Gas Source Localization via Behaviour Based Mobile Robot and Weighted Arithmetic Mean

by

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TABLE OF CONTENTS

THESIS DECLARATION **II**

ACKNOWLEDGEMENT **III**

TABLE OF CONTENTS **IV**

LIST OF TABLES **VIII**

LIST OF FIGURES **IX**

LIST OF ABBREVIATIONS **XI**

ABSTRAK **XII**

ABSTRACT **XIII**

CHAPTER 1: INTRODUCTION **1**

1.1 Mobile Olfaction Overview 1

1.1.1 Gas Plume Searching 2

1.1.2 Gas Plume Tracing 3

1.1.3 Gas Source Declaration 3

1.1.4 Chemotaxis 5

1.1.5 Organic Equivalent 5

1.1.6 Behaviour Based Robot 6

1.2 Problem Statement 7

1.3 Research Objectives 9

1.4 Contributions of Study 10

1.5 Scope of Study 11

1.6 Thesis Outline 12

CHAPTER 2: LITERATURE REVIEW 14

2.1 Gas Sensor Technology 14

2.1.1 Metal Oxide (MOX) Gas Sensor 15

2.1.2 Conductive Polymer (CP) 15

2.1.3 Optical Based Sensors 16

2.2 Gas Distribution 16

2.3 Gas Source Localization 17

2.3.1 Chemotaxis 18

2.3.2 Chemo-Anemotaxis 27

2.3.3 Infotaxis 29

2.3.4 Gas Distribution Map 29

2.4 Gas Source Declaration 30

2.5 Mobile Robot Localization 31

2.6 Summary of Literature Review 32

CHAPTER 3: METHODOLOGY AND SYSTEM ARCHITECTURE 39

3.1 Overall Research Approach 39

3.2 Gas Source Localization System 43

3.2.1 System Architecture 43

3.2.2 Integrated Mobile Robot 44

3.3.3 Integrated Mobile Robot Testbed 51

CHAPTER 4: PRELIMINARY EXPERIMENTS 67

4.1 Introduction of Preliminary Experiments 67

4.2 Testbed Observation 68
4.2.1 Objective of Testbed Observation 68
4.2.2 Experimental Setup of Testbed Observation 69
4.2.3 Results and Discussion of Testbed Observation 70
4.3 Gas Sensor Performance Test 77
4.3.1 Objective of Gas Sensor Performance Test 77
4.3.2 Experimental Setup of Gas Sensor Performance Test 77
4.3.3 Results and Discussion of Gas Sensor Performance Test 80
4.4 Preliminary Experiments Conclusion 88
CHAPTER 5: GAS SOURCE LOCALIZATION EXPERIMENTS 90
5.1 Introduction of Gas Source Localization 90
5.2 Behaviour Based Algorithm 90
5.2.1 Zig-Zag (Searching Phase) 91
5.2.2 Braitenberg (Tracing Phase) 94
5.2.3 Combined Braitenberg with Zig-Zag (B+Z) 97
5.2.4 Gas Source Declaration Strategy 100
5.3 Experimental Setup of Gas Source Localization Experiments 103
5.4 Results and Discussion of Gas Source Localization Experiments 104
5.4.1 Performance Comparison 106
5.4.2 Successful Tracing Period (STP) 116
CHAPTER 6: CONCLUSION 119
6.1 Research Summary 119
6.2 Highlight of Contributions 122
6.3 Future Work 122

