# An Improved Mobile Robot Based Gas Source Localization with Temperature and Humidity Compensation via SLAM and Gas Distribution Mapping

by

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**THESIS DECLARATION**

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# TABLE OF CONTENTS

# LIST OF TABLES

**LIST OF FIGURES**

## LIST OF ABBREVIATIONS

| | |
|---|---|
| CP | Conductive Polymer |
| CV | Cross Validation |
| DC | Direct Current |
| DP | Distributed Particle |
| EC | Electrochemical |
| EMI | Electromagnetic Interference |
| FOV | Field of View |
| FPGA | Field-Programmable Gate Array |
| GDM | Gas Distribution Mapping |
| GPM | Gaussian Process Mixture |
| GPS | Global Positioning System |
| GSC | Gas Sensor Characterization |
| ICC | Instantaneous Center of Curvature |
| IP | Internet Protocol |
| MOX | Metal Oxide |
| MSE | Mean Square Error |
| PID | Photo Ionization Detector |
| RAM | Random Access Memory |
| RBPF | Rao-Blackwellised Particle Filter |
| RFI | Radio Frequency Interference |
| RGB | Red Green Blue |
| RGB-D | Red Green Blue – Depth |
| ROS | Robot Operating System |
| SLAM | Simultaneous Localization and Mapping |
| SPA | Sparse Pose Adjustment |

| | |
|---|---|
| TCP | Transmission Control Protocol |
| USB | Universal Serial Bus |
| UV | Ultraviolet |
| VOC | Volatile Organic Compound |
| WI-FI | Wireless Fidelity |

**Penambahbaikan Penentuan Lokasi Sumber Gas Berdasarkan Robot Bergerak dengan Mengambil Kira Suhu dan Kelembapan serta Melalui SLAM dan Pemetaan Peredaran Gas**

## ABSTRAK

Kajian ini meliputi masalah menentukan lokasi sumber gas di persekitaran dalaman dengan menggunakan sebuah robot mudah alih. Masalah ini adalah hampir sama seperti situasi kebocoran gas berbahaya dalam bangunan. Memandangkan keadaan persekitaran tempat tersebut tidak diketahui oleh robot, operasi Penempatan dan Pemetaan Serentak (SLAM) diperlukan. Dua teknik SLAM (iaitu Gmapping dan Hector SLAM) telah digunakan untuk memberikan maklumat penting ini. Hasil eksperimen dan analisis menunjukkan bahawa Hector SLAM lebih sesuai untuk tugasan pemetaan peredaran gas (GDM) disebabkan oleh ketepatan yang lebih baik dari segi anggaran kedudukan robot, keperluan pengiraan yang lebih rendah dan hanya membaiki peta di kawasan berhampiran. Oleh itu, Hector SLAM digabungkan dengan algoritma Kernel DM+V untuk mencapai penyelesaian SLAM-GDM bagi meramal kedudukan punca gas. Beberapa eksperimen telah dijalankan untuk mengesahkan prestasi kaedah SLAM-GDM dalam bangunan pejabat dan dengan kehadiran gas etanol. Keputusan eksperimen menunjukkan bahawa ramalan lokasi sumber gas sering tepat pada lingkungan 0.5 hingga 2.0m. Di samping itu, algoritma Kernel DM+V berdasarkan Kernel Epanechnikov juga telah diperkenalkan untuk mengehadkan jarak ekstrapolasi dalam pengiraan GDM. Kelebihannya adalah keperluan pengiraan yang lebih rendah dan ramalan lokasi sumber gas yang lebih tepat. Lebih penting lagi, peta yang dihasilkan dapat menunjukkan kawasan peredaran gas yang belum diterokai oleh robot dan seterusnya boleh digunakan untuk merancang laluan robot. Bahagian akhir dan utama dalam tesis ini membincangkan kesan suhu dan kelembapan persekitaran terhadap tindak balas sensor gas (iaitu TGS 2600) yang seterusnya boleh mempengaruhi keputusan GDM. Proses regresi linear telah dijalankan untuk mewujudkan satu model bagi membetulkan ralat suhu dan kelembapan. Model ini telah diuji dalam pelbagai konfigurasi dan didapati mampu mengurangkan kesan kedua-dua faktor tersebut terhadap tindak balas sensor dalam kepekatan gas yang berbeza. Akhir sekali, dua versi algoritma Kernel DM+V/T/H telah dicadangkan dan digabungkan dengan model tersebut untuk mengambil kira suhu dan kelembapan persekitaran semasa tugasan pemetaan gas. Keputusan eksperimen menunjukkan bahawa algoritma Kernel DM+V/T/H berjaya menghasilkan peta peredaran gas yang lebih stabil dan ramalan lokasi sumber gas yang lebih tepat berbanding Kernel DM+V sebanyak 34%.

