Gas Source Tracing With a Mobile Robot Using an Adapted Moth Strategy

Achim Lilienthal, Denis Reimann, and Andreas Zell

WSI, University of Tübingen, Sand 1, 72074 Tübingen, Germany,
{lilien,reiman,zell}@informatik.uni-tuebingen.de

Abstract. As a sub-task of the general gas source localisation problem, gas source tracing is supposed to guide a gas-sensitive mobile system towards a source by using the cues determined from the gas distribution sensed along a driven path. This paper reports on an investigation of a biologically inspired gas source tracing strategy. Similar to the behaviour of the silkworm moth *Bombyx mori*, the implemented behaviour consists of a fixed motion pattern that realises a local search, and a mechanism that (re-)starts this motion pattern if an increased gas concentration is sensed. While the moth uses the local airflow direction to orient the motion pattern, this is not possible for a mobile robot due to the detection limits of currently available anemometers. Thus, an alternative method was implemented that uses an asymmetric motion pattern, which is biased towards the side where higher gas sensor readings were obtained. The adaptated strategy was implemented and tested on an experimental platform. This paper describes the strategy and evaluates its performance in terms of the ability to drive the robot towards a gas source and to keep it within close proximity of the source.

1 Introduction

Probably all living creatures respond to chemical stimuli. By using their sense of smell or taste, animals acquire information from their environment. Thus, attractive odours enable animals to find food (like sea-birds that do trace the airborne plume of fish oil in order to find their prey), or a mate (like moths, where the male localises its female conspecific guided by pheromones). On the other hand, repulsive odours are often used to avoid possibly dangerous situations. Thus, odours can warn of spoiled food, the presence of a predator or a fire [4]. Furthermore, chemicals are often used for communication among the individuals of a species: ants leave chemical marks that are followed by other ants in order to find a source of food. Honeybees produce repellent odours after gathering nectar to prevent their fellows from trying to collect nectar from the same flower. Finally, dogs mark their territory and organise a rich social behaviour based on odours.

To provide robots with the ability to localise gas sources is very promising for a broad range of applications, including automatic humanitarian demining or enabling an "electronic watchman" that is able to indicate toxic gas leaks, leaking solvents or a fire at its initial stage. In addition to existing gases, self-produced odours can also be used, for example in cleaning applications to mark those parts of an area that are already covered [11].

Chemical sensing entered the field of mobile robotics in the beginning of the 1990's by initial experiments, which applied gas source tracing strategies based on gradient-following [15, 21]. Although such strategies can improve the tracing performance on average [13], they are prone to be mislead by the non-smooth and multimodal character of gas distribution in real-world environments. Due to the slow diffusion velocity at room temperature, the spread of gas in closed rooms without artificial ventilation is dominated by turbulence and weak convective airstreams caused by spatial temperature differences [24]. Thus, a patchy, temporally fluctuating gas distribution is formed consisting of a number of local concentration maxima. Remarkably, the location of the global maximum is usually *not* located at the location of the gas source if this source has been active for some time.

On this account most publications in the field of mobile noses assume an experimental setup that minimizes the influence of turbulent gas transport by either shortening the source-to-sensor distance in *trail following* [17, 20, 22, 23] or by assuming a strong unidirectional airstream in the environment for gas source localisation. Primarily, a strong airstream can be used for this purpose to get additional information about the local wind speed and direction from an anemometer. Thus, strategies become feasible that utilise the instantaneous direction of flow as an estimate of source direction [2] to combine gas searching behaviour with periods of upwind movement [5, 6, 16, 19]. Without a strong artificial airflow, however, the detection limits of the available wind measuring devices (anemometers) are not low enough to measure weak convective airflows. With state of the art anemometers based on the cooling of a heated wire [7], the bending of an artificial whisker [18] or the influence on the speed of a small rotating paddle [16] reliable readings can be obtained only for wind speeds in the order of at least 10 cm/s.

