Chemical Scanner for Mobile Robot Navigation

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Abstract:
The paper presents a tentative solution to the problem of olfaction-based mobile robot navigation in the chemical plume. This type of navigation requires fast and reliable detection of small gradient of gas concentration in 3D space. The special sensor system designed to detect odour plume with significantly reduced inertia named "chemical scanner" was proposed [5]. A special attention has been given to evaluate sensing system performance in stable and repeatable conditions. The ability to detect small gradient of gas concentration was examined on a special test bench. The real spatial distribution of tested gas in the air was estimated using CFD simulation. The results proved that the real-time detection of small (a few percent of measured value) difference in gas concentration on very short distance (a several centimetres range) is possible. The next stage of research will examine of the developed sensor system on the mobile platform for its navigation.

Keywords: *odours, volatile compounds, semiconductor gas sensors*

1. Introduction

Olfaction-based navigation underlies the efficient operation of most species of terrestrial fauna. The odour image of the environment integrates two (important for the animal) categories of information:
- information defining the type of the animal activity,
- information designating the way the activity is executed.

Especially the pattern-key recognition, initiating the animal activity, is in this modality extremely simple and consists in distinguishing between particles of a given substance from the others by its sensor system. A significant drawback of odour modality is limited speed and geometric precision of reaction, which resulted in the evolution of faster and more accurate navigation – acoustic and optical. However, for those modalities the recognition of pattern-keys is definitely more expensive. That is why in most species the vision-based navigation is used only for local activities. Adopting the odour-based approach in robotics can be advantageous. The well-known approach, readily used in the navigation of industrial mobile robots consists in marking in the environment an easily observable path that can be followed by the robot. Painted lines or cables powered by high frequency alternating current are usually used for this purpose. The robots moving along the wires or lines are called Automated Guided Vehicles (AGV). The major disadvantage of this navigation method is its low flexibility – to change the route one should remove the old lines and paint new ones. Volatile chemical compounds give new capabilities in this field. The lines marked in this way vaporise after the robot has completes its task – similarly to the odour trails created by insects. Binding the odour substance with the ground allows it to be sufficiently long exposed while maintaining the primary advantage, that is the path transfer. Applying this approach to the mobile robot navigation gave positive results. The new challenge is to track an odour trace (odour plume) in the robot ambient air. This article is dedicated to the research aimed at solving this problem.

2. Gas Sensors in Mobile Robotics

Gas sensors for mobile robotics should meet the following requirements:
- low detection threshold, for detection of weak odour sources,
- high sensitivity to concentration changes, for detection of small difference in local odour intensity and consequently for local gradient estimation,
- low inertia, for real time measurements,
- small dimensions and low weight, for application on mobile platforms.

Also several, not vital but advantageous features can be listed:
- low power consumption, for longer operation time in the case of battery powered mobile platform,
- easy data acquisition systems,
- low price.

An ideal gas sensor for mobile robots does not exist nowadays. Available gas sensors have severe limitations concerning detection threshold and selectivity, and cannot be compared with human (or animal's) sense of smell. On the other hand, chemical sensors are still improving [1, 23], and many researchers try to use different kinds of chemical sensors in mobile robots:
- quartz microbalance sensors [6, 22],
- conducting polymer sensors [11, 16, 18],
- miniaturised photo ionisation detector (miniPID) [14, 17],
- semiconductor gas sensors [7, 8, 19, 20]

Semiconductor gas sensor was also used in this research.

2.1. Quartz Microbalance Sensors

The basic element of such a sensor is quartz crystal with special chemical layer which attracts gas particles. The oscillating mass rises with an increase in gas concentration, and declines with an decrease in gas concentration, which can be measured as different resonant frequency. Quartz sensors are characterised by small dimensions, high sensitivity, and low power consumption because of lack of heating elements [15].

2.2. Conducting Polymer Sensors

The majority of traditional plastic materials are commonly known as good insulators, but there is possibility of obtaining conducting polymers with conductance comparable with metals. Conductance of polymers, such as polyaniline or polypyrol, depends on gas atmosphere above surface. Properties of conductive polymers depend strongly on doping level, ion size of the dopant, protonation level and water content [10]. Sensors based on conducting polymers are still under study [3, 13] and until now there is no repeatable, commercially available sensor modules.