**An Improved Mobile Robot Based Gas Source Localization with Temperature and Humidity Compensation via SLAM and Gas Distribution Mapping**

## ABSTRACT

This research is concerned with the problem of localizing gas source in indoor environment using a mobile robot. The problem could be seen as similar to the event of hazardous gas leak in a building. Since the environment is often unknown to the robot, the Simultaneous Localization and Mapping (SLAM) operation is required. Two open source SLAM techniques (i.e. Gmapping and Hector SLAM) were implemented to provide this crucial information. Extensive experiments and analysis on both SLAM techniques yielded that the Hector SLAM is more suitable for gas distribution mapping (GDM) application due to the improved robot pose estimation, less computational requirement and only performs map correction locally. Therefore, the Hector SLAM is combined with Kernel DM+V algorithm to achieve real-time SLAM-GDM for predicting gas source location. Rigorous real-time experiments were conducted to verify the performance of the proposed SLAM-GDM method in an uncontrolled office building with the presence of ethanol emission. The experimental results showed that the prediction of gas source location is often accurate to 0.5 to 2.0m. Furthermore, an Epanechnikov based Kernel DM+V algorithm was also introduced to limit extrapolation range in GDM computations. The observed advantages were lower computational requirement and slightly more accurate prediction on gas source location. More importantly, it was found that the maps produced were able to indicate the areas of unexplored gas distribution and therefore could be used for the robot's path planning. The final and the main part of the thesis deals with the effect of ambient temperature and humidity on metal oxide gas sensor (i.e. TGS 2600) response; which could affect the GDM results. Linear regression processes were conducted to create a model to correct the temperature and humidity drift of the gas sensor response. The model (i.e. function) was tested in various configurations and was found to minimize the effects of the two environmental factors on the gas sensor response in different gas concentrations. Finally, two versions of Kernel DM+V/T/H algorithms were proposed and coupled with the drift model to compensate for temperature and humidity variation during the GDM task. The experimental results showed that the Kernel DM+V/T/H algorithms were able to produce more stable gas distribution maps and improve the accuracy of gas source localization prediction by 34%.

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Olfaction is the ability of an organism to sense smell by detecting tiny particles of substance that evaporate and spread through air. Most animals and insects use their olfactory senses in order to locate food sources, find mate, detect predator and mark territory (Wyatt, 2003). While in human, the sense of smell has been said to influence emotional and aesthetical aspects that affect the social interaction with others as well as subjective perception to the surrounding. Even though the olfactory system is important, human still lack proper vocabularies to describe odour precisely. They tend to describe smells using vague or abstract terms related to their personal experience or similarity to other odour (Loutfi, 2006). Animals have been said to have more sensitive olfactory system compared to human. For instance, a dog that possesses around 220 million olfactory receptors has a thousand times more sensitive sense of smell than a human with 5 million receptors (Correa, 2005).

Furthermore, the human's olfactory sense has limited capability such that it is not able to detect the presence of certain gases and distinguish between them. Although there are gases that could be sensed, often the source's location could not be determined accurately. There could also be situations where human get exposed to harmful gas and being silently harmed or killed.

