Gas Distribution in Unventilated Indoor Environments Inspected by a Mobile Robot

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Abstract

Gas source localisation with robots is usually performed in environments with a strong, unidirectional airflow created by artificial ventilation. This tends to create a strong, well defined analyte plume and enables upwind searching. By contrast, this paper presents experiments conducted in unventilated rooms. Here, the measured concentrations also indicate an analyte plume with, however, different properties concerning its shape, width, concentration profile and stability over time. In the results presented in this paper, two very different mobile robotic systems for odour sensing were investigated in different environments, and the similarities as well as differences in the analyte gas distributions measured are discussed.

1 Introduction

Providing mobile robots with a "sense of smell" could be useful for a variety of tasks. A robot equipped with gas sensors could be utilised as an electronic watchman, that is able to detect, localise and identify existing odours, perhaps indicating toxic gas leaks, leaking solvents or a fire at its initial stage. Furthermore self-produced odours can be used to aid navigation [1] or to communicate with other robots, for instance by sending a chemical SOS signal [10].

Gas sensitive systems used in mobile robotics are sometimes refered to collectively as a "mobile nose", following the definition of an electronic nose as an instrument comprising an array of heterogeneous electrochemical gas sensors and a pattern recognition system [3]. Considering a mobile nose as a single sensor, the term comprises the complete setup of such a system, including the ventilation of the sensors and their relative position with respect to the robot.

A reasonable sensor for a mobile robot should be able to provide measurements that allow sufficient discrimination of different situations, while the amount of signal processing needed must be feasible in real time. Moreover, it should be possible to use the sensor under different and changing environmental conditions. To specify these requirements precisely, they have to be seen in connection with an intended application. For the investigations presented in this paper metal-oxide gas sensors were used. Utilising these sensors to *detect increased concentrations* of volatile organic substances can be done in most real world scenarios regardless of changes in temperature, humidity or the local flow rate. These factors do not have to be considered explicitly if an appropriate detection threshold is applied. In addition, seasonal as well as environmental changes in the gas sensor readings might be compensated by adjusting the base level of sensor response.

Concerning the task of *localising an odour source* the dependency on the environment is much stronger. Next to the sensor characteristics the physical properties of gas propagation play a decisive role. Because of the slow diffusion velocity, propagation of gases in unventilated indoor environments is dominated by turbulence [8]. Thus a patchy distribution of temporally fluctuating eddies results, rather than a smoothly broadening one with a single peak at the location of the source [6, 9]. In this respect, the robot itself can be seen as part of the environment due to its influence on physical parameters such as local air currents.

Apart from simple environments, it is not possible to model the airflow dynamics accurately. One way to overcome this problem is to add a sufficiently strong artificial air current (> 10 cm/s) that superimposes the complicated turbulent gas distribution with a more simple plume-like structure and enables upwind searching utilising an anemometer [4, 5, 11].

Using local wind measurements is, however, currently not feasible in unventilated indoor environments because the wind speeds observed are usually too low. Thus, an algorithmic treatment of the gas sensor readings is needed that enables a mobile robot to localise an odour source under typical conditions in unventilated indoor environments.

This paper addresses the question of determining these typical conditions. It summarizes results of experiments carried out in two unpopulated, medium sized rooms without ventilation. To study the influence of the measuring device, two different sized robots equipped with different mobile noses were used. In the experiments presented, the relative concentration was measured over several hours with Figaro metal-oxide sensors while the robot traversed a predefined path.

The rest of this paper is structured as follows. In section 2 the experiments and corresponding setups for both tested scenarios are described, including the respective gas sensor systems and environments. The corresponding experimental results are then presented in section 3, followed by conclusions and suggestions for future work (section 4 and 5).