2.3. Photo-ionisation Detector

Photo ionisation detector contains an ultraviolet lamp and a pair of electrodes. Photons with sufficient energy (above the barrier characteristic of each chemical compound) can ionise the gas particles between the electrodes allowing the flow of electric current. The current amplitude is proportional to chemical compound concentration. The photo-ionisation is a fast process, so this kind of sensor has lowest inertia, but also the UV-lamp has short lifetime and is quite expensive. The photo-ionisation detector is generally non selective, but it is possible to use different UV-lamps (e.g. xenon, krypton, hydrogen, argon) generating photons with different energy from 8.4 eV to 11.8 eV [12].

2.4. Semiconductor Gas Sensors

The main part of such a gas sensor is a chemosensitive semiconductor layer heated to a high temperature, for example 400°C. The oxygen in the air causes an oxidation of the surface layer. Due to the granular structure, oxidation induces a high potential barrier on a grain boundaries. In the case of presence of reducing gas in sensor vicinity, for example ethanol or other volatile organic compound, potential barrier on a grain boundary declines, which can be easily measured as a change in sensor resistance. Ambient air temperature, humidity or velocity can affect this process. Sensor susceptibility for such environmental factors is a result of the working principle. This kind of a sensor has a low detection threshold, generally below 1 ppm, relatively good dynamic characteristics and is easy to manufacture and to miniaturise, which results in low price. Sample sensor, which was used in this research was shown in Fig.1. Physical principles of operation of semiconductor gas sensors and technical implementation details are extensively described in the literature [2].

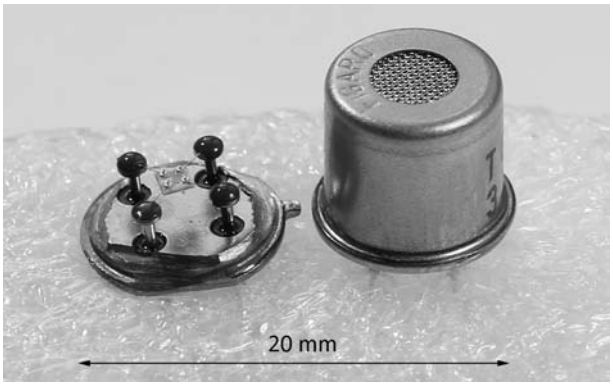


Fig. 1. Commercial Figaro TGS 2620 Gas Sensor with and Without Cover

3. Developed Active Sensor Module

In the case of olfacion-based navigation the information about the environment is acquired by measuring the temporary concentration of odorous substance at a given point. The propagation of medium of information is very slow in comparison to both acoustic and optical waves. In commercially available gas sensors there is no enforced flow through the sensor housing, so the natural diffusion is only mechanism of gas transport between the gas sensing element neighbourhood inside housing and the environment outside. This diffusive (passive) gas sampling method significantly slowdowns the overall dynamic performance of the sensors.

Construction of active sensor sampling systems is important if the gas concentration changes can be fast, like in the case of mobile platform. Some researchers took it into account [21], but in the majority of works the gas sensors was used without any adaptation to the specific requirements related with real time measurement.

In previous work [4] it was shown that the overall sensor inertia can be reduced significantly by enforcing gas flow through the sensor housing. In this case the gas flow was made possible by drilling an additional small (⌀=3 mm) hole in a sensor casing. In this way the free gas flow around the gas sensitive element was enabled. A small (⌀=25 mm) electronic fan was applied to create the pressure difference (Fig. 2). The maximum static pressure of such a fan is small, below 50 Pa, but it is sufficient for this application. Measured air velocity at air inlet of the sensor was about 0.4 m/s. Commercially available, low cost SnO_2 sensor designed to detect of ethanol, TGS 2620 [9] was used as a sensing element. It should be mentioned that enforced flow (about 5 cm^3/s) increased heat dissipation in sensor housing, so applying higher heater voltage was needed to provide proper operating temperature of the gas sensitive semiconductor layer. In the described case the heater voltage was changed from 5 V, suggested by the manufacturer, to 7 V, which means about 2 times higher heating power.