REFERENCES **124**

APPENDIX – A **132**

LIST OF PUBLICATIONS **134**

LIST OF TABLES

NO		PAGE
2.1	Summary of research of chemotaxis algorithms for gas source localization.	34
4.1	Gas distribution map at time, t=60s, 180s, 300s, 480s, 600s, 1200s, 1800s, and 2400s for Testbed Observation 1.	71
4.2	Gas distribution map at time, t=60s, 180s, 300s, 480s, 600s, 1200s, 1800s, and 2400s for Testbed Observation 2.	74
4.3	Summary of the analysis of the effects of mobile robot movement speed on gas sensor performance.	87
5.1	Full results of the Zig-Zag algorithm from Run 1 to Run 5.	107
5.2	Full results of the Braitenberg (Attract) algorithm from Run 1 to Run 10.	107
5.3	Full results of the Braitenberg (Repel) algorithm from Run 1 to Run 10.	108
5.4	Full results of the B+Z (Attract) algorithm from Run 1 to Run 20.	108
5.5	Full results of the B+Z (Repel) algorithm from Run 1 to Run 20.	109
5.6	Calculated gas source declaration errors from Type-E and Type-F GSD.	116
5.7	Summary of STP count and average time spent in STP effects on Type-C GSD error for the Braitenberg and B+Z algorithms.	118

LIST OF FIGURES

NO		PAGE
3.1	Overall research process.	42
3.2	Overview of the integrated system used throughout this work.	43
3.3	The modified Arduino Mobile Robot platform.	44
3.4	The Arduino Uno microcontroller board mounted on the mobile robot.	45
3.5	The Arduino Wi-Fi shield board.	46
3.6	TGS 2600 sensitivity characteristics.	48
3.7	Pre-calibrated sensor signal, *s* values corresponding to the actual gas concentration in ppm	49
3.8	The IR01A sensor module.	50
3.9	The mobile robot testbed consisting of A: Ceiling mounted cameras, B: Gas sensors, C: MEMSIC wireless module and D: Sensor board.	51
3.10	Gas sensor configurations in the array.	53
3.11	WSN transmitting flowchart.	56
3.12	Flowchart of the robot tracking system process.	58
3.13	Calibration grid with radial distortion.	59
3.14	Calibration template.	59
3.15	Images from all four cameras with fish eye effect (a) and the calibrated image (b).	62
3.16	Pattern templates used to track mobile robots position.	63
3.17	Perspective error due to mobile robot height.	66
4.1	The robot's trajectory and gas sensor measurements for 5cm/s Type-A Run 3.	83
4.2	Interpolated LGSA measurements on t=157s (left) and t=179s (right).	84
4.3	The interpolated LGSA measurements on t=253s (left) and t=263s (right).	84
4.4	The robot's trajectory and gas sensor measurements for 5cm/s Type-A Run 3.	85

4.5	Interpolated LGSA measurements on t=122s (left) and t=126s (right).	86
4.6	The interpolated LGSA measurements on t=152s (left) and t=171s (right).	86
5.1	Flowchart of the Zig-Zag algorithm for the mobile robot's gas searching phase.	93
5.2	Pseudocode for ZigZag algorithm.	93
5.3	Flowchart of the Braitenberg strategies where (a) shows the repel strategy and (b) shows the attract strategy.	96
5.4	Pseudocode for Braitenberg algorithm.	97
5.5	Flowchart of the B+Z algorithm.	99
5.6	Pseudocode for B+Z algorithm.	100
5.7	Sensor signal values from Braitenberg (Attract) Run 4.	105
5.8	The mobile robot's trajectory after implementing the Zig-Zag algorithm.	106
5.9	The robot's trajectory implementing the Braitenberg Attract algorithm.	111
5.10	A part of the sensor signal values and robot's trajectory for B+Z Attract Run 1.	113
5.11	Robot's trajectory and LGSA measurements of the B+Z Attract Run 7.	114
5.12	Robot's trajectory and LGSA measurements of the B+Z Repel Run 10.	115

LIST OF ABBREVIATIONS

ACK	Acknowledgement
ANN	Artificial Neural Network
BBR	Behaviour Based Robot
BE	Backoff Exponent
BI	Bio-Inspired
CP	Conductive Polymer
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
GD	Gas Detection
GSD	Gas Source Declaration
IDE	Integrated Development Environment
IGD	Initial Gas Detection
I/O	Input Output
LGSA	Large Gas Sensor Array
MLFF	Multi-layered Feedforward
MOX	Metal Oxide
OSL	Odour Source Localization
PF	Particle Filter
RF	Radio Frequency
STP	Successful Tracing Period
WSN	Wireless Sensor Network

