UNIVERSITI PUTRA MALAYSIA

GAS INSPECTOR MOBILE ROBOT AS CARBON MONOXIDE SOURCE FINDER

SARAH REZAEIAN

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By

SARAH REZAEIAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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DEDICATIONS

In dedication to my beloved ones for making me be who I am,

my parents, my only sister, and my best friend Hamidreza

for their support and encouragement in all ways.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

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Chair: Assoc. Prof. Mohd Nizar b Hamidon, PhD
Faculty: Engineering

By increasing the production and emission of chemical compounds and toxic gases due to development of cities, industries and technology, control and monitoring the environment in order to prevent the emissions of hazardous air pollutants have became one of the most important issues that have been conducted. If there is any toxic gas present in the environment, it has to be detected and its source must be localized. Fire is one of the most possible and common disasters, which in many cases occurs accidentally and produces a large portion of toxic gases and smoke, and threatens the environment's safety and human's life. Therefore there have been great attentions to fire-related issues including fire detection, localization and extinguishing. Although significant improvements in fire detection systems provide more reliable and faster detection, which is very effective to control the damage at early stages of fire, still localizing the source of fire is a dangerous process, which is primarily done by human operators with high life-threatening risks. Various intelligent mobile systems are proposed for this application but they mostly operate according to the visible characteristics of fire, which in many potentially harmful circumstances like smouldering, they could fail. As carbon monoxide is one of important components of every type of fire and presents in every stage of combustion and doesn't exist in ambient air, it can be considered as a reliable target gas to localize fire source. In this project an inspector mobile robot is implemented to localize fire as a CO source, and a novel searching strategy including a sensing unit and a searching method is proposed. For sensing unit, an array of three different kinds of semiconductor sensors of TGS series are used to detect the CO, which are inexpensive and commercially available. Experiments of sensing unit show the ability of this structure to estimate the source location in right, left, front or back side of robot. Navigation of this robot is based on the gas concentration in environment by air sampling in regular intervals. Algorithms used for exploration and localization by mobile robots are mostly been developed to run on a PC, so they are not

executed in real-time. Using FPGA is proposed by related works as a solution to have complex computations done in a single chip without the need for an external processing unit and to speed up the localization process. Therefore, Altera Cyclone II FPGA was used as the main processing and control unit because of its availability in the research lab. This robot could localize and declare the CO source successfully in 80 percent of experiments.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

GAS ROBOT UNTUK MENCARI MUDAH ALIH SUMBER KARBON MONOKSIDA

Oleh

SARAH REZAEIAN

Julai 2015

Pengerusi: Prof Madya. Mohd Nizar b Hamidon, PhD
Fakulti: Kejuruteran

Dengan meningkatkan pengeluaran dan pelepasan sebatian kimia dan gas-gas toksik disebabkan oleh pembangunan bandar, industri dan teknologi, kawalan dan pemantauan alam sekitar untuk mengelakkan pelepasan pencemar udara yang merbahaya telah menjadi salah satu isu yang paling penting yang telah dijalankan. Jila ada mana-mana gas tosik yang wujud dalam persekitaran, ia perlu dikesan dan sumbernya mesti dikenalapasti. Api adalah salah satu bencana yang paling mungkin dan biasa berlaku dan dalam banyak kes berlaku secara tidak sengaja dan menghasilkan sebahagian besar gas tosik dan asap, dan mengancam keselamatan alam sekitar dan kehidupan manusia. Oleh itu terdapat perhatian yang besar kepada isu-isu yang berkaitan dengan kebakaran termasuk pengesanan kebakaran, penyetempatan dan pemadam. Walaupun peningkatan yang ketara dalam sistem pengesan kebakaran membolehkan pengesanan yang lebih dipercayai dan lebih cepat, yang mana sangat berkesan untuk mengawal kerosakan di peringkat awal kebakaran mengenalpasti sumber api adalah satu proses yang berbahaya kerana ianya dilakukan oleh pengendali manusia yang mengancam nyawa. Pelbagai sistem mudah alih pintar yang dicadangkan untuk aplikasi ini tetapi mereka kebanyakannya beroperasi berdasarkan ciri-ciri kebakaran yang boleh dilihat , yang mana dalam banyak keadaan berbahaya seperti dalam keadaan membara, mereka boleh gagal. Karbon monoksida adalah salah satu komponen penting dalam setiap jenis kebakaran dan wujud di setiap peringkat pembakaran dan tidak wujud dalam udara persekitaran, ia boleh dianggap sebagai gas sasaran yang boleh dipercayai untuk melokalisasikan sumber api. Dalam projek ini robot pemeriksa mudah alih telah dibangunkan untuk mengenalpasti api sebagai sumber CO, dan satu strategi pencarian novel termasuk sebuah unit penderia dan, satu kaedah pencarian adalah dicadangkan. Untuk unit penderia, jujukan tiga jenis pengesan semikonduktor TGS siri telah digunakan untuk mengesan CO, yang mana ianya murah dan boleh didapati secara komersial. Eksperimen daripada unit penderia menunjukkan keupayaan struktur ini untuk menganggar kedudukan sumber di sebelah kanan, kiri, depan

atau belakang robot. Navigasi daripada robot ini adalah berdasarkan kepekatan gas dalam persekitaran oleh persampelan udara dalam jangka masa yang tetap. Algoritma yang digunakan untuk penerokaan dan penyetempatan oleh robot mudah alih kebanyakannya telah dibangunkan untuk beroperasi menggunakan PC, maka ianya tidak dilaksanakan dalam masa nyata. Penggunaan FPGA dicadangkan sebagai penyelesaian untuk pengiraan kompleks dalam cip tunggal, tanpa perlunya unit pemprosesan luaran dan untuk mempercepatkan proses penyetempatan. Oleh itu, Altera Cyclone II FPGA telah digunakan sebagai pemprosesan dan unit, kerana ia boleh didapati di makmal penyelidikan. Robot ini boleh berjaya menyetempatkan dan mengisytiharkan sumber CO, dalam 80 peratus daripada eksperimen.