Following a suggestion of Hayes et al. [5], the problem of gas source localisation in an enclosed 2D area assuming a sufficiently strong constant airflow, can be broken down into three subtasks:

– *plume finding*: detecting an increased concentration
– *plume traversal*: following the gas plume to its origin
– *source declaration*: determining that the source was found

Although the existence of a constant plume is not guaranteed in an unventilated indoor environment, this classification can be applied without the assumption of a strong constant airflow in a similar way:

– *gas finding*: detecting an increased concentration
– *source tracing*: following the cues determined from the sensed gas distribution (and eventually using other sensor modalities) towards the source
– *source declaration*: determining the certainty that the source was found

This paper addresses the problem of gas source tracing. The algorithm proposed in this paper is based on the strategy to search a pheromone source, applied by the male silkworm moth, *Bombyx mori*. When this moth detects the particular pheromones released by conspecific females, it uses the local wind direction in order to estimate the direction to the pheromone source. For the implementation on a real robot, however, an indoor environment without a strong unidirectional airflow is considered. Thus, it is not possible to use the same mechanism because of the mentioned limitation of currently available anemometers. Therefore, an alternative method was applied that uses the gas sensor readings only.

The rest of this paper is structured as follows: in Section 2, the tracing behaviour of the moth *Bomby mori* is introduced. Next, the adapted algorithm based on the moth's strategy is explained in Section 3. Then, the experimental setup is introduced in Section 4, followed by a discussion of the experiments (Section 5) and a statistical evaluation of the performance of the applied strategy in terms of its ability to drive the robot towards a gas source and to keep it nearby (Section 6). Finally, conclusions are given in Section 7.

2 Gas Source Tracing: Behaviour of *Bombyx Mori*

The behaviour of the silkworm moth *Bombyx mori* is well-investigated and suitable for adaptation on a wheeled robot, because this moth usually does not fly [10]. The behaviour is mainly based on three mechanisms [9]:

- *a trigger*: if the moth's antennae are stimulated by intermittent patches of pheromones, a fixed motion pattern is (re-)started
- *local search*: the motion pattern realises an oriented local search for the next pheromone patch
- *estimation of source direction*: the main orientation of the motion pattern that implements the local search is given by the instantaneous upwind direction, which provides an estimate of the direction to the source

Stimulation to either antenna triggers the specific motion pattern of the *Bombyx* males. This fixed motion sequence starts with a forward surge directed against the local air flow direction. Afterwards, the moth performs a "zigzag" walk, while it starts to turn to that direction where the stimulation was sensed. The turn angles and the length of the path between subsequent zigzag turns is increased with each turn [8]. Finally, a turning behaviour is performed, while the turns can be more than 360°. This "programmed" motion sequence is exactly restarted from the beginning if a new patch of pheromones is sensed. As it could be shown in wind tunel experiments by Kanzaki [9], this behaviour results in a more and more straightforward path directed towards the pheromone source if the frequency of pheromone stimulation is increased.

3 Gas Source Tracing: Implementation

3.1 Fixed Motion Pattern

For the implementation on a real robot, the gas source tracing strategy of the moth *Bombyx mori* had to be adapted because information about the local wind direction is not available. For the algorithm that is used by the robot, those parts of the biological strategy mentioned above, which rely on the local air stream direction are therefore skipped. Thus, the robot's orientation is not changed at the beginning of the fixed motion pattern