A various combination of several active sensors, fixed to the robot chassis or moving, can be applied to a mobile robot. In this case, a ”double odour scanner”

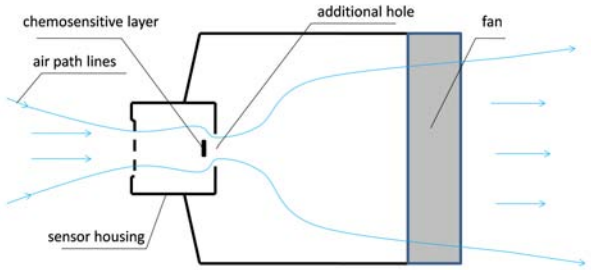


Fig. 2. The sensor system diagram

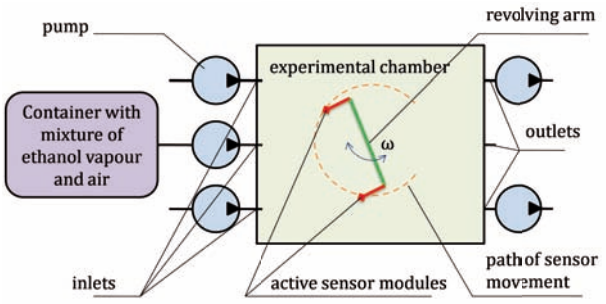


Fig. 3. Simulation image of steady state distribution of tested odour in air in the horizontal cross-section of the experimental chamber

was created by placing a developed sensor system on both ends of the revolving arm.

4. Experimental Test Bench

A stable and repeatable chemical plume was needed to obtain a credible result. However, a propagation of odour in the air is inherently unstable and hard to predict. Creation of detectable, stable difference in gas concentration on a small distance is uneasy due to high diffusivity of volatile organic compounds and natural tendency to level the concentration difference in space. These difficulties were overcame by applying intensive and controlled gas inlets and outlets in a limited space.

The basic part of the test bench was an airtight chamber. The chamber dimensions (50x30x12 cm) were a compromise between maximisation of ability to predict gas concentration distribution and minimisation of the influence of moving sensor system. Large open space is hard to simulate by CFD methods, because greater distance from the surfaces where the boundary conditions (inlets and outlets) were specified causes bigger uncertainty. However, in a smaller chamber the influence of arm movement will be greater.

In two opposite sides of the chamber 3 inlets and 3 outlets were created. Pure air flowed through 2 inlets at a constant rate (10 l/min), and air with constant concentration (900 ppm) of ethanol vapour flowed through the third inlet (2 l/min). Air was sucked by two outlets at a constant rate 10 l/min per outlet, the third outlet was free. Diaphragm pumps were applied to enforce the airflow.

Thanks to a relatively big flow rate (22 l/min) compared to the chamber volume (18 l), the air exchange rate in the chamber was faster than 1 per minute, so local disturbances caused by movement of the sensor arm can be neglected. The gas sample was created by evaporating a well known amount of liquid ethanol to Tedlar Bag filled up with clean air to a given volume (100 l). The gas concentration (molar fraction of ethanol vapour in air) can be easily calculated by the following equation:

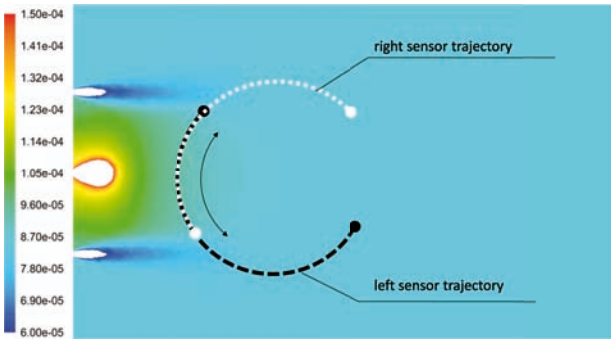


Fig. 4. The results of CFD simulation – molar fraction of ethanol vapour in experimental chamber cross-section