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I certify that a Thesis Examination Committee has met on 13 July 2015 to conduct the final examination of Sarah Rezaeian on her thesis entitled "Gas Inspector Mobile Robot as Carbon Monoxide Source Finder" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science.

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I hereby confirm that:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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Signature: ____________________	Signature: ____________________
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CHAPTER 1

INTRODUCTION

1.1 Background of Project

In today's world, with development of cities and significant increase in amount of workshops, manufacturing industries and chemical products, industrial pollution caused by production and emission of chemical compounds and toxic contaminants has became a major concern. Hazardous gases are one of air contaminants, which in an adequate level of concentration can have serious effects on the safety of environment, so, they are required to be monitored in order to be retained under the dangerous level. Investigation of the policies and procedures in order to prevent the emissions of hazardous gases is one of the most important issues that have been conducted in last three decades.

One of the most common sources of toxic gases is fire which, in fact, is a disaster and in many cases occurs accidentally and may cause extreme damage to property and humans' life (Ge et al., 2014). All types of fire contain smoke and toxic gases, which through inhalation and skin absorption, cause serious and fatal effects on people in the fire exposure area, so, fast fire detection as well as accurate fire localization are of main concerns in these research area with the aim of damage control due to the smoke release (Hu et al., 2008).

Heat detectors, smoke detectors, flame detectors and gas sensors are the most generally employed sensor technologies in fire detection systems, which due to their different principal of operations, each type has advantages and disadvantages in various applications and environments (Hangauer et al., 2009). For example, smoke detectors show cross sensitivity to some substances like dust or water vapour, which leads to false alarm. On the other hand except for gas sensors, other detection systems work based on the visible characteristic of the fire like smoke or thermal changes, while slow burning or smouldering, that is a hazard because of producing a high concentration of an important toxics, carbon monoxide, has low heat output and is flameless, which make it hard to be detected by these systems (Jackson and Robins, 1994). Therefore, it seems that among all these detection systems, gas sensing-based fire detection is more reliable, because of presence of toxic gases in every stages of combustion (Nebiker and Pleisch, 2001). Since CO is not supposed to be present in fresh and ambient air, it is a well-known gas to be detected during the fire detection and localization (Hangauer et al., 2009), hence, checking the existence of CO in the environment is an effective way for both poisoning and fire prevention (Zhuiykov, 2008).

Carbon monoxide (CO) is one of main toxic gases which is produced in all types of fire and presents in every stage of combustion and depend on fast or slow burning, its concentration could be low or high respectively (Liu and Kim, 2003). This gas is invisible, tasteless, odourless, poisonous, and lethal. Moreover, this is undetectable to the human senses, which is also called "silent killer". Depending on its level and length of exposure, it can cause some symptoms such as headache, dizziness, nausea, vomiting and chest pain. Higher level of poisoning can result in permanent brain damage, suffocating and death (Tsai et al., 2014). Relationship between CO concentration, time of disclosure and health effects to a person in the area of exposure is given in table 1.1 (NEMA, 2013).

Table 1.1: Effects of CO disclosure over time

Concentration (ppm of CO)	Time of exposure (Minutes)	Symptoms
50	480	No adverse effects.
200	120∼180	Mild headache.
400	60∼120	Headache & nausea.
800	45	Headache, nausea & dizziness.
	120	Collapse & loss of consciousness.
1000	60	Loss of consciousness.
1600	20	Headache, nausea & dizziness.
3200	5∼10	Headache, nausea & dizziness.
	30	Collapse & loss of consciousness.
6400	1∼2	Headache & dizziness.
	10∼15	Loss of consciousness & danger of death.
12800	1∼3	Immediate physiological effects, unconsciousness & danger of death.

Different types of CO detectors are commonly used to do this task. CO detectors are generally devices composed of gas sensors, control components and an alarm notification appliance in a single unit. Operation power of these devices is from either batteries inside the unit or obtained at the point of installation. They work based on the concentration of CO over time and trigger an alarm immediately when they detect the specific amount of CO (NEMA, 2013). These detectors are available as stand-alone, system-connected and portable models.

Stand-alone models are including single or multiple stations CO detectors. Therefore, they can detect CO and as soon as the level of the gas exceeds safe level, 50 ppm, (table 1.1), an audible signal will alert occupants . Stand-alone detectors need at least one person to be available near the detector to be alerted and have access to the source of CO in order to cut off the source or do any other proper action. Hence, if the place being empty or occupants are not capable of responding to local alarm as they are elders, disabled individuals, small children, or individuals already unconscious due to the CO, this detector seems useless.

System-connected models are CO detectors connected to a dedicated CO control unit or a fire alarm control unit. Task of control unit in this system is to monitor initiating and notification circuits for integrity and send the trouble signals to a remote monitoring location. In the case of CO detection while the place is empty or residents are sleeping or they are already unconscious due to the high level of CO, the remote central station will be alerted and has the capability of sending proper authorities to investigate the place (McDermott, 2004). System-connected models try to eliminate this problem by monitoring and supervisory the interconnected detectors, so that in such situation central station attempt to alert property owners and send emergency responds in the case of high concentration of CO. However, there maybe unwanted delay in between the time of dispatching emergency team and when they reach to the area which may lead to disaster.

Portable CO detectors are hand-held devices which can be used in any indoor and outdoor area (Brown, 2006) with the advantages of high mobility, low power consumption, no sample preparation, and capability of real time monitoring (Bufaroosha et al., 2013). They are appropriate for professional applications and can be used for manually inspection by individuals or property managers with the purpose of maintain and diagnosis issues like finding the CO emission source. These detectors also have a weakness which is the need for having someone to carry the them and manually search which in fire situation or high concentration of smoke and CO is not safe.

