EXPERIENCES USING GAS SENSORS ON AN AUTONOMOUS MOBILE ROBOT

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Abstract

This paper reports on experiences concerning the deployment of gas sensors on an autonomous mobile robot. It particularly addresses the suitability of the developed system to localize a distant odour source. First experiments were undertaken in which the robot was ordered to move along different weakly ventilated corridors, while keeping track of its center (framing a '1D' scenario). The measured sensor values show evident peaks that roughly indicate the location of the odour source, if the robot moves with a speed not too low. In this case the system proved to be well suited to detect even weak odour sources. Otherwise the observed course of the received values show many peaks hardly correlated with the location of the odour source. Several investigations were performed to clear up this behaviour but it is still not possible to make concluding statements about the reasons. Finally the setup to perform experiments in a '2D' scenario is described and concerning results of first investigations are presented. It was shown that the utilized system is also capable of detecting a distant odour source in a 2D environment and that the somewhat harder localization task has to account for some weak airflow even in closed, unventilated rooms.

1. Introduction

Gas Sensor Systems that are generally summarized with the term 'electronic noses' [1] have been widely used under laboratory conditions. Numerous investigations have been done on food analysis, for example. Some striking results include tests on the freshness of fish [2], quality estimation of ground meat [3], recognition of illegally produced spirituous beverages [4] or the discrimination of different coffee brands [5], to name only a few.

Considering the multitude of such remarkable results, it seems to be promising to use gas sensor systems to establish a 'sense of smell' on mobile robots. But, although electronic noses apparently proved to perform well in the above mentioned laboratory-based applications, it is not straightforward to use these sensor systems on mobile platforms. This is mainly caused by the sample handling process, which is a major factor that influences the successful application of an electronic nose. In laboratory-based applications usually much effort is expended to prepare the volatile components that are analyzed with the gas sensor system. Often headspace samplers are used, which prepare the headspace of an analyzed material in a well defined way and deliver the headspace sample into a chamber containing the gas sensors [6]. Moreover, best performance in such applications was achieved by using a special measurement technique that requires a second gas component (e.g. clean air with known humidity) to be available. This gas serves as both reference and carrier gas, that is periodically routed to the sensor chamber and analyzed by the gas sensor system (thus enabling to track the evolution of the baseline) and is also used to carry the prepared headspace sample from the sample vessel into the sensor chamber. It is almost impossible to realize the same process on mobile platforms because of weight, space and power restrictions.

Additionally there are environmental influences which are hard to control in real world applications. Gardner and Bartlett reported usual accuracies of $\pm 0.1^{o}C$ (temperature), $\pm 1\%$ (relative humidity) and $\pm 1\%$ (flow rate) as important conditions when employing electronic nose technology [7]. It is desirable to control these variables as much as possible to reduce experimental errors, but it is also hard to realize the claimed precision due to the given restrictions of a mobile platform.

Because of these problems this work[1] concentrates on the

[1]This work is part of the project 'Senses for Mobile Robots', which is supported by the state of Baden-Württemberg.

task of detecting rather than discriminating gases. To investigate the facilities of these sensors on autonomous mobile platforms, a mobile robot was equipped with a gas sensor system and its ability to measure concentrations of a defined volatile substance in unmodified indoor environments was tested.
The intention of our project is to establish an 'electronic watchman', who is able to detect volatile components and localize the respective source. Furthermore the used gas sensor system could enable other interesting applications, which make use of self-produced odourous markers to aid navigation [8, 9] or to communicate with other robots [10].
A very challenging problem is posed by the condition that the environment in which the robot should be utilized, is not supposed to be modified (just to allow the electronic watchman to operate in). This means that only poor assumptions about the airflow situation could be made. Especially one has to deal with indoor environments without a constant airflow. This rules out localization strategies which involve an upwind-search after plume acquisition [11, 12]. The localization task is also complicated by the fact that little information about the propagation of volatile substances is available if the propagation is not caused by a constant laminar flow.
Moreover the absence of a constant airflow also affects the detection process, because the response of the used metal oxide gas sensors is often dominated by even small, indiscernible air turbulences rather than concentration differences. It was shown that this kind of problem could be weakened by driving the robot with a constant speed [13, 14].
It should be noticed that the sensor system used is not a complete electronic nose following the commonly accepted definition, which claimes an electronic nose to comprise a sample handling tool, an array of electronic chemical sensors with partial specificity and an appropriate pattern recognition system [15].
Considering the mentioned problems, the goal of the presented work is to enable an autonomous mobile robot to detect surged concentrations of beforehand known volatile substances in indoor environments without a constant airflow and to localize the originating source.