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ABSTRAK

Kajian ini bertujuan untuk menyelesaikan masalah mencari lokasi sumber gas di persekitaran dalaman yang dinamik menggunakan sebuah robot bersepadu mudah alih yang automatik. Disebabkan robot tidak mempunyai apa-apa pengetahuan tentang persekitarannya, sebuah algoritma yang bijak diperlukan untuk membolehkan robot mengatur pergerakan di dalam persekitaran tersebut tanpa masalah seperti bertembung dengan objek lain. Semua eksperimen yang dijalankan didalam kajian ini dijalankan di atas sebuah kawasan ujian yang dilengkapi dengan jajaran sensor gas besar untuk memerhati kepekatan gas di dalam kawasan ujian tersebut. Sebuah sistem penjejakan corak juga digunakan untuk menjejaki pergerakan robot. Pada mulanya, dua kajian telah dijalankan untuk menambah pengetahuan tentang persekiran di dalam kawasan ujian tersebut dan juga prestasi sensor gas ketika robot bergerak dengan pelbagai kelajuan. Dari kajian tersebut, didapati bahawa, persekitaran di dalam kawasan ujian adalah dinamik dan prestasi sensor gas ketika robot bergerak perlahan dan laju adalah berbeza. Dengan pengetahuan ini, kajian diteruskan dengan ujian mencari lokasi sumber gas dengan dua algoritma iaitu Zig-Zag dan Braitenberg. Algortima Braitenberg boleh dipecahkan kepada dua jenis iaitu 'Tarik' dan 'Tolak'. Dari ujian ini, didapati bahawa pergerakan robot adalah terhad dengan algoritma Zig-Zag tetapi ia berjaya meliputi keseluruhan kawasan ujian tanpa masalah. Manakala, pergerakan robot adalah lebih bebas dengan algoritma Braitenberg dan robot berjaya menjumpai kawasan yang berkepekatan gas tinggi dengan lebih cepat. Tetapi robot tidak dapat meliputi seluruh kawasan ujian kerana ia lebih kerap berkeliaran di kawasan berkepekatan gas yang tinggi sahaja. Dengan data yang diperolehi dari kedua algoritma ini, kedua-dua algoritma digabung menjadi satu algoritma berbilang fasa iaitu algoritma B+Z. B+Z boleh menukar fasanya secara automatik berdasarkan bacaan sensor gas. Dengan algoritma ini, robot berjaya meliputi seluruh kawasan ujian dan memiliki sensitiviti yang baik terhadap kepekatan gas di kawasan persekitaran. Bagi proses mendeklarasikan lokasi sumber gas pula, kami menggunakan min aritmetik wajaran. Semua keputusan yang biasa dikaji didalam bidang ini seperti kejauhan robot bergerak dan ralat deklarasi lokasi sumber gas telah disertakan didalam tesis ini. Bagi algoritma berbilang fasa B+Z, kami mendapati bahawa robot berjaya mengira lokasi sumber gas dengan ralat sebanyak 0.5m hingga 1.2m disamping mencatatkan masa ujian dan jarak pergerakan yang lebih singkat dari Braitenberg. Tambahan lagi, kami mendapati bahawa ralat menjadi semakin kecil apabila robot kerap berjalan semasa didalam fasa 'mengesan' gas.

Gas Source Localization via Behaviour Based Mobile Robot and Weighted Arithmetic Mean