1.2 Problem Statements

Carbon monoxide is lighter than air (Hampson et al., 2012), it will distribute quickly, so, early detection and fast source locating are very important. Although CO detectors are very useful safety devices, they cannot provide a full protection. Stand-alone and System-connected models just can alarm as soon as they detect CO, but can't localize or estimate the source. and as mentioned before portable detectors also need human operation and manually inspection. Therefore, despite importance and danger of fire localization, this task is still mainly done by human operators, which has a high risk of injury or poisoning. It even becomes more dangerous when the environment to be investigated is not easily accessible or concentration of CO is very high.

During last two decades, many researchers studied the different ways of fire fighting tasks including detection, localization and extinguishing with less human operation and attempted to develop new strategies, such as proposing smart detection systems and developing intelligent mobile robots to replace the human in fire localization (Chien et al., 2007). Proposed autonomous mobile robots for this purpose, operate according to the visible characteristics of the fire (temperature, smoke, flame) and there is a gap in research for localizing in the case of smouldering when there is no much visible effects, while with high concentration of CO, it is very considerable and dangerous.

In order to fill this gap, in this thesis, an CO inspection mobile robot is proposed with the ability of CO detecting and tracing, with the aim of using in the fire localization application. So contribution of this research is to propose a new fire localizing strategy by design and implementation of a mobile robot with:

1. A new sensing unit structure

2. A new plum tracing method (searching strategy) for CO source finding

1.3 Aim and objectives of the Study

The aim of this project is to develop a smart mobile robot as an autonomous inspector to localize the CO source after detecting its presence. This is desired to early detection of fire and smouldering as well as to eliminate the role of human in fire localization, as much as possible.
The main objectives of this project are:

1. To develop a gas sensing unit in order to detect CO and determine the source position.
2. To develop a prototype mobile system that employs searching algorithm in order to localize the CO source.
3. To validate the performance of sensing unit and searching algorithm through experimental works.

1.4 Scope and Limitations

There are limitations for this project from the aspects of cost, performance, and efficiency. Therefore this project is limited to develop a single mobile robot equipped with nonexpensive gas sensors calibrated to detect up to 300 ppm which referring to the table 1.1 is the maximum average possible level of CO concentration to release during the experiments before causing serious effects. The total area of experimental environment for CO gas localization was limited to a $160cm \times 90cm \times 50cm$ enclosed environment which can be filled with 300 ppm of CO in an adequate time. More details about the boundary time would be described in methodology, chapter 3. As the focus of this thesis is on the gas sensing for fire localization, no other sensor would be used, so, there is no strong wind and obstacle in the environment and robot moves on a flat ground. It is assumed that there was a constant smooth airflow to create a concentration gradient at the test environment during the experiment.

1.5 Outline of thesis

This masters thesis is divided into five chapters. The first chapter gives an introduction to toxic gases and fire as the most common sources of toxic gases. Then followed by problem statement, aims and objectives, and scope and limitations. The second chapter is including the review of hazardous gases and CO as the major component of fire, mobile robots, sensors and searching techniques in previous studies, and a brief explanation of used techniques and hardware for fabricating this robot. In chapter three an overview of project is given and then the process of hardware implementation and software development of the system are explained. Chapter four focuses on testing the system, results and discussions. In fifth chapter the study is concluded and suggestions for potential future works are offered.

REFERENCES

Al-Omary, A. 2010. Autonomous object seeking robot based on FPGA and a single chip microcontroller. In *Computer and Communication Engineering (ICCCE), 2010 International Conference on*, 1–6. IEEE.

Arshak, K., Moore, E., Lyons, G., Harris, J. and Clifford, S. 2004. A review of gas sensors employed in electronic nose applications. *Sensor review* 24 (2): 181–198.

Bailey, J. K., Willis, M. A. and Quinn, R. D. 2005. A multi-sensory robot for testing biologically-inspired odor plume tracking strategies. In *Advanced Intelligent Mechatronics. Proceedings, 2005 IEEE/ASME International Conference on*, 1477–1481. IEEE.

Bakker, E. 2004. Electrochemical sensors. *Analytical chemistry* 76 (12): 3285–3298.

Balkovsky, E. and Shraiman, B. I. 2002. Olfactory search at high Reynolds number. *Proceedings of the national academy of sciences* 99 (20): 12589–12593.

Baquero Velasquez, A. E., Borrero Guerrero, H., Pedraza, I. L. A., Magalhaes, D. V., Becker, M. and Caurin, G. A. d. P. 2013. Navigation control in FPGA for a differential-drive mobile robot. In *Advanced Robotics (ICAR), 2013 16th International Conference on*, 1–6. IEEE.

Belanger, J. H. and Willis, M. A. 1998. Biologically-inspired search algorithms for locating unseen odor sources. In *Intelligent Control (ISIC), 1998. Held jointly with IEEE International Symposium on Computational Intelligence in Robotics and Automation (CIRA), Intelligent Systems and Semiotics (ISAS), Proceedings*, 265–270. IEEE.

Bennetts, V. H., Lilienthal, A. J., Neumann, P. P. and Trincavelli, M. 2011. Mobile robots for localizing gas emission sources on landfill sites: is bio-inspiration the way to go? *Frontiers in neuroengineering* 4.

Bennetts, V. H., Lilienthal, A. J. and Trincavelli, M. 2012. Creating true gas concentration maps in presence of multiple heterogeneous gas sources. In *Sensors, 2012 IEEE*, 1–4. IEEE.