2. Hardware Setup

This section describes relevant properties of the engaged setup consisting of the gas sensor system and the mobile robot ARTHUR (see fig.1).
ARTHUR is based on the model ATRV-Jr from RWI[2], which is a four wheeled, skid steered vehicle (permitting turns on the spot). The robot is equipped with a Pentium based dual processors system working at a clock rate of 333 MHz, which is integrated into the local network over a wireless LAN connection and operated under Linux. During the experiments the robot moves autonomously, controlled by an algorithm that mainly uses the output of the laser range finder (SICK LMS200 [3]) mounted on ARTHUR's top (see fig.1) at a height of about 60 cm.
This system was extended by the commercial gas sensor system VOCmeter Vario[4] which was described in detail elsewhere [14]. For flexibility it consists of two main

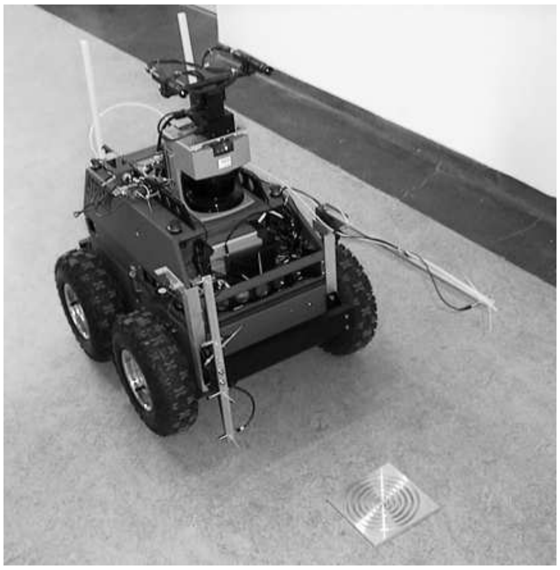

Figure 1: The autonomous mobile robot ARTHUR equipped with a gas sensor system. On the floor, in front of the robot, the vessel which served as an odour source is depicted (see fig.5 for details). Inside the robot's body (above the front side sonar sensors) the basic unit of the gas sensor system can be seen. Notice that this basic unit is also depicted in fig.2. Four identical MOX gas sensors are mounted on a vertical cantilever (4.5*cm*, 17.5*cm*, 32.5*cm* and 48.5*cm* above the floor). The cantilever is mounted 38*cm* in front and 21*cm* sidewards of the robot's center, that is supposed to be the point of intersection of the intended connections between the opposing wheels. Another two MOX sensors of the same type (also integrated in sensor sticks like the ones shown in fig.2) are mounted on the outstanding bar at the left side of the robot. They are fixed 46.5*cm* above the floor, 24*cm* sidewards and 35*cm* respectively 81*cm* in front of the robots center. Finally two supplementary MOX sensors are placed inside a pumped cell, which can be seen on the right side of the robots top. This cell is pumped by a tube whose orifice is placed on the outer end of the outstanding bar too (87*cm* in front of the robots center). Furthermore the picture shows the laser range finder (mounted on ARTHUR's top), which is mainly used for concerns of the employed steering algorithm. Above the laser range finder a stereo camera system is situated on a pan tilt unit, which was not utilized during the experiments described in this paper.