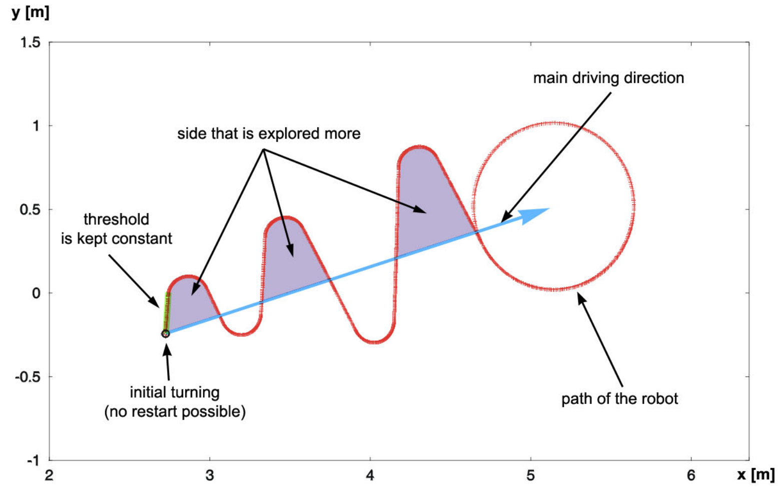

Fig. 1. Fixed motion pattern that is executed by the robot in response to an increased gas concentration.

and the initial forward surge is omitted. The resulting path is shown in Fig. 1. After being triggered by increased sensor readings, the robot starts the zigzag movement by turning approximately 65° to the side at which the higher concentration was sensed. Afterwards it performs six zigzag turns (with a length of the successive straight movements of approximately 20 cm, 30 cm, 50 cm, 70 cm, 90 cm, and 55 cm, respectively), followed by a circular motion with a radius of approximately 50 cm.

The main direction of the zigzag motion is equal to the current heading of the robot when the fixed motion pattern is triggered. However, the robot can change its orientation if the motion sequence is restarted. Because the asymmetric path is biased towards the side where the higher sensor readings were obtained, this side is explored more (see Fig. 1). Consequently, the chance that the motion pattern is restarted on this side is higher. Assuming that there is a higher chance to find the gas source on the side where the stronger concentration is sensed, a robot controlled by this gas tracing strategy should be able to move towards a gas source and to stay within close proximity to it.

3.2 Trigger

Sensor Preprocessing In order to compensate for the sensitivity mismatch of individual sensors as well as for seasonal drifts, the raw sensor readings r_i were normalised to the range of [0,1]. To avoid frequent elaborate calibration and to realise automatic adjustment to changing environmental conditions, a dynamically maintained normalisation was chosen. Both the minimum $r_{min,i}$ and maximum readings $r_{max,i}$ were constantly updated for each sensor and were used to calculate the normalised response x_i as

$$x_i^{(t)} = \frac{r_i^{(t)} - r_{min,i}^{(t)}}{r_{max,i}^{(t)} - r_{min,i}^{(t)}}. \tag{1}$$

Note that the normalisation range gets wider and might not cover the actual range of values with time. This causes changes in response r to be less pronounced in the normalised value x. To avoid this problem the normalisation range is dynamically trimmed by means of increasing the minimum and decreasing the maximum value in eq. 1 by a fixed fraction of the normalisation range - Δx_{min}^{trim}, and Δx_{max}^{trim}, respectively - and constantly repeating this procedure after each Δt^{trim} seconds. During the experiments described in this paper the values $\Delta x_{min}^{trim} = \Delta x_{max}^{trim} = 1\%$ and $\Delta t^{trim} = 30$ s were used. Finally, the normalised response values belonging to one side of the robot were combined by averaging.

Releasing the Trigger The trigger that (re-)starts the motion pattern operates on the normalised sensor readings. It is released if the normalised value exceeds a threshold that is initially set to a value η. Gas-sensitive systems based on metal oxide sensors exhibit a long recovery time, with a time constant of decay in the order of typically more then ten seconds (see [12] that investigates a similar mobile nose). Consequently, a prolonged period of increased sensor readings results, if the robot enters an area with an elevated gas concentration. To avoid permanent triggering due to this effect, two additional mechanisms are used: first, the motion pattern cannot be triggered before the robot starts to drive along the first straight line. In addition, the threshold is set to the value that triggered the motion sequence and kept constant until the robot reaches the end of the first straight track. Both mechanisms are indicated in Fig. 1. After the first straight movement has been completed, the threshold is decreased at a rate of $\Delta\eta$ until it reaches the minimum value η. For the experiments in this paper, values of $\eta = 0.2$ and $\Delta\eta = 0.01$ s^{-1} were used.