Bennetts, V. H., Schaffernicht, E., Stoyanov, T., Lilienthal, A. J. and Trincavelli, M. 2014. Robot assisted gas tomographyLocalizing methane leaks in outdoor environments. In *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, 6362–6367. IEEE.

Blanco, J. L., Monroy, J. G., Lilienthal, A. and Gonzalez-Jimenez, J. 2013. A kalman filter based approach to probabilistic gas distribution mapping. In *Proceedings of the 28th Annual ACM Symposium on Applied Computing*, 217–222. ACM.

Bonato, V., Marques, E. and Constantinides, G. A. 2009. A floating-point extended kalman filter implementation for autonomous mobile robots. Journal of Signal Processing Systems 56 (1): 41–50.

Bonow, G. and Kroll, A. 2013. Gas leak localization in industrial environments using a TDLAS-based remote gas sensor and autonomous mobile robot with the Tri-Max method. In Robotics and Automation (ICRA), 2013 IEEE International Conference on, 987–992. IEEE.

Brauns, E., Morsbach, E., Kunz, S., Baeumer, M. and Lang, W. 2014. Temperature Modulation of a Catalytic Gas Sensor. Sensors 14 (11): 20372–20381.

Brown, V. R. 2006, In The Grey House Safety and Security Directory, In The Grey House Safety and Security Directory, 291–293, California: Grey house publishing, 291–293.

Bufaroosha, M. S., Alnaqbi, M. A., Al-Marzouqi, M. H. and Marzouk, S. A. 2013. Portable dual-channel gas analyzer for continuous monitoring of carbon dioxide in gas streams. Microchemical Journal 110: 185–191.

Cardé, R. and Knols, B. 2000. Effects of light levels and plume structure on the orientation manoeuvres of male gypsy moths flying along pheromone plumes. Physiological Entomology 25 (2): 141–150.

Chien, T. L., Guo, H., Su, K. L. and Shiau, S. V. 2007. Develop a multiple interface based fire fighting robot. In Mechatronics, ICM2007 4th IEEE International Conference on, 1–6. IEEE.

Chou, J. 2000. Hazardous gas monitors: a practical guide to selection, operation and applications. McGraw-Hill New York.

Cordos, E., Ferenczi, L., Cadar, S., Costiug, S., Pitl, G., Aciu, A., Ghita, A. and Chintoanu, M. 2006. Methane and carbon monoxide gas detection system based on semiconductor sensor. In Automation, Quality and Testing, Robotics, 2006 IEEE International Conference on, 208–211. IEEE.

Cui, X., Hardin, T., Ragade, R. and Elmaghraby, A. 2004. A swarm-based fuzzy logic control mobile sensor network for hazardous contaminants localization. In Mobile Ad-hoc and Sensor Systems, 2004 IEEE International Conference on, 194–203. IEEE.

Dhariwal, A., Sukhatme, G. and Requicha, A. A. 2004. Bacterium-inspired robots for environmental monitoring. In Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on, 1436–1443. IEEE.

Edwards, S., Rutkowski, A. J., Quinn, R. D. and Willis, M. A. 2005. Moth-inspired plume tracking strategies in three-dimensions. In Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on, 1669–1674. IEEE.

Farah, A. M. and Duckett, T. 2002. Reactive localisation of an odour source by a learning mobile robot. In In Proceedings of the Second Swedish Workshop on Autonomous Robotics. Citeseer.

Farrell, J. A., Pang, S. and Li, W. 2003. Plume mapping via hidden markov methods. Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on 33 (6): 850–863.

Farrell, J. A., Pang, S. and Li, W. 2005. Chemical plume tracing via an autonomous underwater vehicle. Oceanic Engineering, IEEE Journal of 30 (2): 428–442.

Ferri, G., Caselli, E., Mattoli, V., Mondini, A., Mazzolai, B. and Dario, P. 2006. A biologically-inspired algorithm implemented on a new highly flexible multi-agent platform for gas source localization. In Biomedical Robotics and Biomechatronics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on, 573–578. IEEE.

Ferri, G., Caselli, E., Mattoli, V., Mondini, A., Mazzolai, B. and Dario, P. 2007. A biologically-inspired algorithm for gas/odor source localization in an indoor environment with no strong airflow: First experimental results. In Proceedings of IEEE International Conference on Robotics and Automation, 566–571.

Ferri, G., Caselli, E., Mattoli, V., Mondini, A., Mazzolai, B. and Dario, P. 2009. SPIRAL: A novel biologically-inspired algorithm for gas/odor source localization in an indoor environment with no strong airflow. Robotics and Autonomous Systems 57 (4): 393–402.

Fine, G. F., Cavanagh, L. M., Afonja, A. and Binions, R. 2010. Metal oxide semiconductor gas sensors in environmental monitoring. Sensors 10 (6): 5469–5502.

Ge, Q., Wen, C. and Duan, S. 2014. Fire Localization Based On Range-Range-Range Model for Limited Interior Space. Instrumentation and Measurement, IEEE Transactions on 63 (9): 2223–2237.

Ghorbel, A., Amor, N. B., Jallouli, M. and Amouri, L. 2012. A HW/SW implementation on FPGA of a robot localization algorithm. Systems, Signals and Devices (SSD) 1–7.

Grasso, F. W., Consi, T. R., Mountain, D. C. and Atema, J. 2000. Biomimetic robot lobster performs chemo-orientation in turbulence using a pair of spatially separated sensors: Progress and challenges. Robotics and Autonomous Systems 30 (1): 115–131.

Grasso, F. W., Dale, J. H., Consi, T. R., Mountain, D. C. and Atema, J. 1996. Behavior of Purely Chemotactic Robot Lobster Reveals Different Odor Dispersal Patterns in the Jet Region and the Patch Field of a Turbulent Plume. The Biological Bulletin 191 (2): 312–313.