2 Experimental Setup

This section describes the different experimental setups and the two different robots used: An iRobot ATRV Jr. robot ("ARTHUR") at the University of Tübingen and a K-Team Koala robot at Örebro University. In both cases, the robot was driven along a predefined path (a rectangular spiral) around the location of the odour source. A rectangular spiral was chosen because it covers the available rectangular shaped space and provides the path as a sequence of segments that are easy to follow with the two robots due to their ability to turn on the spot. A constant speed was applied along the straight lines because this was found to enhance the localisation capability of the mobile noses used [2, 7].

To measure relative gas concentrations Figaro metal-oxide sensors were utilised. These sensors contain a heating element to maintain a constant operating temperature of approximately 300^{o}C. The measured quantity is the electrical resistance of the semiconductor, which is is affected by redox reactions of the sensed gas with the sensor surface [3]. Differently doped materials provide slightly varying sensor characteristics, although metal-oxide sensors are not highly selective in general. They were rather chosen for our experiments because of their high sensitivity, sufficient to detect a beaker of ethanol from a distance of several meters [12]. Due to the physics of the measuring principle the time constants of the response and recovery of the sensors are quite long (in the order of a few seconds for response, and a few tens of seconds for recovery). Thus considerable temporal integration of successive readings is always performed implicitly by the sensors themselves.

The odour source used in the experiments was evaporating liquid ethanol at room temperature. Ethanol was chosen because it is highly volatile, non-toxic and easily detectable by the sensors used.

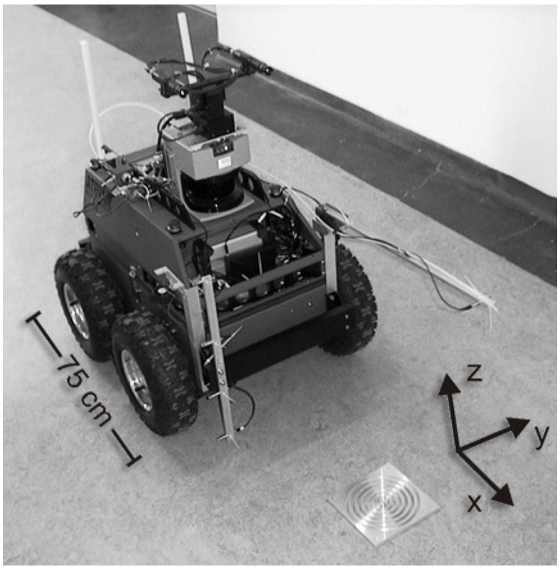

Figure 1: *The robot ARTHUR, equipped with a VOCvario gas sensor system in front of the vessel used to provide an odour source.*

2.1 Experiments at Tübingen University

One set of experiments was conducted in a 12.90 m×7.10 m classroom at the University of Tübingen (see Fig. 2) without an air conditioning system. Here, the comparatively large robot ARTHUR (see Fig. 1) with an enclosing rectangle of 75 cm×65 cm was used.

The robot is equipped with the commercial gas sensor system VOCvario consisting of a base unit (19 cm×12 cm×6 cm) and up to eight gas sensors connected with thin coax cables. The gas sensors are embedded into so-called sensor sticks providing a flexible setup that facilitates positioning and exchanging of individual gas sensors and allows quick swapping between different types of sensors. During the Tübingen experiments presented in this paper no fans were used to ventilate the sensors.

In order to check the suitability of different sensor positions four identical sensors (TGS2620) were mounted to a vertical cantilever at different heights (see Fig. 1). Thus the sensor positions were

$$(0.38, -0.21, [0.045|0.175|0.325|0.485])\ \mathrm{m}$$

with respect to the projection of the robot's center to the floor.