$$c = \frac{V_{in}\rho V_m}{MV_b} \tag{1}$$

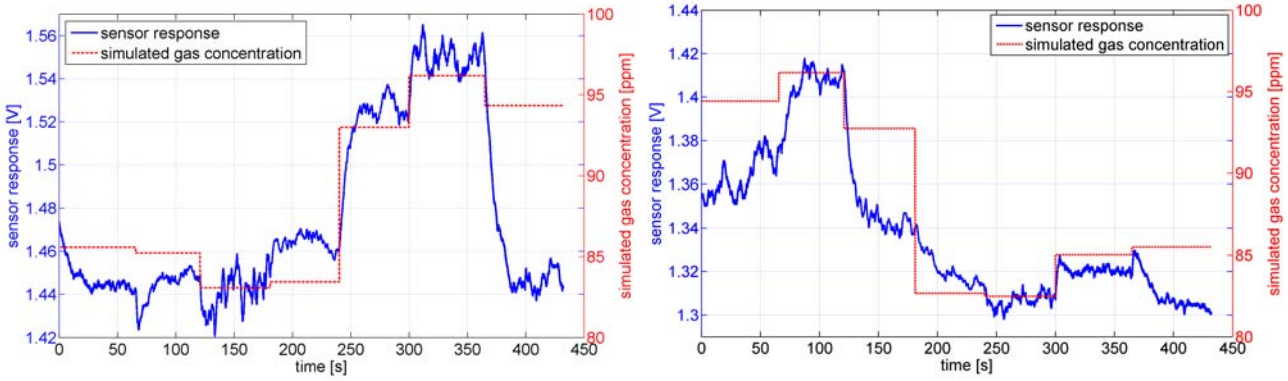
where V_{in} – injected volume of ethanol, ρ – ethanol density, V_m – molar volume of air, M – molar mass of ethanol, V_b – volume of bag,

The interior of chamber was simulated in ANSYS/FLUENT Computational Fluid Dynamics (CFD) environment. The steady state was analysed, assuming k-epsilon model of turbulent flow and boundary conditions mentioned above. The obtained results were shown in Fig. 4.

Inside the chamber a revolving arm with gas sensor and simple data acquisition system were placed. The sensor signals were measured by embedded system and were transmitted to computer in real time. The angular position of the sensor or rotational speed can be set from a host computer. The range of movement of sensors in all experiments was marked by corresponding lines in Fig. 4.

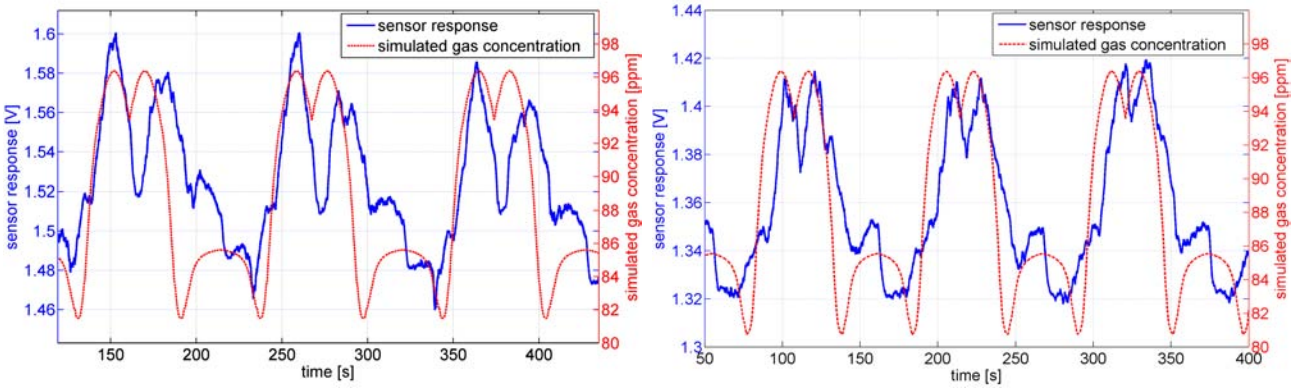
5. The Results of Experiments

The first experiment was conducted in order to examine the sensor response in steady state. The sensors were exposed to a gas sample at a specified position for constant time – 60s, and then the position was changed step-wisely. There were seven steps in the sequence. In Fig. 5 sensor response was juxtaposed with theoretical ethanol concentration calculated by the CFD simulation. It can be observed that concentration changes about 5% of maximum value can be detected easily. Shown raw sensor response is characterised by fluctuations significantly higher than electronic noise in measurement circuit. Such fluctuations correspond to real gas concentration and air velocity fluctuations.