Hampson, N. B., Courtney, T. G. and Holm, J. R. 2012. Should the Placement of Carbon Monoxide (CO) Detectors be Influenced by COs Weight Relative to Air? The Journal of emergency medicine 42 (4): 478–482.

Hangauer, A., Chen, J., Strzoda, R., Fleischer, M. and Amann, M.-C. 2009. Fire detection with a compact, 2.3 μm VCSEL-based carbon monoxide sensor. In Conference on Lasers and Electro Optics (CLEO).

Hayes, A. T., Martinoli, A. and Goodman, R. M. 2002. Distributed odor source localization. Sensors Journal, IEEE 2 (3): 260–271.

Hayes, A. T., Martinoli, A. and Goodman, R. M. 2003. Swarm robotic odor localization: Off-line optimization and validation with real robots. Robotica 21 (04): 427–441.

Hernandez Bennetts, V., Schaffernicht, E., Pomareda, V., Lilienthal, A. J., Marco, S. and Trincavelli, M. 2014. Combining Non Selective Gas Sensors on a Mobile Robot for Identification and Mapping of Multiple Chemical Compounds. Sensors 14 (9): 17331–17352.

Honeywell. 2013. Gas book. Honeywell analytics.

Hu, L., Zhou, J., Huo, R., Peng, W. and Wang, H. 2008. Confinement of fire-induced smoke and carbon monoxide transportation by air curtain in channels. Journal of hazardous materials 156 (1): 327–334.

Hughes-Hallett, D., Gleason, A. M., McCallum, W. G., Lomen, D. O., Lovelock, D., Tecosky-Feldman, J., Tucker, T. W., Flath, D. E., Thrash, J., Rhea, K. R., Pasquale, A., Gordon, S. P., Quinney, D. and Lock, P. F. 2008. Calculus: Single variable. 5th edn. Wiley.

Ishida, H. 2007. Robotic systems for gas/odor source localization: Gap between experiments and real-life situations. In Proceedings of the IEEE International Conference on Robotics and Automation, 2007.(ICRA 2007), 3–8.

Ishida, H., Hayashi, K., Takakusaki, M., Nakamoto, T., Moriizumi, T. and Kanzaki, R. 1996. Odour-source localization system mimicking behaviour of silkworm moth. Sensors and Actuators A: Physical 51 (2): 225–230.

Ishida, H., Nakamoto, T. and Moriizumi, T. 1998. Remote sensing of gas/odor source location and concentration distribution using mobile system. Sensors and Actuators B: Chemical 49 (1): 52–57.

Ishida, H., Nakamoto, T., Moriizumi, T., Kikas, T. and Janata, J. 2001. Plume-tracking robots: A new application of chemical sensors. The Biological Bulletin 200 (2): 222–226.

Ishida, H., Suetsugu, K.-i., Nakamoto, T. and Moriizumi, T. 1994. Study of autonomous mobile sensing system for localization of odor source using gas sensors and anemometric sensors. Sensors and Actuators A: Physical 45 (2): 153–157.

Ishida, H., Tanaka, H., Taniguchi, H. and Moriizumi, T. 2006. Mobile robot navigation using vision and olfaction to search for a gas/odor source. Autonomous Robots 20 (3): 231–238.

Ishida, H., Yoshikawa, K. and Moriizumi, T. 2004a. Three-dimensional gas-plume tracking using gas sensors and ultrasonic anemometer. In Sensors, 2004. Proceedings of IEEE, 1175–1178. IEEE.

Ishida, H., Zhu, M., Johansson, K. and Moriizumi, T. 2004b. Three-dimensional gas/odor plume tracking with blimp. In Proc. ICEE, 117–120.

Jackson, M. and Robins, I. 1994. Gas sensing for fire detection: Measurements of CO, CO 2, H 2, O 2, and smoke density in European standard fire tests. Fire safety journal 22 (2): 181–205.

Janata, J. 2010. Principles of chemical sensors. Springer Science & Business Media.

Jatmiko, W., Ikemoto, Y., Matsuno, T., Fukuda, T. and Sekiyama, K. 2005. Distributed odor source localization in dynamic environment. In Sensors, 2005 IEEE, 4–pp. IEEE.

Jatmiko, W., Sekiyama, K. and Fukuda, T. 2006. A Mobile Robots PSO-Based for Odor Source Localization in Extreme Dynamic Advection-Diffusion Environment with Obstacle. In Sensors, 2006. 5th IEEE Conference on, 526–529. IEEE.

Jatmiko, W., Sekiyama, K. and Fukuda, T. 2007. A pso-based mobile robot for odor source localization in dynamic advection-diffusion with obstacles environment: theory, simulation and measurement. Computational Intelligence Magazine, IEEE 2 (2): 37–51.

Justus, K. A. and Cardé, R. T. 2002. Flight behaviour of males of two moths, Cadra cautella and Pectinophora gossypiella, in homogeneous clouds of pheromone. Physiological Entomology 27 (1): 67–75.

Justus, K. A., Schofield, S. W., Murlis, J. and Carde, R. T. 2002. Flight behaviour of Cadra cautella males in rapidly pulsed pheromone plumes. Physiological entomology 27 (1): 58–66.

Kazadi, S., Goodman, R., Tsikata, D., Green, D. and Lin, H. 2000. An autonomous water vapor plume tracking robot using passive resistive polymer sensors. Autonomous robots 9 (2): 175–188.

Kennedy, J. and Eberhart, R. 1995. Particle swarm optimization. In Neural Networks, 1995. Proceedings., IEEE International Conference on, 1942–1948 vol.4.

Kennedy, R. and Nahavandi, S. 2010. Neural net device for IED gas identification. In Industrial Electronics & Applications (ISIEA), 2010 IEEE Symposium on, 727–732. IEEE.