ABSTRACT

This research is concerned with the localization of gas source in a dynamic indoor environment problem using a single mobile robot system. Since the environment is unknown to the robot, an intelligent algorithm is required to enable the robot to traverse through the environment without any interruption from obstacles. All experiments were done on an experimental testbed consisting of a large gas sensor array (LGSA) to monitor real-time gas concentration within the testbed. The measurements from the LGSA were taken as the ground truth and were useful as it can be compared to the measurements taken from the gas sensors on the mobile robot. A pattern tracking system was also utilized to record the robot's odometry. Initially, two preliminary experiments were conducted to better understand the conditions within the experimental testbed and the gas sensor's performance within the environment when the robot is moving at different speeds. From the preliminary experiments, we can confirm that the conditions within the testbed are indeed dynamic and gas sensor's performance differs when the mobile robot is moving at different speeds. We then proceed to implement two algorithms (i.e Zig-Zag and Braitenberg) to test the robot's performance in traversing through the experimental testbed while taking gas sensor measurements. The Braitenberg algorithm was separated into two variants (i.e Repel and Attract) which then were implemented with the mobile robot. From the experiments, we found that the Zig-Zag were too rigid but can ensure complete coverage of the testbed. Meanwhile, the Braitenberg can arrive at higher gas concentration areas faster but covering the whole testbed is unlikely as the mobile robot lingered more around higher gas concentration area. With the information gained from the two algorithms, we then implemented a multiphase algorithm (i.e B+Z algorithm) consisting the best of both. The B+Z was able to switch between states (i.e. searching and tracing) based on gas sensor measurements and was able to ensure full coverage of the testbed while being more sensitive to gas sensor measurements. For gas source declaration, we exploited the weighted arithmetic mean to calculate and predict the source location. Typically measured results such as run time, distance traveled and localization errors were presented. Gas source localization errors for the B+Z algorithm were around 0.5m to 1.2m with average traveled distance and faster runtime than the original Braitenberg. Lastly, we did a slight study on how the 'tracing' phase affected the gas source localization errors for the B+Z algorithm. From the short analysis, we found that the localization errors are smaller when the mobile robot spent more time in 'tracing' phase.

CHAPTER 1

INTRODUCTION

1.1. Mobile Olfaction Overview

Mobile olfaction is a research field which emphasizes on searching, tracking and localizing the location of gas or odor sources in the environment using mobile robots. It is motivated by studies on chemotaxis in living organisms such as insects and bacteria. This research field is still young and just recently gained its momentum amongst researchers with the advancement of available gas sensors. In the 20th century or earlier, robots that can sense changes in the environment only exist in imagination or often projected in Sci-Fi films. The need for industrial and field applications of mobile robots are continuously being sought and gaining quite a reasonable importance, especially for autonomous operation with high reliability (uninterrupted, error-free and seamless manoeuvers) performing inspection, surveillance or even search and rescue task.

Work on mobile olfaction began by mimicking the behaviour of organisms based on the studies of chemotaxis on bacteria being attracted or repelled by chemicals. Combining our understanding of chemotaxis with the recent advancements in mobile robotics, the world now have a mature and popular research field which consists of using mobile robots and gas sensors to find, trace and localize chemical gas plumes. While the early works on mobile olfaction only began in the early 1990s, it was believed that Larcombe and Halsall (1984) was the first work where chemically sensitive robot devices were seriously being discussed to be deployed in the hazardous nuclear industry's environment. Since then, gas mobile olfaction and mainly gas source localization in general can be divided into three equally important sub problems that need to be solved:

a. Gas plume searching.
b. Gas plume tracing.
c. Gas source declaration.

1.1.1. Gas Plume Searching

The first and the most crucial stage in mobile olfaction is gas plume searching. This is where the mobile robot is being tasked to find or detect the odor clues in a given space or an environment. With an unsuitable gas plumes searching technique, the mobile robot might get stuck in this phase perpetually which makes this step very crucial. In a dynamic real world environment, wind speed and direction is constantly changing and could be the determining factor in the success and failure of solving gas plume searching.

Commonly used technique or algorithm for gas plume searching is by searching upwind because gasses will always travel in the air along with the wind in the same direction. The mobile robot might still miss the gas plume as it travels upwind if the implemented searching technique is not able to cover a large dynamic environment. There are also other factors that are detrimental to the success of solving this step such as gas sensor position, gas sensor sensitivity, gas sensor response time and others.

In an indoor environment where the physical state of the space or room inside a building is known, wind information is less likely needed. A carefully planned searching algorithm can manage to traverse through the whole area without problems but the time to cover the whole area might differ based on the mobile robot's speed and the size of the area.