[2] www.irobot.com/rwi (iRobot/RWI, USA)

[3] www.sick.de

[4] www.appliedsensor.com/products_vocmeter.htm (MoTech, Reutlingen, Germany)

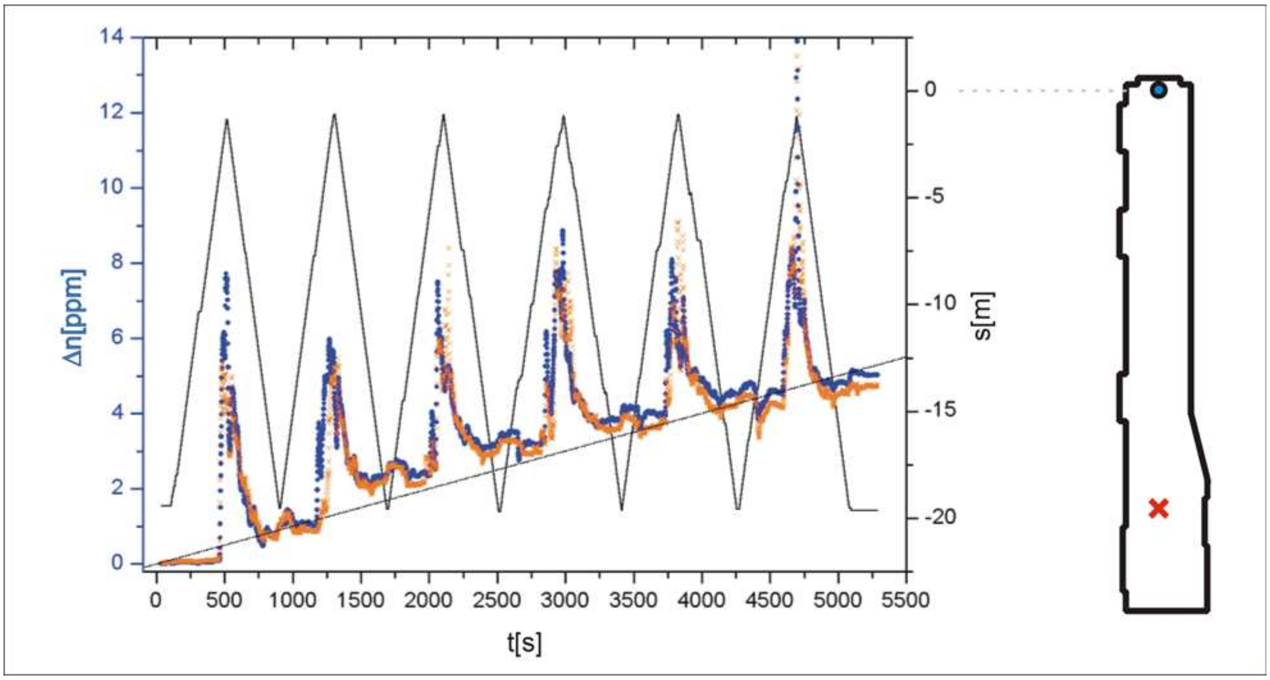

Figure 3: Chemical concentration measurements taken in a weakly ventilated corridor. The corridors outline including the position of the odour source representing $s = 0m$ (indicated by a heavy, bordered dot) as well as the robot's turning point (indicated by a heavy cross) are drafted in the right side of the picture. The plot that is shown on the left side, exhibits the robot's position (jagged solid line, refering the right ordinate), the measured values of two identical MOX gas sensors (strong dots/light crosses: the sensor is placed on the outermost end of the outstanding bar on the right/left side of the robot, refering the left ordinate), and the regression line indicating the rising base level of the sensors (smoothly rising solid line). The robot moved with a constant speed of $5cm/s$ along the corridor, stopped in front of the odour source (a jar with an opening area of $130cm^2$ filled with ethanol) and moved back without being rotated.

Figure 2: The commercial odour sensing system VOCmeter Vario[4]. The basic unit of the used system can be seen on the right side of the picture. It is able to operate up to eight tube-shaped sensor sticks (like the ones shown in the left side of the picture) over thin coax cables. Notice that the basic unit is placed inside the robots body during the performed investigation (see fig.1).

components: First, there is a small-sized basic unit (see fig.1,2) that is able to gather the measured values of up to eight single gas sensors and to transfer them to the host computer. These gas sensors are embedded into so-called sensor sticks, that are connected with the basic unit over thin coax cables. Thus the particular gas sensors can be easily placed on different positions on the robot (see fig.1).