Kowadlo, G., Rawlinson, D., Russell, R. A. and Jarvis, R. 2006. Bi-modal search using complementary sensing (olfaction/vision) for odour source localisation. In Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on, 2041–2046. IEEE.

Kowadlo, G. and Russell, R. A. 2006. Using naïve physics for odor localization in a cluttered indoor environment. Autonomous Robots 20 (3): 215–230.

Kowadlo, G. and Russell, R. A. 2008. Robot odor localization: a taxonomy and survey. The International Journal of Robotics Research 27 (8): 869–894.

Kowadlo, G. and Russell, R. A. 2009. Improving the robustness of naïve physics airflow mapping, using Bayesian reasoning on a multiple hypothesis tree. Robotics and Autonomous Systems 57 (6): 723–737.

Kuenen, L. and Rowe, H. 2006. Cowpea weevil flights to a point source of female sex pheromone: analyses of flight tracks at three wind speeds. Physiological Entomology 31 (2): 103–109.

Kuwana, Y., Nagasawa, S., Shimoyama, I. and Kanzaki, R. 1999. Synthesis of the pheromone-oriented behaviour of silkworm moths by a mobile robot with moth antennae as pheromone sensors. Biosensors and Bioelectronics 14 (2): 195–202.

Kuwana, Y. and Shimoyama, I. 1998. A pheromone-guided mobile robot that behaves like a silkworm moth with living antennae as pheromone sensors. The International Journal of Robotics Research 17 (9): 924–933.

Kuwana, Y., Shimoyama, I. and Miura, H. 1995. Steering control of a mobile robot using insect antennae. In Intelligent Robots and Systems 95.'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on, 530–535. IEEE.

Kuwana, Y., Shimoyama, I., Sayama, Y. and Miura, H. 1996. Synthesis of pheromone-oriented emergent behavior of a silkworm moth. In Intelligent Robots and Systems' 96, IROS 96, Proceedings of the 1996 IEEE/RSJ International Conference on, 1722–1729. IEEE.

Lee, D.-D. and Lee, D.-S. 2001. Environmental gas sensors. IEEE Sensors Journal 1 (3): 214–224.

Li, J.-G., Meng, Q.-H., Li, F., Zeng, M. and Popescu, D. 2009. Mobile robot based odor source localization via particle filter. In Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference. CDC/CCC 2009. Proceedings of the 48th IEEE Conference on, 2984–2989. IEEE.

Li, J.-G., Meng, Q.-H., Wang, Y. and Zeng, M. 2011. Odor source localization using a mobile robot in outdoor airflow environments with a particle filter algorithm. Autonomous Robots 30 (3): 281–292.

Li, W., Farrell, J. A. and Card, R. T. 2001. Tracking of fluid-advected odor plumes: strategies inspired by insect orientation to pheromone. Adaptive Behavior 9 (3-4): 143–170.

Lilienthal, A. and Duckett, T. 2003a, In Autonome Mobile Systeme 2003, In Autonome Mobile Systeme 2003, 161–171, Springer, 161–171.

Lilienthal, A. and Duckett, T. 2003b. Experimental analysis of smelling Braitenberg vehicles. environment 5: 10.

Lilienthal, A. and Duckett, T. 2003c. A stereo electronic nose for a mobile inspection robot. In Robotic Sensing, 2003. ROSE'03. 1st International Workshop on, 6–pp. IEEE.

Lilienthal, A. and Duckett, T. 2004a. Building gas concentration gridmaps with a mobile robot. Robotics and Autonomous Systems 48 (1): 3–16.

Lilienthal, A. and Duckett, T. 2004b. Experimental analysis of gas-sensitive Braitenberg vehicles. Advanced Robotics 18 (8): 817–834.

Lilienthal, A., Reimann, D. and Zell, A. 2003, In Autonome Mobile Systeme 2003, In Autonome Mobile Systeme 2003, 150–160, Springer, 150–160.

Lilienthal, A., Streichert, F. and Zell, A. 2005. Model-based shape analysis of gas concentration gridmaps for improved gas source localisation. In Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on, 3564–3569. IEEE.

Lilienthal, A., Ulmer, H., Frohlich, H., Stutzle, A., Werner, F. and Zell, A. 2004. Gas source declaration with a mobile robot. In Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on, 1430–1435. IEEE.

Lilienthal, A. J., Duckett, T., Ishida, H. and Werner, F. 2006a. Indicators of gas source proximity using metal oxide sensors in a turbulent environment. In Biomedical Robotics and Biomechatronics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on, 733–738. IEEE.

Lilienthal, A. J., Loutfi, A. and Duckett, T. 2006b. Airborne chemical sensing with mobile robots. Sensors 6 (11): 1616–1678.

Lilienthal, A. J., Reggente, M., Trincavelli, M., Blanco, J.-L. and Gonzalez, J. 2009. A statistical approach to gas distribution modelling with mobile robots-the kernel dm+ v algorithm. In Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on, 570–576. IEEE.

Litwhiler, D. and Lombardi, B. 2009. Testing of carbon monoxide and carbon dioxide sensors with simple apparatus in an engineering education laboratory. In American Society for Engineering Education. American Society for Engineering Education.

Liu, Z. and Kim, A. K. 2003. Review of recent developments in fire detection technologies. Journal of Fire Protection Engineering 13 (2): 129–151.

Lochmatter, T. 2010. Bio-inspired and probabilistic algorithms for distributed odor source localization using mobile robots. PhD thesis, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE.

Lochmatter, T. and Martinoli, A. 2009. Tracking odor plumes in a laminar wind field with bio-inspired algorithms. In Experimental robotics, 473–482. Springer.

Lochmatter, T., Raemy, X., Matthey, L., Indra, S. and Martinoli, A. 2008. A comparison of casting and spiraling algorithms for odor source localization in laminar flow. In Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on, 1138–1143. IEEE.