Fig. 2 shows the floor plan of the classroom. Obstacles are represented by dark shaded regions, windows and doors by narrow rectangles, and the odour source by a circle in the middle of the room. Also included is a sketch of the path driven indicating a complete inward spiral (from 'start:in' to 'end:in') and the beginning of the successive outward movement (starting at

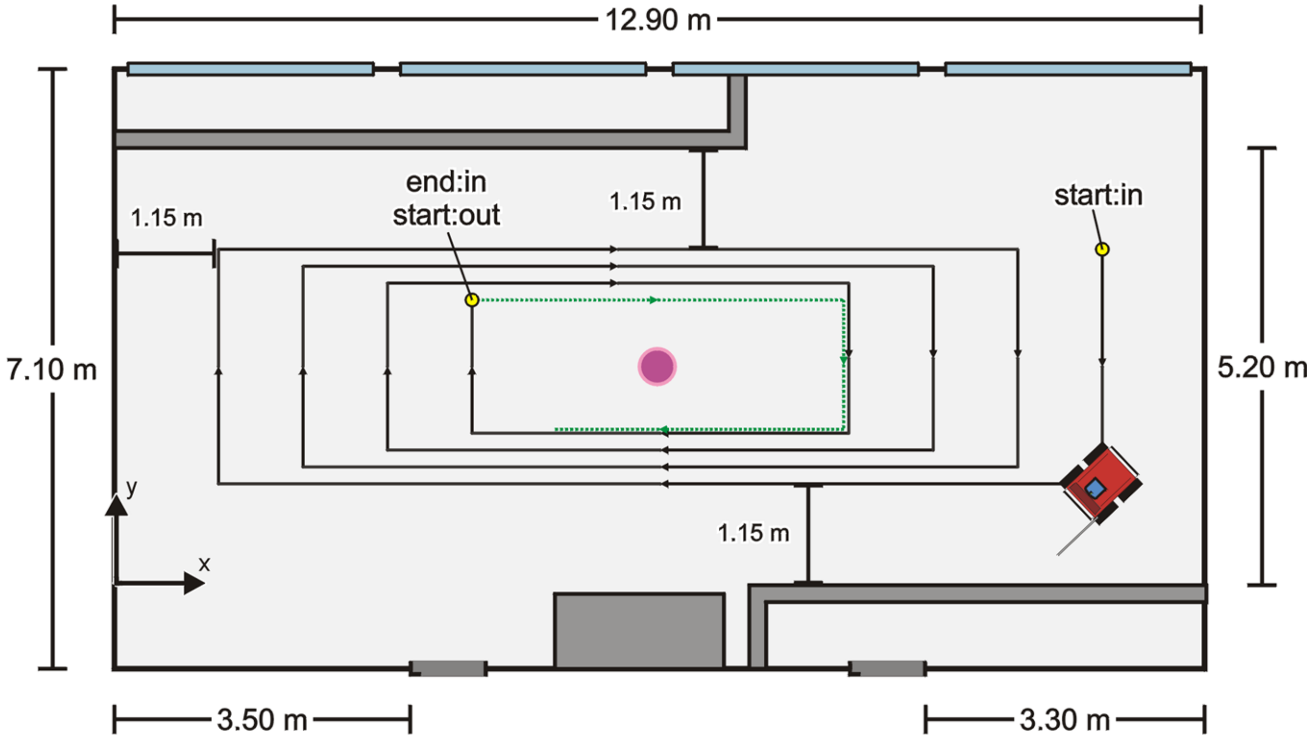

Figure 2: *Experiments at Tübingen University: The figure shows a floor plan of the classroom at Tübingen University - including the positions of the windows (top), doors (bottom), and obstacles (inside the room) - the inward section of the path driven, and the location of the odour source (see text for further details).*

'start:out'). The robot's speed along the straight lines was set to 15 cm/s. Here, the robot constantly aligned itself with the room's main axes determined by a laser range finder [7]. In order to minimize self-generated turbulence the 90-degree turns were performed with low speed and the robot was stopped for 10 seconds after every turn. Thus a complete cycle (including an inward and a subsequent outward movement) lasted about 30 minutes.