3. Performance Measurements in '1D' Environments

First experiments were undertaken in weakly ventilated corridors (see [14] for details). The robot was ordered to move up and down the corridor while keeping track of its middle. This experimental setup framed a unidimensional axis on which the source of the volatile substance was placed as well. Different jars containing liquid ethanol or acetone were used to serve as odour sources. The cross sections of the respective jars (from 20 to $130cm^2$) were chosen to simulate rather small gas concentrations comparable to small puddles of leaking liquid chemicals.

Two different sets of experiments were performed, distinguishable by the position of the odour source. In the first series the vessel containing the liquid chemical was placed at the end of the corridor and the robot had to stop in front of it. This scenario prevents the robot from top-

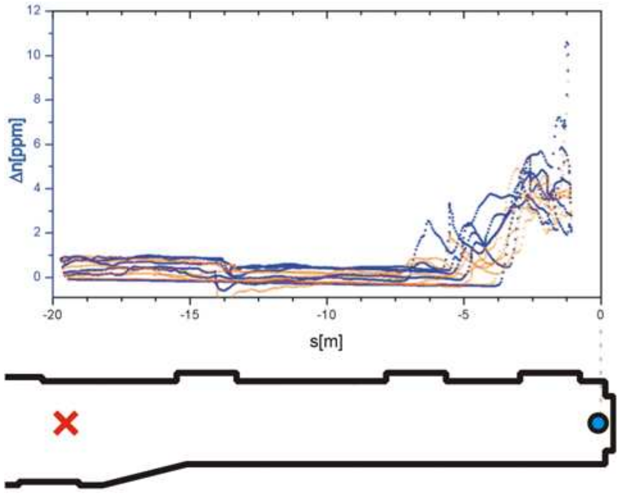

Figure 4: Chemical concentration measurements during the approaching phase of the runs that are shown in fig.3, plotted against the distance to the odour source.

pling or even breaking the jar.

Results of a run using the just described scenario utilizing the analyte ethanol are shown in fig.3. Rightmost a draft of the corridor, in which the respective experiments were undertaken, is drawn. The robot position is given by a solid line referencing the right ordinate. It indicates the distance between the robot and the odour source, which was placed at $s = 0m$. In addition, the sensor data of two single gas sensors were also plotted into the same graph against the left ordinate. In this investigation two outstanding bars like the one that is shown in fig.1 were used as stiff extensions on either side of the robot. Measured values of a gas sensor, which was placed at the outer end of the right bar, are plotted with strong dots, whereas values of an identical sensor placed at the respective position on the left bar are indicated by lighter crosses. Sensor data were normalized to their base level, which is the output of the individual sensor without an odour source being present. Though it was not possible to reproduce exactly the same conditions in calibration measurements, the stated values can only serve as a rough scale of concentration differences rather than absolute values. Both sensor data and the robot position were plotted against the time since the odour source had been filled ($t = 0s$). It can be seen that the robot clearly senses the presence of the volatile ethanol. Approaching the odour source leads to rising sensor outputs, and the resulting peak indicates the position of the odour source. Moreover, the spreading of the volatile substance is reflected by a rising baseline that is superimposed by the mentioned peaks. This baseline is also plotted in fig.3.

To clarify the ability of the used mobile system to localize the odour source, another plot was drawn that shows the values, that were gathered during the phases in which the robot was approaching the source only, depending on the distance to the odour source (fig.4). In contrast to

Figure 5: Vessel used as an odour source, that the robot is able to drive over without wetting its tyres by picking up the chemical. It is made of a square aluminium plate (having a width of $18.4cm$) in which six nuts ($7mm$ wide, $7mm$ deep) were milled along concentric circles of the radii $1.25cm$, $2.55cm$, $3.95cm$, $5.35cm$, $6.75cm$ and $8.15cm$ respectively. Thus offering surfaces of $5.5cm^2$, $11.2cm^2$, $17.3cm^2$, $23.5cm^2$, $29.7cm^2$ and $35.8cm^2$, which adds up to a maximum total amount of $123.2cm^2$ (equal to a jar with a diameter of $12.5cm$).

the plot in fig.3, the values were normalized to the rising baseline to make them comparable. Although some minor peaks can be seen, the measured values tend to be maximal when the distance to the odour source is minimal. The rise of the curves starts at about $5m$ in front of the source (except for the first approach, where the rise started at about $4m$ in front of the source). Therefore our mobile system should be able to detect the presence of the respective odour source within the given distance.