1.1.2. Gas Plume Tracing

After finding the gas plume, the mobile robot will need to solve the second problem of mobile olfaction which is gas plume tracing or in other words, move reactively along or within the gas plume. The most common technique in plume tracing is by taking measurements of the gas concentration at different points and calculates its difference to gain information about the gas plume gradient which then can be exploited to navigate the mobile robot to the gas source. In a multiple gas sensor configuration, a sufficiently separated gas sensors may help tremendously in steering the mobile robot to the best direction to navigate through by comparing all of its sensor values. Nearly equal measurements may be obtained by placing the gas sensors too close together thus making it difficult to navigate the mobile robot.

A robust algorithm to control the robot motor's speed is needed to successfully trace a plume because gas dispersion is unpredictable it is easy to oversteer and moving out of the plume thus cutting short the tracing phase.

1.1.3. Gas Source Declaration

The definition of gas source declaration varies from research group to research group. According to Lilienthal et al. (2004), gas source declaration is the process of determining the certainty that the gas source is in the immediate vicinity thus ending the robot's run. The main obstacle in solving this problem is the turbulent nature of gas flow in natural environment which may lead to multiple locations with gas concentration maxima thus making the search for instantaneous concentration maxima an unreliable technique to solve the problem because the first concentration maxima found by the mobile robot might not be accurate if the source has been active for some time.

Up till now, there are only a few techniques to solve the gas source declaration problem and most of them involved the authors of past works to declare an area surrounding the known gas source location as the goal which means that if the mobile robot enters the area, it is count as a successful experimental run. Recently there have been machine learning and neural network algorithms to identify and classify the robot of being in the proximity of a gas source in certain conditions. The mobile robot will end its experimental run when the certain conditions are met and declare the gas source is in the near proximity but machine learning and neural network algorithms require more memory and processing power.

Gas distribution mapping technique by combining gas sensor data with location estimations can also be classified as a gas declaration technique by some research groups where the declaration is performed by the researcher by interpreting the map generated by the robots (Cabrita & Marques, 2013). To avoid semantics and definitions, this thesis takes both cases into consideration to approach the gas source declaration problem. In this research, we would like to implement weighted arithmetic mean to calculate the position of the gas source instead of using the traditional way which is declaring the run as successful or a failure depending on the mobile robot's ability to get into the close proximity of the source.

1.1.4. Chemotaxis

The term chemotaxis is common used in this thesis. According to Kowadlo and Russell (2008), the term can become inconsistent as different authors give different meanings but it is often used to characterize their algorithms where a measured chemical gradient is used in a specific way. In a more generic way to explain the term, Merriam-Webster Medical Dictionary defined it as "Orientation or movement of an organism or cell in relation to chemical agents". Therefore, the term chemotaxis in this thesis is not just exclusive to referring the use of any sort of chemical gradient but all actions done by responding to chemical agents.

1.1.5. Organic Equivalent

Mobile olfaction is highly related to some living organisms such as moths, *E.coli* bacteria, dung beetles and lobsters. Researchers has been mimicking and implementing the behaviours of these organisms on mobile robots because it is one of the viable ways to solve the problems in mobile olfaction.

A male moth for example is focused on the species-specific sex attractant to locate potential mates. Studies of the moth's olfactory-guided navigation have been thoroughly done. Moths often respond to the wind by flying or walking to into the direction of where the wind came from or typically called moving upwind. Moths are also internally programmed to counterturn upon detection of an attractive odour. By combining these two key mechanisms, a behaviour where the moth will travel in zig-zag upwind path to track airborne plumes of attractive odours can be mimicked. This particular behaviour can be implemented on a mobile robot to perform olfactory tasks. A work was done by Webb et al. (2004) on implementing and comparing between robotic and biological behaviour has found that the tracking behaviour is a viable method to solve gas plume searching and tracing where the tracking behaviour depends on reacting upon the detection and the loss of the gas plume.