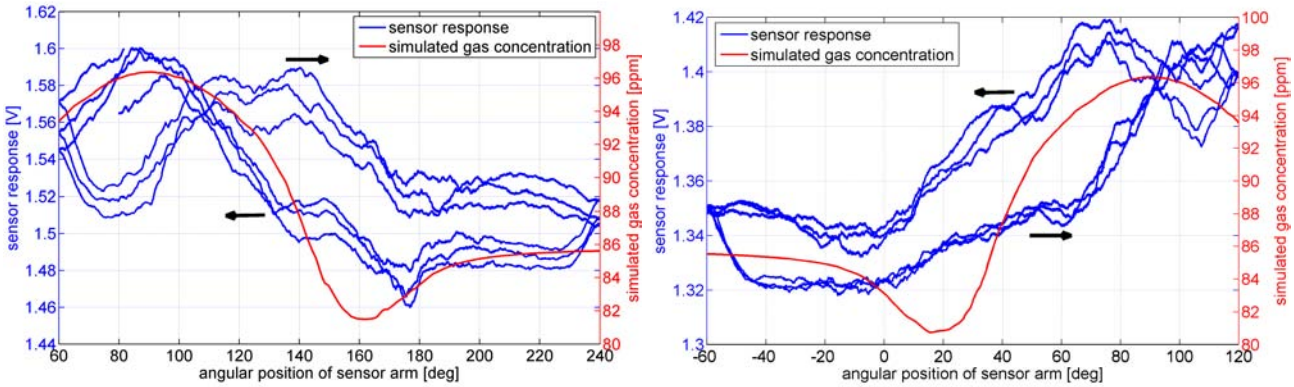
(a) left sensor (b) right sensor

Fig. 5. Sensor signals registered during step-wise positioning of scanner arm inside the experimental chamber in comparison to simulated concentration of volatile compounds at chosen space points



(a) left sensor (b) right sensor

Fig. 6. The comparison in time domain of real signals from sensors and numerically estimated gas concentrations, during rotation of the scanner arm at low speed ω= 7°/s



(a) left sensor (b) right sensor

Fig. 7. The comparison in angular position domain of real signals from sensors and numerically estimated gas concentrations, during rotation of the scanner arm at low speed ω= 7°/s

In the second kind of experiments the dynamic sensor response during movement was tested. The sensor was moving smoothly (at a low constant rotational speed ω= 7°/s) and was scanning the gas concentration in the neighbourhood, alternately counterclockwise (0 to 180°) and clockwise (180 to 0°). The sensor responses were shown in Fig. 6. Data from a several consecutive scans, shown in Fig.6 in time domain, were superimposed in Fig. 7 in angular position domain. It can be observed that sensor signal is correlated to the concentration changes, but also a shift in time/angular position – hysteresis related to sensor inertia is visible.

A sensor moving towards positive gradient (increasing gas concentration) causes response lower than expected, and moving along negative gradient (decreasing concentration) causes response higher than expected. In time domain, the shift is similar for both left and right sensors. In angular position domain the shift is symmetric, and depends on direction of movement (marked by arrows, in Fig. 7).

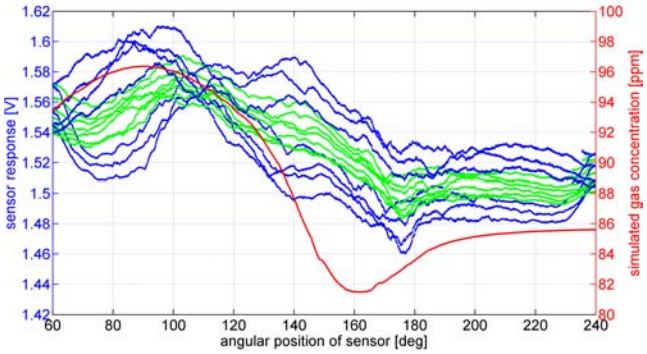
In both figures, (Figs. 6a and 6b) a shift in time is visible. The difference is connected with direction of scan, angle of sensor inlet during movement, and error in fixed sensor positioning on moving arm. The left sensor response in steady state (Fig. 5a) shows a big difference between simulated concentration and sensor response at the last stage (time 370 to 430s) – the sensor suck air from the area of lower concentration (see right extreme position of the left sensor in Fig. 4). In the case of dynamic measurement, this causes a fast decrease in sensor response (Fig. 6a, time 160, 260,360), and the sensor is not able to react fast enough to next gas concentration peak which can be observed as a shift in time and lower value of response for the second peak.

In the case of the right sensor, the sequence is reversed: the first maximum is more shifted in time, than the second maximum, which is better correlated with simulation.