For the evaluations presented in this paper the four sensors mounted at the vertical cantilever were used. Because the readings of these four sensors do not show a significant dependency on the height, the average of the four readings was used to provide a robust estimate of the relative concentration at the given location (x,y). The odour source was realised by a special vessel [7] shown in Fig. 1 filled with ethanol at the beginning of the experiments.

Due to the applied obstacle clearance of 1.15 m the area used for the experiments was bounded by a 10.20 m×4.80 m rectangle.

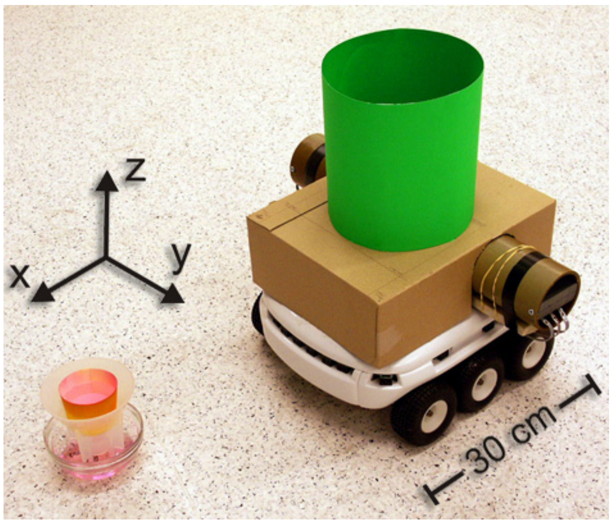

Figure 3: *Koala robot with the Örebro Mark III mobile nose. The picture shows the odour source, the gas sensors inside the two suction tubes mounted at the rear of the robot and the coloured "hat" used for determining the absolute position of the robot.*

2.2 Experiments at Örebro University

A second set of experiments was performed with the Koala robot (enclosing rectangle 30 cm×30 cm), which is shown in Fig. 3. This robot was equipped with 6 Figaro metal-oxide gas sensors placed in sets of three (of type TGS2600, TGS2610 and TGS2620) inside two separate tubes containing a suction fan each