Lobsters are also capable to track plumes to its source. It is important for decapod crustaceans to overcome of its challenges in life that is to locate food, shelter and conspecifics. Lobsters rely heavily on their olfactory senses to solve the problems. Unlike vertebrates which have an enclosed olfactory system, decapod crustaceans have external antennae that are studded with mechanical and chemical sensors. This can be applied to mobile robotics by placing gas sensors spatially on mobile robots. The spatially placed sensors act as external antennae to guide the robot's movement to the gas source just like the lobster uses its external antennae to sense and guide its way during its search for food.

Other than moths and lobsters, multiple studies have shown that there are other organisms which use olfactory senses to complete some of their tasks. *E.coli* bacteria use odour localization to detect nutrients. Dung beetles also use odour localization to locate feces for food and shelter. The algorithms and mobile robot design in this work took some of the best part of all mentioned organism behaviours and characteristics.

1.1.6. Behaviour Based Robot

A behaviour based robot (BBR) will react and correct its actions with the information gained from the robot's sensors which is similar to reactive algorithms. The correction made by the robot must have zero outside intervention such as human intervention or intervention from the programming side of the robot. This means that an ideal BBR relies fully on its electronics capabilities and does not need the programming of its corrective actions or a correct model of the environment. This will result in much less computational cost and the BBR will exhibit behaviours that can be commonly observed on living organisms. Such behaviours that were shown by the BBR can be interpreted as the robot possesses low level artificial intelligence. Some behaviour could also exhibit anthropomorphic qualities.

In recent years, the increase of interest in BBR can be witnessed especially in developing behaviour based architecture for complex autonomous systems. While in theory a BBR could solve the difficulties it faces and achieve its goal independently, it also introduces new questions and problems such as the coordination of multiple possible behaviours trying to act on the same actuators. The continuances of such problems are signs of the research and development of BBR is still an open research field.

1.2. Problem Statement

Advancements in technology and industry are leading us towards a high standard of living. However, the advancements also introduced some negative effects into our daily lives such as combustible and toxic gas leakages. Although the development of gas monitoring and detection system has been improved in recent years because of the advancements of gas sensor technology, the methods of detection and monitoring have stagnated. Static gas detectors are still being widely used in buildings while human operated portable gas detector has the probability to harm the human operator during its operation. Furthermore, there are limitations on current gas sensors in terms of response time, recovery time, sensitivity and even life span. As an example, pheromone and polymer gas sensors degrade too fast while metal oxide gas sensors can last a longer but the response and recovery time still needs improving.

When mobile robots were introduced as an aid or even a substitute in gas sensing and monitoring tasks, it presents additional problems. To develop an autonomous gas sensing mobile robots, there are a few critical systems of the mobile robots besides the e-nose systems that are needed to be simultaneously develop too such as path planning, mobile robot localization and real-time data analysis. These aspects of mobile robotics are turning the straight forward goal of localizing gas sources into multiple complex problems. While precise ready-made mobile robots are available on the market, they are expensive which might not be cost-effective for widespread usage.

In terms of algorithms, earlier works in this field often utilized set of rigid instructions that were implemented on mobile robots. Moreover, the algorithms often require the robot to first stop then measure the gas concentration value before proceeding with the desired maneuver. The instructions act as a ‘what to do list’ in a certain situations that will move the robot towards the goal. As an example, a certain radius of turning maneuver or a certain distance of forward movement after stopping for a certain amount of time to take gas sensor measurements. In time, researchers in this field proceed to integrate wind information into their algorithm. This leads to some new gas searching techniques. Although wind information is helpful, the searching techniques by exploiting wind information sometimes lead the mobile robot to traverse upwind while entirely missing the gas plume that is travelling downwind but not crossing the path of the mobile robot.

With regard to the gas source declaration method, earlier works focused on making the mobile robot to arrive within a certain radius from the actual gas source. This method while valid is biased with the assumption that the mobile robot knows that it has arrived near the actual gas source. Furthermore, artificial neural network (ANN) was utilized to make the mobile robot recognize that it has found the actual gas source but this technique requires extensive development time for training. Moreover, recently researchers have made advancements in Gas Distribution Mapping (GDM) to solve the gas source localization problem, but the requirements that are needed to be met by the mobile robot in terms of computing and memory is too costly.