3.3 Random Search

As long as increased sensor readings are not obtained, the robot explores the available area by applying a randomized search strategy. Here, the robot drives along straight paths until it enters the clearance area around an obstacle. If so, a direction is randomly chosen from the set of valid options. Then, the robot rotates to this direction and proceeds with a straight movement.

If the robot enters the clearance area around an obstacle while performing the fixed motion pattern, the translation speed is set to zero (without changing the rotational fraction) until the robot is able to continue driving.

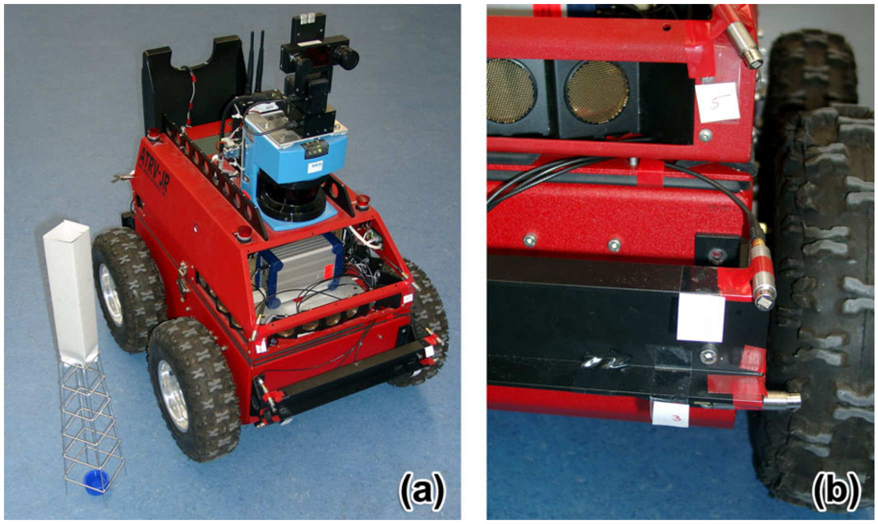

Fig. 2. (a) The mobile robot Arthur equipped with two sets of three gas sensors on each side at the front corner. Also shown is the gas source to the left of the robot. (b) Position and orientation of the gas sensors.

4 Experimental Setup

4.1 Robot and Gas Sensors

The adapted gas source tracing strategy was implemented on the mobile robot Arthur that is based on the model ATRV-Jr. from iRobot (see Fig. 2 (a)). The robot is equipped with several external sensors. In addition to the gas sensitive system, only the data from the SICK laser range scanner were used for the experiments presented below to correct the position data obtained from odometry. Remarkably, the robot (length = 80 cm, width = 65 cm, height without laser range scanner = 55 cm) is considerably bigger than a silkworm moth, where the antennae are separated by just a few centimeters.

The mobile nose is based on the commercial gas sensor system VOCmeter-Vario from AppliedSensor, which was described in detail in [14]. For the experiments presented in this paper two sets of three metal oxide sensors (of type TGS 2600 from Figaro) were used. These sensors were symmetrically mounted at a height of 21 cm, 29 cm and 40 cm on each side at the front corners of the robot (see Fig. 2 (b)).

Metal oxide sensors comprise a heating element coated with a sintered semiconducting material. The measured quantity is the resistance R_S of the surface layer at an operating temperature of between 300 °C and 500 °C [3]. Exposed to a reducing gas, the potential barrier at the grain boundary is lowered, and thus the resistance of the surface layer decreases. In consequence of the measurement principle, metal oxide sensors exhibit some drawbacks. Namely the low selectivity, the comparatively high power consumption (caused by the heating device) and a weak durability. Furthermore, metal oxide sensors are subject to a long response time and an even longer recovery