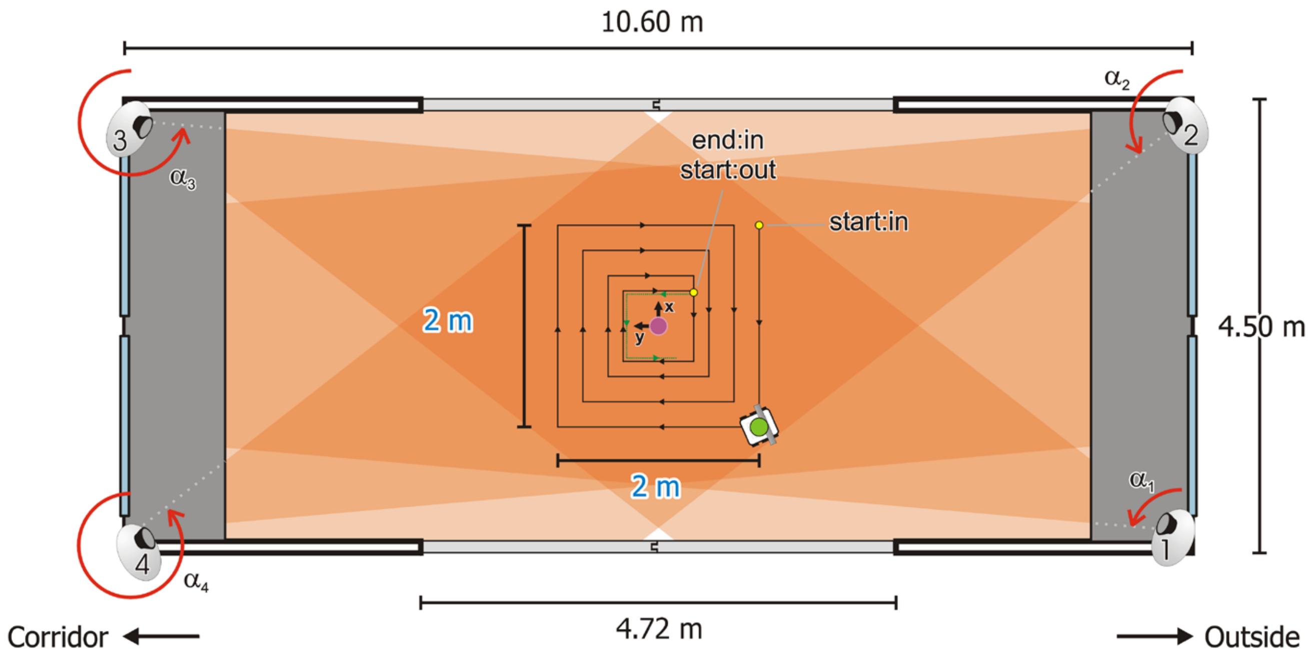

Figure 4: *Experiments at Örebro University: The figure shows a floor plan of the laboratory room, the inward section of the path driven, and the location of the odour source (see text for further details).*

(the Örebro Mark III mobile nose, see Fig. 3). Papst Fans (405F) were used to generate an airflow of 8 m^3/h. For the investigations presented in this paper, the sensor arrays were used to increase the robustness of the measured signal rather than to discriminate different odours. The distance between the two sets of sensors was 40 cm resulting in sensor positions of

([-0.07|-0.045|-0.03], -0.20, 0.18) m

([-0.07|-0.045|-0.03], 0.20, 0.18) m

with respect to the projection of the robot's center to the floor.

The experiments were performed in a rectangular 10.6m × 4.5m laboratory room at Örebro University (see Fig. 4). To record the position of the robot a vision-based absolute positioning system was applied which tracks a distinctly coloured object mounted on top of the robot. The positioning system uses four Philips PCVC 740K web-cameras with a resolution of 320×240 pixels to triangulate the (x,y)-position of the center of the colour blob. By combining up to 6 single position estimates it provides an accuracy of approximately 1 cm inside the central region that can be sensed by at least three cameras [6]. Fig. 4 shows the camera positions and the respective fields of view. The picture also shows with graded shadings the number of cameras that can sense each part of the environment.

The air conditioning system in the room was deactivated in order to eliminate the possibility of a dominant constant airflow. To simulate a typical task for an electronic watchman, the odour source was chosen to imitate a leaking tank. This was realised by placing a paper cup filled with ethanol on a support in a bowl with a perimeter of 12 cm (see Fig. 3). The ethanol dripped through a hole in the cup into the bowl at a rate of approximately 50 ml/h.

The robot's speed along the straight lines of the the path driven (see Fig. 4) was set to 5 cm/s. As in the Tübingen experiments slow rotation was performed (10^o/s) in order to minimise turbulence. Thus a complete cycle lasted about 25 minutes.

3 Results

In the right part of Fig. 5 the results of the Tuebingen experiments are shown. Here, thick black lines indicate the outline of the room, while the dots represent the sum of all signals of the four sensors mounted on the vertical cantilever. The windows are shown by the rectangles at the right side wall (2).

Looking at the summertime measurement in the left of Fig. 5 it can be easily seen, especially on the projection to the walls (2, 3), that the highest ethanol concentration is located at the side wall (2). This can be explained by a convection air stream, indicated by the arrows. This air stream is caused by the sun warming the windows. Under these conditions the concentration is higher at the wall compared to the middle of the room at the source.