Finally, there is no standard external system or method to verify the gas sensor measurements from the mobile robot. Researchers have been using cameras to verify the mobile robot's trajectory, pose and odometry in the past but very few have tried to verify the gas sensor measurements taken by the mobile robot.

1.3. Research Objectives

The main objective of this research is to study, implement and analyze the performance of the implemented algorithms to solve the three main problems of gas source localization. The proposed system focuses on building a reactive mobile robot equipped with gas sensors to find gas plumes and then tracing it to its source. Apart from that, developing a method of declaring the gas plume source is also a focus of this work. This research can be divided into sub-objectives to achieve the stated goal:

1. To design and develop a mobile robot system for mobile olfaction applications.

2. To design and implement a reactive multiphase algorithm on the developed mobile robot system and implement a mathematical gas source declaration method.
3. To analyze the overall performance of the developed mobile robot with its algorithm and the gas source declaration method in an indoor environment.

1.4. Contributions of Study

This research could contribute several ideas and solutions for mobile olfaction applications. This system can be further improved on and deployed in industries that are dealing with highly combustible, hazardous and toxic gasses. The followings are the specific contributions of this thesis:

1. The introduction of new mobile robot system design to perform gas source localization tasks in real-time including gas plume searching, gas plume tracing and gas source declaration by integrating mobile robot, sensors, devices and other sub-systems as well as software implementation. [covered in Chapter 3]
2. Implementation of the Zig-Zag and Braitenberg algorithms to search and trace gas plume inside the implemented testbed and a combination of the two algorithms into one multiphase B+Z algorithm and its implementation.[covered in Chapter 5]
3. Introduction of Weighted Arithmetic Mean to solve gas source declaration problem; allowing the calculation of gas source position. [covered in Chapter 5]

1.5. Scope of Study

The scope of this research is narrowed down to mainly solving the gas source localization problem in an indoor environment. All experimental works involving the mobile robot were done in an uncontrolled indoor environment, specifically on the developed integrated testbed. Wind information was not taken into consideration within this work. It was assumed that the indoor air speed is between 10cm/s to 12cm/s which was rated as the average indoor air speed by ISO Standard 7730 (2005).

Furthermore, the mobile robot in this research utilized dual gas sensor configuration instead of the usual single gas sensor configuration or multiple gas sensor configurations. Two Figaro TGS 2600 MOX gas sensor were mounted on the robot with one on each side with a height of 10cm respective to the testbed floor and 18cm of separation between each other.

Moreover, this work utilized the Large Gas Sensor Array (LGSA) which consisted of 72 TGS 2600 MOX gas sensors for gas sensor measurement verification. This work also utilized a robot tracking system which consisted of four ceiling mounted cameras to verify the mobile robot's position.

Finally, this work only utilized ethanol as the gas source as it is considered to be safe for research purposes. Ethanol was released at a height of 20cm at a location inside the testbed by using a blower mechanism mimicking a gas pipe leakage.

1.6. Thesis Outline

Chapter 1 of this thesis is about the introduction of this research. This chapter started by a brief introduction on mobile olfaction, its problems and some definitions. Furthermore, this chapter also highlights the relation of mobile olfaction to real living organisms and also a short introduction to BBR. Finally this chapter clarified the problem statements, objectives and the contributions of this research.

Chapter 2 is a literature review of related works. A thorough review of previous works that were done by other researchers in the field of mobile olfaction was explained in this chapter. It highlights the types of sensors, mobile robots, method used and results from the researches. More importantly, chapter 2 also highlights the ideas and suggestions discussed by the researchers to improve their work.

Chapter 3 is mainly about the hardware and system architecture of this research. This chapter aims to give an overview about all the developed mobile robot, systems and subsystems during the course of this research. Explanation on each hardware utilized in this work and its functionality were also given for better understanding on why they were chosen.

Chapter 4 of this thesis composed the results and discussions raised from earlier parts of this research which is a set of preliminary experiments to obtain suitable parameters that are needed to fine-tuned the algorithms and experimental setup. The usefulness of the integrated testbed is mainly shown here as the comparison of data