In order to enable investigation, that involve the robot to drive over the odour source, a new vessel was built (see fig.5). It was made of a square aluminium plate (having a width of $18.4cm$) in which several concentric circles were milled. During the experiments the plate was fixed to the ground with adhesive tape and the milled nuts were filled with the respective liquid chemical. In this way the robot is able to drive directly over the source without wetting its tyres by picking up the chemical. Notice that it is possible to simulate odour sources of different strengths by filling a varying number of the milled nuts.

4. Why Does the Robot Receive More Evident Peaks if it Moves ?

The robot moved at a constant speed (of $5cm/s$) within the investigation described above. This was shown to be

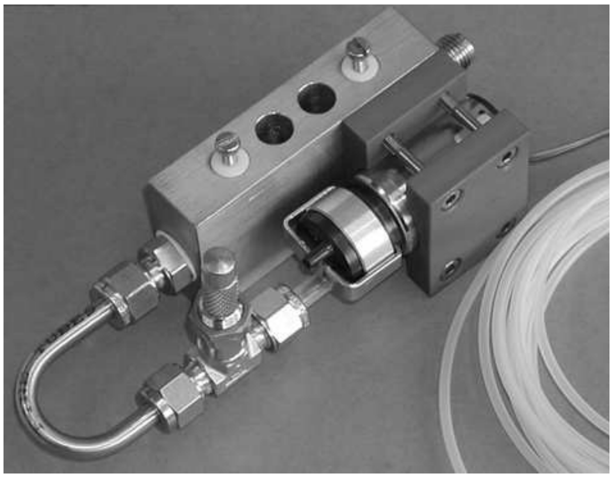

Figure 6: Pumped sensor cell. Left aside of the tube, that was used to aspirate the surrounding air, (only partially depicted) the pump could be seen. The outlet of the pump is connected with the sensor chamber over a bent high-grade steel tube that is intercepted by a valve which is used to throttle the flow. Two sensor sticks are inserted in the sensor chamber, whereas up to four are possible.

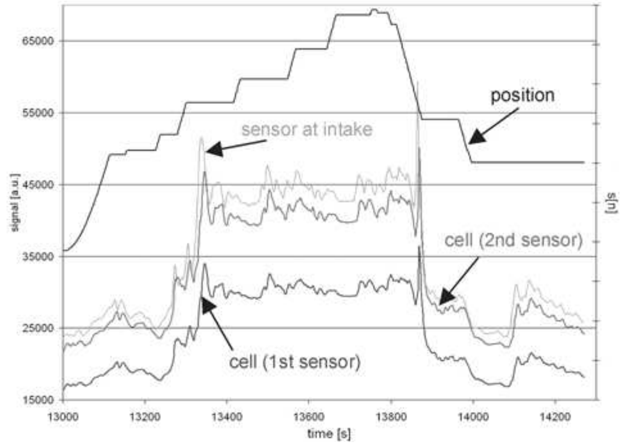

Figure 7: Chemical concentration measurements taken in a weakly ventilated corridor utilizing a stop-and-go strategy. Measured values of three identical MOX sensors are shown (refering the left ordinate). Two of them are are located in the pumped cell and another one is located near the intake of the tube, thus analyzing nearly the same scope. Also the robot's position is plotted against the right ordinate.

an indispensable condition to receive evident peaks indicating the origin of the leaking chemical (see [14]).

It is not definitely obvious why this behaviour occurs. One possible reason is the working principle of the gas sensors used. Experiments were undertaken utilizing TGS2620 metal oxide sensors (MOX sensors) from Figaro[5] because this sensor type is known to be highly sensitive to ethanol and acetone. However, MOX sensors show a decreasing resistivity due to an increasing concentration of combustible volatile chemicals in the surrounding atmosphere. This is caused by an increasing rate of oxidation reactions taking place at the heated surface of the sensor. As a result of this combustion process some material is consumpted at the sensor's surface.