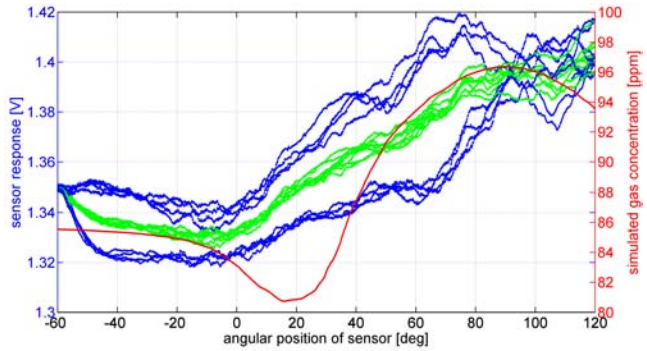
The right sensor steady state response is more symmetric relative to maximum compared to the left sensor one (Fig. 5), so both response peaks of the right sensor have comparable values.

The sensor hysteresis can be reduced significantly by averaging two consequent trails (in different directions) of one sensor. The results of such a process was shown in Fig. 8. In Fig. 9 the effect of averaging normalised signals from two consequent scans of two sensors (blue and magenta curves correspond to normalised left and right sensor signals) are shown. This data fusion was possible only for angular position range from 60°to 120°which was common for both sensors (Fig. 4). It is clearly visible that the repeatability of averaged signals (green curves) is very good.

It should be mentioned that this approach gave good results in the case of test chamber, but when the robot is moving in real environment, the gas concentration and positions of sensors are changing, so the effect of such correction is hard to predict, and have to be tested in the future.



(a) left sensor



(b) right sensor

Fig. 8. The comparison of raw data (blue curves) and data averaged from two scans in different direction (green curves)

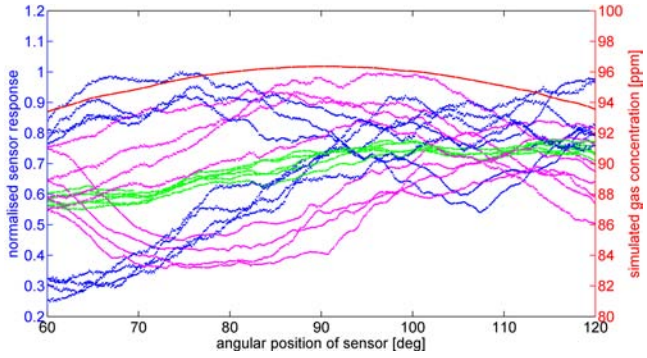


Fig. 9. The comparison of raw data (blue and magenta curves) and data averaged from two scans of two sensors (green curves)

6. Conclusion

Application of odour image of the surrounding environment for navigation of a mobile robot is another step further, which brings today's robots closer to the abilities possessed by of living beings in the nature. Obtained results showed that the basic abilities to localise odour sources can be achieved now, despite the lack of chemical sensors as fast and sensitive as the animals' sense of smell.

The main goal of this research was to evaluate the ability to detect small changes in concentration gradient of chemical compounds in the air. Sensor dynamic performance tests were conducted in repeatable and stable conditions, thanks to the developed test chamber with a gas pumping system. The estima-

tion of gas concentration distribution inside the chamber was calculated by numerical methods.

Proposed movable sensor system reduces the number of needed sensors - which is particularly important when expensive sensors are used, (for example photoionisation sensors). In such solution information is collected along a continuous line in robot neighbourhood, not only in few discrete points. Also some of "searching moves" can be performed using a movable sensor probe, without moving the whole robot - which causes a more stable and smooth trajectory of the robot. The drive and control system is rather simple. The air fluctuation caused by the sensor movement seems to be neglectable compared to the larger scale fluctuations caused by the moving robot. Regardless of the kind of sensor mounting, movable or fixed, the sensor will move in gas distribution field with the robot, and developed test bench provides a possibility of testing the sensor behaviour during movement in a controllable environment.

As a practical conclusion, the ability of detection of small changes in concentration distribution using a system based on cheap semiconductor gas sensors was confirmed and the dynamic performance of the system and its limitation was shown. Described results are useful for further simulation research by providing a realistic mathematical model of sensor dynamics, necessary for reliable numeric simulation of control algorithms.

The performance of developed active sensor modules in real conditions (in uncontrolled environment) will be examined in the future. It was assumed, that firstly a measurement method characterised by enough spatial resolution and fast response should be provided, and the robot control system should be developed later, when the sensor system optimised for dynamic measurements has been obtained. Further research will include the synthesis of the control algorithm for the robot searching odour source. In this case, a method for taking into account the direction of local airflow and also a method for avoiding local extremes of concentration gradient have to be developed.

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