Long, M., Gage, A., Murphy, R. and Valavanis, K. 2005. Application of the distributed field robot architecture to a simulated demining task. In Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on, 3193–3200. IEEE.

López, L. L., Chimeno, A. E., i Lluna, A. P., Ziyatdinov, A., Marcos, E., Verschure, P. F., i Badia, S. B., Vouloutsi, V. and Mathews, Z. 2011. Moth-like chemo-source localization and classification on an indoor autonomous robot. INTECH Open Access Publisher.

Loutfi, A. and Coradeschi, S. 2002. Relying on an electronic nose for odor localization. In Virtual and Intelligent Measurement Systems, 2002. VIMS'02. 2002 IEEE International Symposium on, 46–50. IEEE.

Lytridis, C., Kadar, E. E. and Virk, G. S. 2006. A systematic approach to the problem of odour source localisation. Autonomous Robots 20 (3): 261–276.

Lytridis, C., Virk, G. S., Rebour, Y. and Kadar, E. E. 2001. Odor-based navigational strategies for mobile agents. Adaptive Behavior 9 (3-4): 171–187.

Malavasi, L., Tealdi, C., Montenero, A., Tulliani, J., Moggi, P., Guglielmi, M., Flor, G., Lorenzi, A., Martucci, A., Montanaro, L. et al. 2006. Materials development for CO-detection with improved selectivity through catalytic activation. Sensors and Actuators B: Chemical 118 (1): 121–128.

Mamduh, S., Kamarudin, K., Shakaff, A., Zakaria, A. and Abdullah, A. 2014. Comparison of Braitenberg Vehicles with Bio-Inspired Algorithms for Odor Tracking in Laminar Flow. Aust. J. Basic Appl. Sci 8 (4): 6–15.

Mamduh, S. M., Kamarudin, K., Saad, S. M., Shakaff, A. Y. M., Zakaria, A. and Abdullah, A. H. 2013. Braitenberg swarm vehicles for odour plume tracking in laminar airflow. In Computers & Informatics (ISCI), 2013 IEEE Symposium on, 1–6. IEEE.

Marjovi, A. and Marques, L. 2013a. Optimal spatial formation of swarm robotic gas sensors in odor plume finding. Autonomous Robots 35 (2-3): 93–109.

Marjovi, A. and Marques, L. 2013b. Swarm robotic plume tracking for intermittent and time-variant odor dispersion. In *Mobile Robots (ECMR), 2013 European Conference on*, 379–384. Ieee.

Marques, L., Nunes, U. and de Almeida, A. T. 2002. Olfaction-based mobile robot navigation. *Thin solid films* 418 (1): 51–58.

Marques, L., Nunes, U. and de Almeida, A. T. 2006. Particle swarm-based olfactory guided search. *Autonomous Robots* 20 (3): 277–287.

Martinez, D., Rochel, O. and Hugues, E. 2006. A biomimetic robot for tracking specific odors in turbulent plumes. *Autonomous Robots* 20 (3): 185–195.

Masson, J., Bechet, M. B. and Vergassola, M. 2009. Chasing information to search in random environments. *Journal of Physics A: Mathematical and Theoretical* 42 (43): 434009.

McDermott, H. J. 2004. *Air monitoring for toxic exposures*. 2nd edn. John Wiley & Sons.

Moraud, E. M. and Martinez, D. 2010. Effectiveness and robustness of robot infotaxis for searching in dilute conditions. *Frontiers in neurorobotics* 4.

MSA. 2007. *Gas Detection Handbook*. 5th edn.

Nebiker, P. and Pleisch, R. 2001. Photoacoustic gas detection for fire warning. *Fire Safety Journal* 36 (2): 173–180.

NEMA. 2013. Applications guide carbon monoxide alarms and detectors. *National Electrical Manufacturers Association* .

Neumann, P. P., Hernandez Bennetts, V., Lilienthal, A. J., Bartholmai, M. and Schiller, J. H. 2013. Gas source localization with a micro-drone using bio-inspired and particle filter-based algorithms. *Advanced Robotics* 27 (9): 725–738.

Neumann, P. P., Schnürmacher, M., Bennetts, V. H., Lilienthal, A. J., Bartholmai, M. and Schiller, J. H. 2014. A Probabilistic Gas Patch Path Prediction Approach for Airborne Gas Source Localization in Non-Uniform Wind Fields. *Sensor Letters* 12 (6-7): 1113–1118.

Pollack-Nelson, C. 1996. Differentiated Alarms for Carbon Monoxide Detectors. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 855–859. SAGE Publications.

Pomareda, V., Hernández, V., Khaliq, A., Trincavelli, M., Lilienthal, A. J. and Marco, S. 2013. Chemical source localization in real environments integrating chemical concentrations in a probabilistic plume mapping approach. In *15th International Symposium on Olfaction and Electronic Nose, ISOEN*.

Pyk, P., i Badia, S. B., Bernardet, U., Knüsel, P., Carlsson, M., Gu, J., Chanie, E., Hansson, B. S., Pearce, T. C. and Verschure, P. F. 2006. An artificial moth: Chemical source localization using a robot based neuronal model of moth optomotor anemotactic search. Autonomous Robots 20 (3): 197–213.

Rubio, R., Santander, J., Fonseca, L., Sabate, N., Gracia, I., Cane, C., Udina, S. and Marco, S. 2007. Non-selective NDIR array for gas detection. Sensors and Actuators B: Chemical 127 (1): 69–73.

Russell, R. A. 1999. Odour detection by mobile robots. , vol. 22. World Scientific.

Russell, R. A. 2001a. Survey of robotic applications for odor-sensing technology. The International Journal of Robotics Research 20 (2): 144–162.