Therefore, it was assumed that the robot had to drive at a not too low constant velocity in order to add an extra airflow relative to the gas sensor's location. Without this extra airflow, if there were no air movement relative to the sensors, the consumed analyte would be replaced by diffusion only (which is known to happen at a low rate due to the small diffusion velocity of gases [12]). This results in a significant degradation of the MOX sensors saturation level, which in turn means that weak airflows (which in real world scenarios always exist) could dominate the received sensor signal, superimposing the signals portion that contains the information on the analytes concentration.

To clarify the question if the combustion of the analyte at the sensors surface is accountable for the mentioned effect, the robot was equipped with a sensor cell that was pumped via a tube made of PTFE (see fig.6). The pump was adjusted to yield an airflow of $300 ml/min$ and was used within a test run. To test the effect of the specified cell an experiment was performed utilizing a stop-and-go strategy. This strategy was shown to perform very badly for solving the detection or even the localization task [14]. Notice that the above mentioned vessel (see fig.5) filled with ethanol was used to serve as an odour source. Respective results are shown in fig.7. The plot is arranged in the same way as the plot in fig.3, whereas measured values of three sensors of the same type were plotted into the graph. Two sensors are located in the pumped cell and another one is located near the inlet of the tube. Therefore the sensor's scope was almost the same. It can be seen that the curve received by the sensors in the pumped cell shows almost exactly the same trend as the one received by the sensor which was placed outside the cell. Therefore, it has to be stated, that adding an extra airflow of about $300 ml/min$ doesn't improve the performance of the odour sensitive mobile system considerably. This result is in accordance with preceeding measurements in which different common pc fans were mounted in front of a sensor to add an extra airflow by ventilating the sensor's surface.

Another experiment was done to investigate the influence of the analytes consumption on the measured values. Eight MOX sensors were placed into a chamber with a volume of about $15 cm^3$. A defined airflow of $200 ml/min$ containing a fixed concentration of volatile acetone was routed to this chamber by a flow controller. The airflow was stopped at fixed points in time for a period of 300 s, thus leaving the sealed sensor chamber with (at first) the same concentration but without an airflow to compensate

[5] www.figarosensor.com (Figaro, Japan)

the consumpted volatile substance by means of a laminar flow. After these periods the same flow was adjusted again and the procedure was repeated for different analyte concentrations. This procedure was done in consecutive runs operating either two or eight sensors. In each case the sensor signal slopes at a constant rate after the airflow was stopped, whereas the decline was considerably steeper when eight sensors were operated. Because of the small dimensions of the sensor chamber it is not clear whether the decrease of the sensor signal is caused by the diffusion controlled substitution of the volatile analyte or mainly by the pure consumption of the analyte's material. Therefore this investigation have to be repeated using a considerably bigger cell.

5. Setup to Perform Measurements in '2D' Environments

The intended electronic watchman is supposed to operate on a two dimensional search space. In order to simulate this situation, another series of experiments was arranged in an unventilated room at a university building, that offers a 'more' rectangular outline than the corridor scenario described above. A draft of the used room is depicted in fig.8.

During these experiments the robot moved through the room along a rectangular spiral while keeping a constant velocity during the movement along straight lines. Thus a possible search strategy was implemented, which not only covers the available space of the rectangular area but also takes into account that it is necessary to drive at a constant linear velocity in order to get meaningful and comparable results. Only the values that were measured while the robot moved were evaluated. Moreover the 90-degree turns, which have to be carried out at each corner, were performed at low speed and the robot was directed to stop after every turn for 10 seconds in order to minimize the influence of whirling up air by the robot during the rotation periods.

The employed steering algorithm operates on data gathered by the laser range finder. In a first step line segments were extracted out of the measured data by means of a least squares fit [16]. The orientation angle of these extracted segments are subsequently weighted by their length and collected into a fuzzy histogram. In this way the robot is able to track the main axes of the room (by determining the two main peaks in the histogram) and to use this knowledge for navigation purposes. A fuzzy histogram was used because it allows a precise determination of the mean angle of the line segments that are contributing to a single peak in the histogram, although only 45 histogram classes were used.