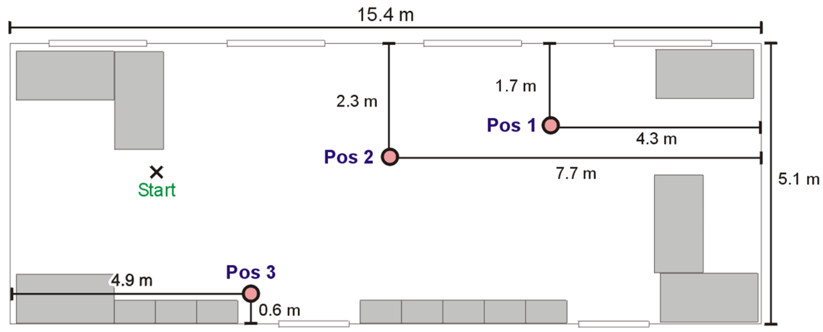

Fig. 3. Floor Plan of the laboratory room, in which the experiments were performed.

time [12]. However, this type of gas sensor is most often used for mobile noses because it is inexpensive, highly sensitive and relatively unaffected by changing environmental conditions like room temperature or humidity.

4.2 Environment and Gas Source

All experiments were performed in a 15.4 m $\times$ 5.1 m room at the University of Tübingen. A floor plan of this room is shown in Fig. 3. In addition, the obstacles in the room (cupboards and desks), the starting position of the robot and the position where the gas source was placed are indicated. During the experiments all attempts were made to keep environment closed. However, due to the fact that the room was also used as an office, up to two persons were working, moving and sometimes leaving or entering the room during the experiments. Thus, the environment can be considered uncontrolled to some extent (although all the persons were told to be careful).

The gas source was chosen to be a cylindric vessel with a diameter of 40 mm and a height of 25 mm filled with ethanol, which was used because it is non-toxic and easily detectable by metal oxide sensors. In order to be recognisable by the laser range scanner, a frame made of wire with a cardboard marking mounted on top was placed above the vessel (see Fig. 2 (a)).

5 Experiments

At the beginning of the experiments the robot was placed at the starting position indicated in Fig. 3. Next, the gas source was uncovered. In order to avoid that an initially produced gas cloud could dominate the gas distribution throughout the whole experiment, the ethanol was poured in the container approximately 90 minutes before at a different location. Then, the robot was started, and the initially applied exploration behaviour starts to drive with a randomly chosen forward direction. The velocity was limited to 4 cm/s. In order to be able to escape U-shaped obstacles a clearance of 85 cm had to be used. Therefore, this represents the minimum distance to the gas source the robot could reach during the experiments.

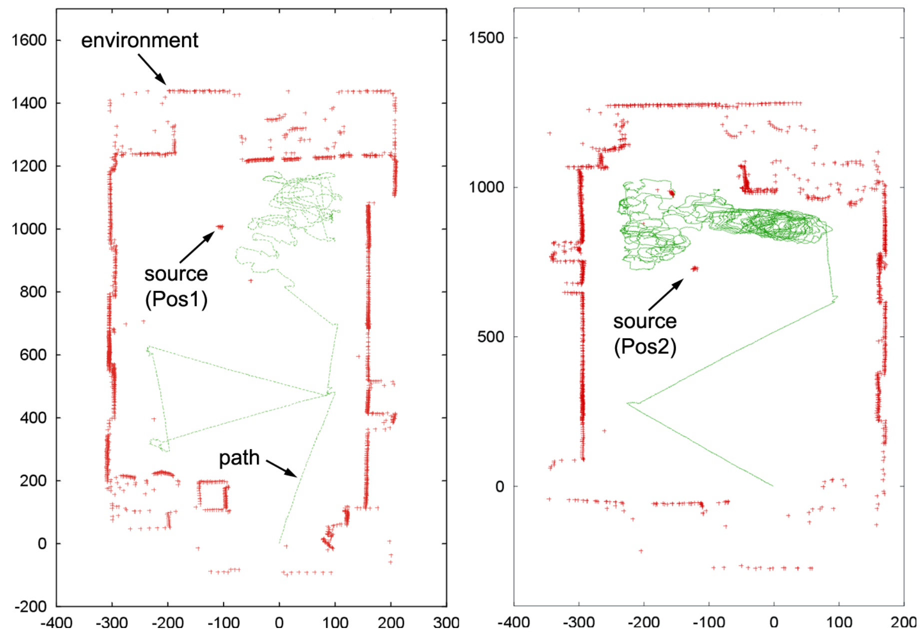

Fig. 4. Two experiments with an active source placed at “Pos1” (left side) and “Pos2” (right side) respectively.