Since the beginning of the 1990s, the gas sensing technology with mobile robot has been an active research study. The motivations are due to critical problems such as detecting drugs and explosive, identifying gas leaks location, early detection of fire and as well as monitoring polluted area. One real example of such problem is the massive explosion in Koahsiung, Taiwan on the 31st July 2014. It was reported that there were a series of five explosions along sewage system's pipeline; killing at least 25 people and injuring 265 people. The event was described to have been caused by gas leak and among the victims were four fire-fighters who were inspecting for the leakage (MailOnline, 2014).



## 1.2 Problem Statement

The presence of toxic gases in the environment can be harmful to human. A person may not be aware of their presence and can be silently poisoned or killed. On the other hand, the leakage of natural gases could cause headache, fatigue, loss of consciousness and death. More importantly, this type of gas is highly flammable; thus a tiny spark could result in massive fire or explosion. The current technique of detecting the gas leak location requires involvement of human operators on-site. For instance, the rescuers need to carry portable gas detectors to several suspected area for monitoring the gas concentration. However, this practice could risk their lives and prone to error or misinterpretation.

Mobile robot equipped with olfactory system could be used to determine the location of gas source while being monitored remotely by human operators. Nevertheless, in a real-life situation, the surrounding area is often unknown; thus requiring the robot to localize itself and map the environment. Moreover, the current gas sensor technologies also suffer from many issues such as slow response, non-selectivity and highly affected by temperature and humidity of the surrounding. The problems are further enhanced by the existence of wind and the variability of gas movement such as through diffusion and turbulence (Patrick P Neumann, 2013). In particular, this thesis attempts to solve the problem of localizing gas source in indoor environment, such as the condition of gas leak in a building.

## 1.3 Objectives

The main objective of this research is to improve the existing methods of finding location of gas source in indoor environment using a mobile robot. The work consists of two major aspects. First is to combine Simultaneous Localization and Mapping (SLAM) and Gas Distribution Mapping (GDM) operations to achieve real-time SLAM-GDM solution. The SLAM is implemented to map the unknown area, while the GDM is utilized for representing the areas of high concentration of gas, where the gas source may exist. The combined map from both operations could provide real-time prediction of the gas source location. The second and more important aspect is to further enhance the performance of gas source localization by compensating ambient temperature and humidity in GDM operation. The specific objectives of the research are as follow:



i. **To design robust and reliable mobile robot olfaction system for gas source localization.**
ii. **To improve SLAM operation and select the suitable SLAM algorithm for GDM.**
iii. **To propose real-time SLAM-GDM combination and further improve the performance of gas source localization by introducing an improved GDM method.**

iv. **To model the gas sensor drift due to the changes in ambient temperature and humidity, and subsequently propose novel GDM algorithm that compensate for these two factors.**

## 1.4 Scope

This thesis concerns the tasks of finding the location of gas source using a single mobile robot. The robot was remotely controlled to perform gas sensing measurements across different areas in a building. Path planning strategy is out of scope of this thesis since the focus is rather on the SLAM and GDM algorithms. Instead, the robot was manually controlled to maneuver and cover as much areas as possible in all experiments presented.

Metal oxide (MOX) gas sensor particularly TGS 2600 (i.e. sensitive to volatile organic compound) was used throughout the research as it was proven to produce relatively reliable results and by far the most employed technology in mobile robotics (Trincavelli, 2010). The gas sensor was mounted on the robot at fixed position and exposed directly to the environment, rather than enclosing it in a chamber. No calibration has been performed on the gas sensor to measure the actual concentration of gas. This is due to the unavailability of ground truth information and considering to the fact that the sensor itself suffers from temperature, humidity and long-term drifts (C. Wang, Yin, Zhang, Xiang, & Gao, 2010). Instead, only the sensor's signal was used to indicate relative gas concentration. This information is sufficient for the project's objective of building gas distribution map and localizing gas source.

In addition, ethanol solution was utilized as the gas source since it is volatile and not dangerous to human. Single or multiple cups of the solution were placed at different locations while allowing the robot to build the gas distribution maps. A