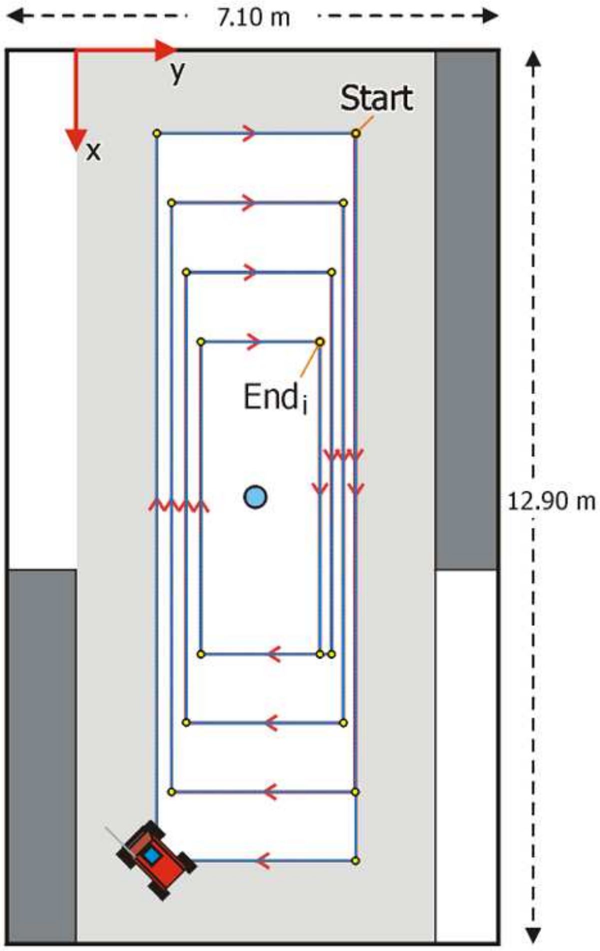

Figure 8: Floor plane of the room that was used to perform '2D measurements'. One can see two dark shaded areas (on the upper right and the lower left side) representing obstacles. The lightly shaded part indicates the obstacle clearance area that was chosen to begin at a distance of 1.15 meters in front of the wall in order to avoid damaging the gas sensors placed at the outstanding bar (See fig.1). Also the robot is shown in the lower left corner during one of the 90-degree turns. A sketch of the robot's course is denoted by a sequence of straight lines including an arrow tip in their middle that indicates the direction of the movement. Starting at the upper right corner the robot moved along the depicted path 'orbiting' the odour source that was placed in the middle of the room. The position End_i indicates the end of the inward phase. Up to this point the turning distance is incremented after every fourth turn. For clarity reasons the draft shows only one straight line that belongs to the outward phase following the position End_i. During the not shown second part of the movement the turning distance is decremented until the robot reaches the $Start$ point again.

6. Results

One result of an inward run that was performed in the above described way is shown in fig.9. In order to avoid