In Fig. 4 and Fig. 5 the path of the robot during four trials is shown. In order to determine accurate information about the path driven, a scan matching algorithm [1] was used for offline correction of the odometry data.

In the trial that is shown on the left side of Fig. 4 an active gas source was placed at “Pos1”. After a short period of exploration the trigger was frequently fired and the robot stayed in the vicinity of the gas source. During that period, the average distance to the gas source was approximately 1.9 m. In the trial that is shown on the right side of Fig. 4 an active gas source was placed at “Pos2”. Here, a comparable result was obtained. After being triggered first, the robot succeeded in staying near the gas source, while the average distance to the gas source was approximately 1.8 m during that period.

For the two gas source positions used in the trials shown in Fig. 4, the robot was able to move around the gas source. In such a case, the robot was usually staying on one side of the source, probably indicating the existance of a plume-like gas distribution oriented towards that side. If the source was placed at “Pos3” like in the trial shown on the left side of Fig. 5, the robot was not able to drive around it. Here, the robot firstly drove past the source and “found” it later after exploring the room for approximately 15 minutes. After a period of 35 minutes, where the robot stayed in the vicinity of “Pos3”, it departed for another 15 minutes of random exploration. Finally, the source was found again and the robot managed to stay there during the remaining 50 minutes of the trial.

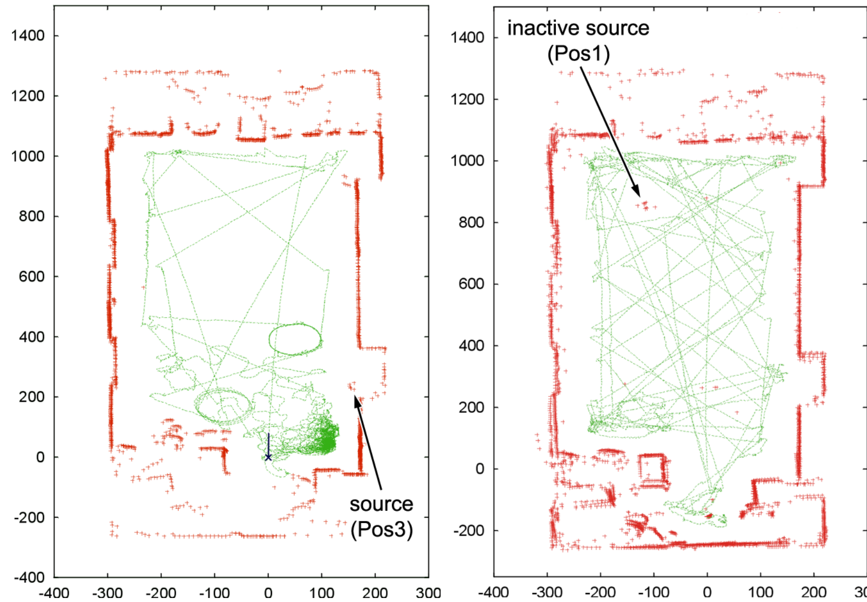

Fig. 5. An experiment with an active source placed at "Pos3" (left side) and a reference trial with an inactive source placed at "Pos1" (right side).