Russell, R. A. 2001b. Tracking chemical plumes in constrained environments. Robotica 19 (04): 451–458.

Russell, R. A. 2003. Chemical source location and the robomole project. In Proceedings Australian Conference on Robotics and Automation. Citeseer.

Russell, R. A., Bab-Hadiashar, A., Shepherd, R. L. and Wallace, G. G. 2003. A comparison of reactive robot chemotaxis algorithms. Robotics and Autonomous Systems 45 (2): 83–97.

Rutkowski, A. J., Quinn, R. D. and Willis, M. A. 2007. A sensor fusion approach to odor source localization inspired by the pheromone tracking behavior of moths. In Robotics and Automation, 2007 IEEE International Conference on, 4873–4878. IEEE.

Rutkowski, A. J., Willis, M. A. and Quinn, R. D. 2006. Simulated odor tracking in a plane normal to the wind direction. In Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on, 2047–2052. IEEE.

Sohail, M. S., Saeed, M. O. B., Rizvi, S. Z., Shoaib, M. and Sheikh, A. U. H. 2014. Low-Complexity Particle Swarm Optimization for Time-Critical Applications. arXiv preprint arXiv:1401.0546 .

Stachniss, C., Plagemann, C., Lilienthal, A. J. and Burgard, W. 2008. Gas Distribution Modeling using Sparse Gaussian Process Mixture Models. In Robotics: Science and Systems.

Suzuki, T., Kitamura, M., Amano, Y. and Hashizume, T. 2010. 6-DOF localization for a mobile robot using outdoor 3D voxel maps. In IROS, 5737–5743.

Thrun, S. et al. 2002. Robotic mapping: A survey. Exploring artificial intelligence in the new millennium 1–35.

Tong, Z., Tong, M.-M., Meng, W. and Li, M. 2014. Inflammable Gas Mixture Detection with a Single Catalytic Sensor Based on the Electric Field Effect. Sensors 14 (4): 6409–6418.

Tsai, C.-F., Yip, P.-K., Chen, S.-Y., Lin, J.-C., Yeh, Z.-T., Kung, L.-Y., Wang, C.-Y. and Fan, Y.-M. 2014. The impacts of acute carbon monoxide poisoning on the brain: Longitudinal clinical and 99mTc ethyl cysteinate brain SPECT characterization of patients with persistent and delayed neurological sequelae. Clinical neurology and neurosurgery 119: 21–27.

Turduev, M., Cabrita, G., Kırtay, M., Gazi, V. and Marques, L. 2014. Experimental studies on chemical concentration map building by a multi-robot system using bio-inspired algorithms. Autonomous agents and multi-agent systems 28 (1): 72–100.

Vergassola, M., Villermaux, E. and Shraiman, B. I. 2007. Infotaxis as a strategy for searching without gradients. Nature 445 (7126): 406–409.

Vijayakumaran, S., Levinbook, Y. and Wong, T. F. 2007. Maximum likelihood localization of a diffusive point source using binary observations. Signal Processing, IEEE Transactions on 55 (2): 665–676.

Wandel, M., Weimar, U., Lilienthal, A. and Zell, A. 2001. Leakage localisation with a mobile robot carrying chemical sensors. In Electronics, Circuits and Systems, 2001. ICECS 2001. The 8th IEEE International Conference on, 1247–1250. IEEE.

Wang, L.-C., Tang, K. T., Kuo, C.-T., Ho, C.-L., Lin, S.-R., Sung, Y. and Chang, C.-P. 2010. Portable electronic nose system with chemiresistor sensors to detect and distinguish chemical warfare agents. Journal of Micro/Nanolithography, MEMS, and MOEMS 9 (3): 031010–031010.

Webb, B., Harrison, R. R. and Willis, M. A. 2004. Sensorimotor control of navigation in arthropod and artificial systems. Arthropod structure & development 33 (3): 301–329.

Webster, J. G. and Eren, H. 2014. Measurement, Instrumentation, and Sensors Handbook: Spatial, Mechanical, Thermal, and Radiation Measurement. , vol. 1. CRC press.

Wieneke, M., Safenreiter, K. and Koch, W. 2008. Hazardous material localization and person tracking. In SPIE Defense and Security Symposium, 696919–696919. International Society for Optics and Photonics.

Wolf, D., Holanda, J., Bonato, V., Peron, R. and Marques, E. 2007. An FPGA-based mobile robot controller. In Programmable Logic, 2007. SPL'07. 2007 3rd Southern Conference on, 119–124. IEEE.

Yang, X.-S., Cui, Z., Xiao, R., Gandomi, A. H. and Karamanoglu, M. 2013. Swarm intelligence and bio-inspired computation: theory and applications. Newnes.

Zarzhitsky, D. and Spears, D. F. 2005. Swarm approach to chemical source localization. In Systems, Man and Cybernetics, 2005 IEEE International Conference on, 1435–1440. IEEE.

Zarzhitsky, D., Spears, D. F. and Spears, W. M. 2005a. Distributed robotics approach to chemical plume tracing. In Intelligent Robots and Systems, 2005.(IROS 2005). 2005 IEEE/RSJ International Conference on, 4034–4039. IEEE.

Zarzhitsky, D., Spears, D. F. and Spears, W. M. 2005b. Swarms for chemical plume tracing. In Swarm Intelligence Symposium, 2005. SIS 2005. Proceedings 2005 IEEE, 249–256. IEEE.

Zhao, T. and Nehorai, A. 2007. Distributed sequential Bayesian estimation of a diffusive source in wireless sensor networks. Signal Processing, IEEE Transactions on 55 (4): 1511–1524.

Zhuiykov, S. 2008. Carbon monoxide detection at low temperatures by semiconductor sensor with nanostructured Au-doped CoOOH films. Sensors and Actuators B: Chemical 129 (1): 431–441.