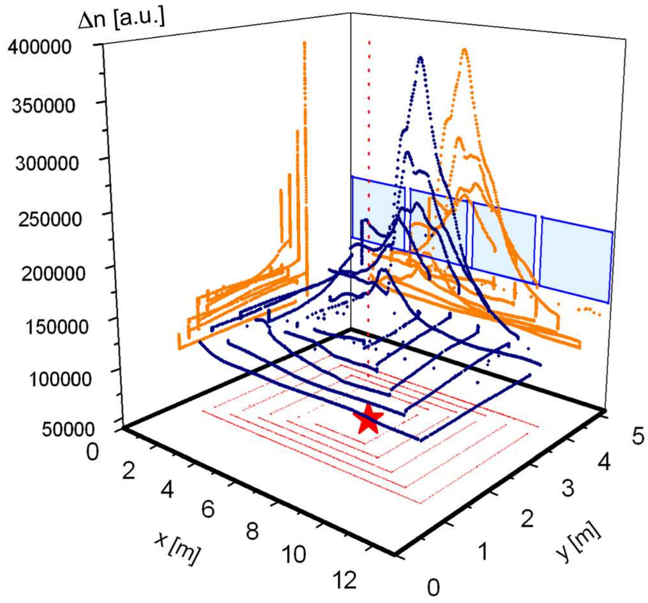

Figure 9: Chemical concentration measurements taken in an unventilated room. The room's outline is shown in fig.8. (Notice that the given x, y values refer to the coordinate system that is sketched in this figure.) The thick black line covers the base of the room without the obstacles. Summarized values of four gas sensors that are mounted on the vertical cantilever (see fig.1) are depicted against the position of the concerning measurement. Also the projections along the x, y and z (Δn) axis were shown. The position of the odour source which was situated in the middle of the appartement is marked by a pentagonal star and a dotted vertical line. The sketch of the windows at the rear side indicates a source of heat. The other walls contain no windows. Further details are given in the text below.

effects by the pouring process, the robot started to move 15 minutes after the odour source has been filled with ethanol. A complete spiral movement containing both an inward and an outward phase was performed. Along the straight lines the robot's speed was set to $15cm/s$. Therefore the whole cycle lasted about 30 minutes (including the required time to perform the turns and to wait after each one). The graph in fig.9 shows the summarized values of the four gas sensors that are mounted on the vertical cantilever (see fig.1). It also shows the projection of these values along the axes of the room.

The depicted values form outstanding peaks at the height of the odour source. Like in the '1D' case the run of the curve shows a rising baseline. (Notice that this can hardly be seen in the plot in fig.9).

Apart from one (a very distinctive peak that was sensed by the lowest sensor only) all peaks emerge while the robot moves along the direction *away* from the point *Start* (at greater y values). This feature which occured in all of the three runs that were performed in this environment, is apparently caused by air current that constantly takes place in the room as a result of local temperature differences. The rear wall of the used room (situated at $y = 6.05m$) contains big windows (see fig.9). Although the blinds were strictly closed during the experiments the respective side of the room was heated by sunshine whereas the front wall which contains no windows remained relatively cool. Thus the resulting convection flow is directed to the windowed wall which explains the onesidedness of the measured values.

Notice that the peaks don't show their maximum height at the innermost path. To reveal the concrete reason for this an extensive aerodynamical analysis of the given room would be necessary. Without actually having performed such an analytical investigation, a qualitative expertise of the situation yielded that the occurence of two room scale, cylindric, counterrotating airflow structures (both circulating around an axis parallel to the x axis) is likely [17]. From this point of view it seems reasonable that the room is clearly separated in two halfs with little exchange of gas. Moreover the higher velocity of the ascending air near the windowed wall and also extra turbulences at this side might account for the rising absolute height of the detected peaks.

Outstanding peaks could hardly been detected while the robot moves along the y axis. Because of the greater sensor to source distance, it can't be decided if this also happens due to the mentioned air current, or if it is caused by the larger distance only.

7. Summary and Outlook

The presented gas-sensitive robot proved to be well suited to detect and also to localize an odour source within a one dimensional setup.

During all the experiments distinctive peaks that are correlated with the position of the odour source were only encountered if the robot moved with a constant velocity not to slow. Although the performed experiments were designed to enlighten the contribution of several potential mechanisms it remains unclear what is ultimately accountable for this behaviour. Further investigation has to be done to change this dissatisfying state.

The experiments using a two dimensional setup showed distinctive peaks along the (one dimensional) pathways, too but the gathered two-dimensional peaks weren't centered at the position of the odour source.

This is mainly due to light air flows (that always exist in real world situations) which affects the spread of the gaseous analyte. Compared to the experiments performed in '1D' environments the influence of air movement is basically stronger in '2D' environments because the component perpendicular to the robot's movement couldn't be neglected.

Besides, one has to take into account that, due to the greater temporal distance, the absolute values of measurements which were taken at adjacent positions on *dif-*

ferent pathways are less comparable than those consecutive measurements on the same one
However, these problems should be overcome by using intelligent search strategies rather than by performing extensive aerodynamical analysis because this is not only a very extensive task but also because it is known that even minimal changes (like a different temperature distribution or relocated furniture) are able to significantly change the overall airflow situation. Thus the electronic watchman has to deal with a partially unknown airflow situation anyway.

8. Acknowledgement

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