6 Results

The typical trials discussed in the previous section suggest that the modified moth strategy is able to perform the intended task. In order to quantify this result, the average distance to the center of the gas source was determined for six trials with an active source and three reference trials. During these reference trials no gas source was used, but the wire frame was present as an obstacle at one of the positions indicated in Fig. 3. An example of such a reference experiment with the source placed at position "Pos1" is shown on the right side of Fig. 5. Two different methods were applied to calculate the average distance for those experiments with an active gas source: considering all the distance values during the trial or just those that were obtained after the fixed motion pattern was triggered for the first time. The corresponding results, applying both methods as well as the reference value obtained from the trials without an active gas source, are itemised in Table 1. Assuming a symmetrical distribution, the corresponding standard deviation is also given.

Comparing the reference experiments with the trials where an active source was present using a Student t-test reveals no significant difference. This holds whether all the distance values are considered ($p_{H_0} = 0.433$) or just those after the motion pattern was triggered first ($p_{H_0} = 0.167$). Due to the limited number of experiments as well as the limited space, a statistically validated statement is not possible. However, the statistical and the qualitative analysis of the experiments indicate that the suggested modifications of the moth's gas source tracing behaviour are suitable to adapt this biologically inspired strategy to a robot, even one of considerably larger size.

experiment	average distance [cm]
active source, all	225.6 ± 179.6
active source, after first trigger	195.5 ± 119.8
inactive source	317.7 ± 235.2

Table 1. Statistics of 6 trials with an active source and 3 reference trials with an inactive source.

7 Conclusions

This paper introduces a gas source tracing strategy, which was adapted for use on a mobile robot based on the behaviour of the silkworm moth *Bombyx mori*. The moth uses a combination of a fixed motion pattern and a triggering mechanism that (re-)starts the motion pattern if a pheromone patch is sensed. Additionally, the motion pattern is oriented towards the instantaneous upwind direction. Due to the detection limits of currently available anemometers, information about the local wind direction is not available on a mobile robot. Besides from the larger size this is the main difference compared to the biological system. Therefore, a strategy that uses gas sensor readings only had to be applied. The proposed algorithm was implemented and tested in an indoor environment without artificial ventilation. The experiments indicate that the modified strategy is able to decrease the average distance between the robot and the gas source compared to random walk. An advantage of the suggested algorithm is that the potential vicinity to a gas source is indicated (by a high triggering frequency). Therefore, this strategy in combination with a method to declare that the gas source was found could be a possible approach to the full gas source localisation problem.

References

1. Peter Biber and Wolfgang Straßer. The Normal Distributions Transform: A New Approach to Laser Scan Matching. In *Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'03)*, 2003.
2. C.T. David, J.S. Kennedy, J.S. Ludlow, and J.N. Perry. A Re-Appraisal of Insect Flight Towards a Point Source of Wind-Borne Odor. *Journal of Chemical Ecology*, 8:1207–1215, 1982.
3. Julian W. Gardner and Philip N. Bartlett. *Electronic Noses - Principles and Applications*. Oxford Science Publications, Oxford, 1999.
4. Elise Hancock. A Primer on Smell. *Johns Hopkins Magazine, Electronic Edition – A Special Issue on the Senses*, 9, September 1996.
5. A.T. Hayes, A. Martinoli, and R.M.Goodman. Swarm Robotic Odor Localization. In *Proceedings of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS-01)*, volume 2, pages 1073–1078, Maui, Hawaii, USA, October 2001.
6. Hiroshi Ishida, Yukihiko Kagawa, Takamichi Nakamoto, and Toyosaka Moriizumi. Odour-Source Localization in the Clean Room by an Autonomous Mobile Sensing System. *Sensors and Actuators B*, 33:115–121, 1996.
7. Hiroshi Ishida, K. Suetsugu, Takamichi Nakamoto, and Toyosaka Moriizumi. Study of Autonomous Mobile Sensing System for Localization of Odor Source Using Gas Sensors and Anemometric Sensors. *Sensors and Actuators A*, 45:153–157, 1994.
8. Ryohei Kanzaki. Self-generated Zigzag Turning of *Bombyx Mori* Males During Pheromone-mediated Upwind Walking. *Zoological Science*, 9:515–527, 1992.

