mode and faulty mode are compared. Also, this Chapter discusses the ability of the developed structure to discriminate similar odor samples. Applicability of the developed system in analyzing components of green tea drinks from different manufacturers is investigated. The discrimination performance of k-NN and MLP classifiers is also evaluated.

The future directions, applications and conclusions drawn from this research are summarized in Chapter 5.

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