In Fig. 5, right the same room is shown, but in wintertime. In contrast to the summertime, the ethanol

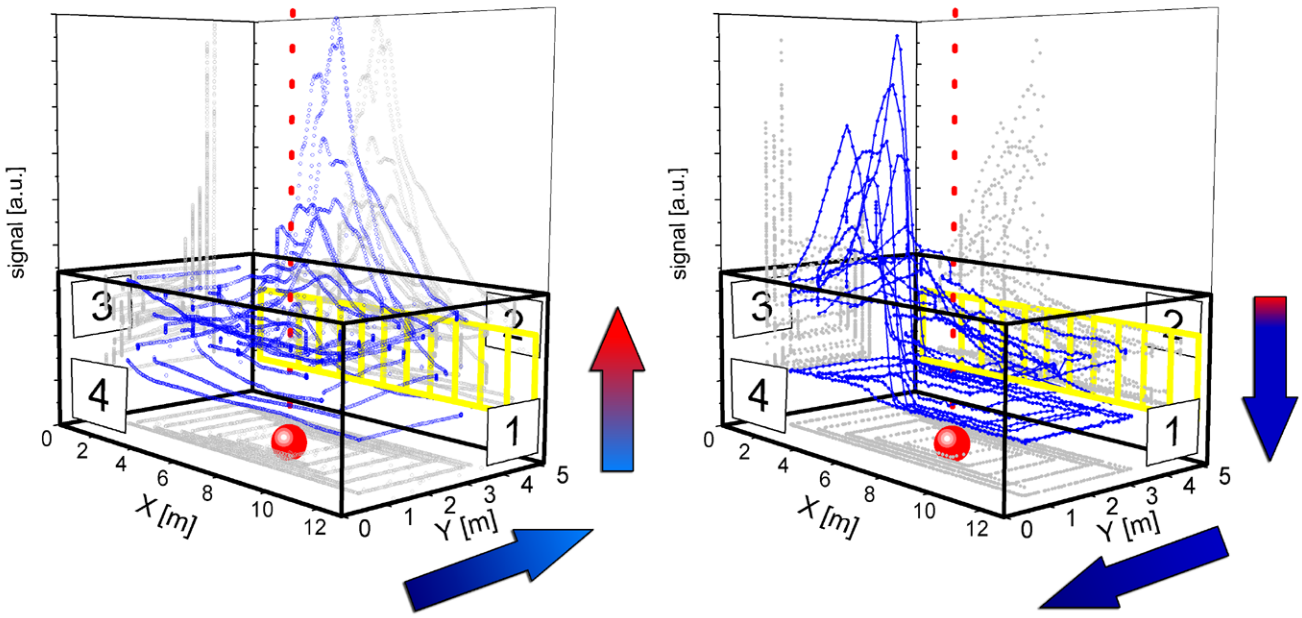

Figure 5: *Experiments at Tübingen University (see Fig. 2). The pictures show results of measurements performed at summertime (left) and wintertime (right) respectively. During both measuremnts the source was placed in the middle of the room indicated with a ball.*