9. Ryohei Kanzaki. Behavioral and Neural Basis of Instinctive Behavior in Insects: Odor-Source Searching Strategies without Memory and Learning. *Robotics and Autonomous Systems*, 18:33–43, 1996.
10. Ryohei Kanzaki. Coordination of Wing Motion and Walking Suggests Common Control of Zigzag Motor Program in a Male Silkworm Moth. *J Comp Physiol A*, 182:267–276, 1998.
11. Svetlana Larionova, Nuno Almeida, Lino Marques, and A. T. de Almeida. Olfactory Coordinated Area Coverage. In *Proceedings of the IEEE International Conference on Advanced Robotics (ICAR 2003)*, pages 501–506, Coimbra, Portugal, 2003.
12. Achim Lilienthal and Tom Duckett. A Stereo Electronic Nose for a Mobile Inspection Robot. In *Proceedings of the IEEE International Workshop on Robotic Sensing (ROSE 2003)*, Örebro, Sweden, 2003.
13. Achim Lilienthal and Tom Duckett. Experimental Analysis of Smelling Braitenberg Vehicles. In *Proceedings of the IEEE International Conference on Advanced Robotics (ICAR 2003)*, pages 375–380, Coimbra, Portugal, 2003.
14. Achim Lilienthal, Michael R. Wandel, Udo Weimar, and Andreas Zell. Sensing Odour Sources in Indoor Environments Without a Constant Airflow by a Mobile Robot. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2001)*, pages 4005–4010, 2001.
15. Roberto Rozas, Jorge Morales, and Daniel Vega. Artificial Smell Detection for Robotic Navigation. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 1991)*, pages 1730–1733, 1991.
16. R. A. Russell, L. Kleeman, and S. Kennedy. Using Volatile Chemicals to Help Locate Targets in Complex Environments. In *Proceedings of the Australian Conference on Robotics and Automation*, pages 87–91, Melbourne, Aug 30- Sept 1 2000.
17. R. Andrew Russell. Ant Trails - an Example for Robots to Follow? In *IEEE Int Conf. Robotics and Automation (ICRA 1999)*, pages 2698–2703, 1999.
18. R. Andrew Russell and Anies H. Purnamadjaja. Odour and Airflow: Complementary Senses for a Humanoid Robot. In *IEEE Int Conf. Robotics and Automation (ICRA 2002)*, pages 1842–1847, 2002.
19. R. Andrew Russell, David Thiel, Reimundo Deveza, and Alan Mackay-Sim. A Robotic System to Locate Hazardous Chemical Leaks. In *IEEE Int Conf. Robotics and Automation (ICRA 1995)*, pages 556–561, 1995.
20. R. Andrew Russell, David Thiel, and Alan Mackay-Sim. Sensing Odour Trails for Mobile Robot Navigation. In *IEEE Int Conf. Robotics and Automation (ICRA 1994)*, pages 2672–2677, 1994.
21. G. Sandini, G. Lucarini, and M. Varoli. Gradient-Driven Self-Organizing Systems. In *Proceedings of the 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 429–432, Yokohama, Japan, July, 26–30 1993.
22. Titus Sharpe and Barbara Webb. Simulated and Situated Models of Chemical Trail Following in Ants. In R. Pfeifer, B. Blumberg, J.-A. Meyer, and S.W. Wilson, editors, *Proceedings of the 5th Conference on Simulation of Adaptive Behaviour*, pages 195–204, 1998.
23. E. Stella, F. Musio, L. Vasanelli, and A. Distante. Goal-oriented Mobile Robot Navigation Using an Odour Sensor. In *Proceedings of the Intelligent Vehicles Symposium '95*, pages 147–151, 1995.
24. Michael R. Wandel, Achim Lilienthal, Tom Duckett, Udo Weimar, and Andreas Zell. Gas Distribution in Unventilated Indoor Environments Inspected by a Mobile Robot. In *Proceedings of the IEEE International Conference on Advanced Robotics (ICAR 2003)*, pages 507–512, Coimbra, Portugal, 2003.