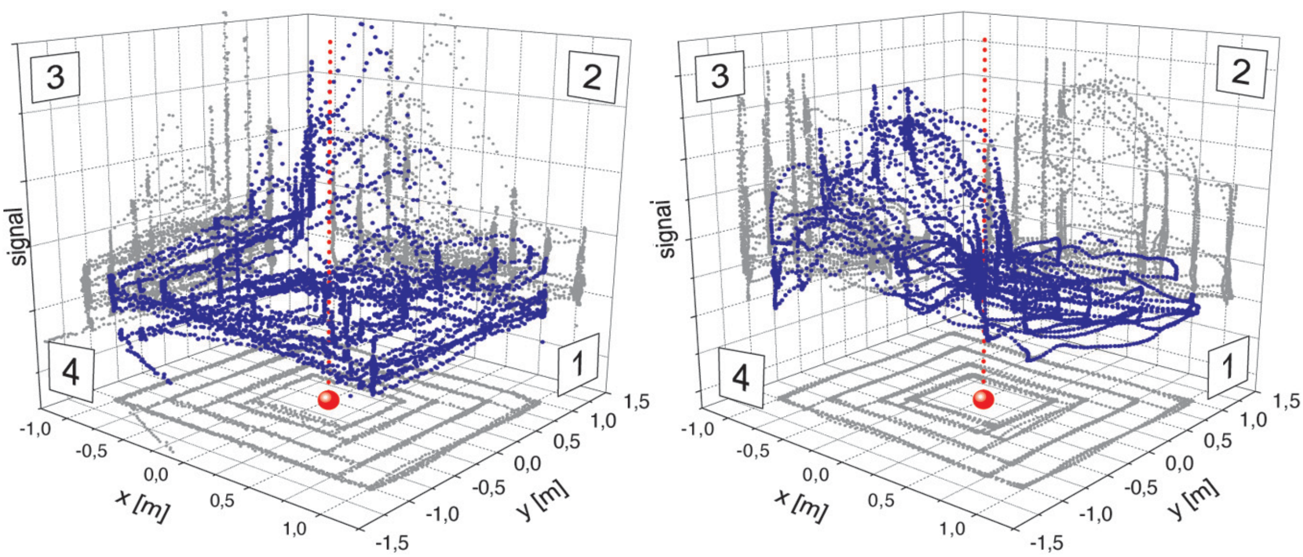

Figure 6: *Two examples obtained during the experiments at Örebro University (see Fig. 4).*

was found at the front wall (4), because the windows at the side wall (2) were the coldest part of the room in this case.

The situation observed in Tübingen was nearly as stable as with an artificially created air stream. Because the velocity of convection induced air streams is much lower than the velocity of typical artificially created air streams, the width of the plume (perpendicular to the direction of the air current) is much bigger than in ventilated rooms.

Results of the experiments at Örebro University are shown in Fig. 6. The left picture shows a remarkable similarity to the summertime measurements in the classroom at Tübingen (Fig. 5, left). It depicts a period of one hour, and the situation was found to be stable for at least two more hours.

During another measurement performed four weeks later (Fig. 6, right) the maximum concentration of the analyte was found at the opposite wall (4). It is unclear what caused this shift, while the reason for such a change (the different temperature distribution at different seasons [7]) was easily determined in the case of the Tübingen experiments. The whole system was more unstable during these observations: After 80 minutes there was a slight clockwise turn (in the ground plane) of the analyte plume, then 50 minutes later the plume turned back to its initial origin.

During both series of experiments, at Örebro and Tübingen, an uniform distribution of the analyte throughout the test environment was never observed. Even after a prolonged period of time there were still clear concentration differences across the area observed. The nearly constant plume formed mainly by convection was stable over the whole measurement period.

4 Conclusions

The two experimental setups were very different, nevertheless the results are similar, giving the chance to find a unified algorithm to localise the odour source. A precondition to localise the source in real world applications is the relative stability of the concentration profile over time, which was observed in both cases. This is important to be able to localise the source some time after the occurrence of a leak. A second common observation is the shape of the plume: one end with lower concentration near the source and one with higher concentration pointing to the wall.

Beside these similarities there are differences between the two scenarios investigated. During the experiments in Tübingen a constant, almost linear increase of the ethanol concentration in the whole room was observed. By contrast, the overall concentration reached a steady state during the Örebro experiments. Here, the lab was a more open one, allowing mass exchange with the surrounding rooms, thus resulting in a steady concentration. This would result in problems for an algorithm to compute the time of occurrence some time after the event itself, as proposed in [12].

5 Outlook

The results corresponding to the two scenarios investigated show clear similarities refered to the analyte gas distribution. For localisation an algorithm to compute a grid map of the analyte concentration will be developed, and first tested offline.

A further aspect of the research will be the relationship between the gas concentration and the distance to the odour source. The biggest concentration was never measured close to the source. To get an idea of the effect that causes this distribution further measurements and numerical simulations will be performed.

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