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Relying on an Electronic Nose for Odor Localization

Amy Loutfi and Silvia Coradeschi
Center for Applied Autonomous Systems
Örebro University
701-82 Örebro, Sweden
email: amy.loutfi@tech.oru.se / silvia.coradeschi@tech.oru.se

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***Abstract* – In this work we integrate an electronic nose with a mobile robot for the purpose of detecting odor leaks in a 1-dimensional environment. The robot relies on two mechanisms, the navigational algorithms to manoeuver in the environment and its sensing mechanism to adequately represent odors and their intensities. The emphasis of the proposed odor tracking strategy is placed on the cooperation between these two mechanisms particularly by allowing the sensor dynamics to guide the robot. We then obtain a graphical representation of the distribution of odour as the robot moves in a path. The results presented were designed and tested considering a specific application, however, the odor tracking strategy may offer a basis for odor source localization in more complex environments.**

I. INTRODUCTION

In this work, we address such a situation where a mobile robot is integrated with an electronic nose for the purpose of odor localization. The mobile robot has IR sensors and can perform simple wall-following behaviours as well as detect obstacles within its surroundings. For the purpose of detecting an odor, however, the robot solely relies on the tin oxide gas sensors [1]. The presented features include a system that adjusts the movements of the robot according to the sensor's behavior for fast odor detection. We also present a bi-directional sensing mechanism capable of capitalizing on the sensor behavior to extract an interpretation of an odor's intensity. The final result is the ability to autonomously track an odor and signal to a host computer when it has reached the point of maximum odor intensity.

Tracking an odor to its source is a difficult task and there are several challenges which attribute to this. Firstly, under real world experimental situations there are many factors, such as humidity, temperature and odor distribution that affect the accuracy of the gas sensors. Secondly, if the sensors have a latency or delay period before they react to the presence of an odor, then that latency needs to be addressed within the motion routines of the agent [3]. Thirdly, the sensors can become overexposed to an odorant and saturate which may result in a false interpretation of the odor distribution. Therefore, the presented odor tracking strategy is designed with the sensor dynamics in mind. Unlike other localization techniques which may be biologically inspired [4] [6] [7] or use common search algorithms [2] [8], our strategy relies on the sensors' behavior to determine future motions of the mobile device. The result is an integral cooperation between the sensing mechanism and the movement of the robot. Through the manipulation of both the configuration of the sensors and the movement of the robot, we are able to collect results which are more representative of the odor distribution. This cooperation then facilitates the correspondance between the readings from the sensors to the intensity of the sampled odor and from these readings, a graphical representation of the odor distribution is obtained.

There are many methods available for processing the sensor data to reflect the sampled environment. In a study made by Loutfi et al. [10], data from a static electronic nose was analysed using fuzzy clustering techniques. Linguistic symbols were then grounded to the sensor data in order to identify particular substances. In this paper, we are not currently using fuzzy techniques to handle the data, however, we shall consider using them in future work.

Beginning with a description of related works in Section II, we provide a brief overview of previous attempts of autonomous olfaction with a mobile robot. We further introduce our contributions with a necessary discussion of the sensor properties in Section III. In Section IV, we introduce a unique tracking strategy. We then apply this strategy to a leak detection application described in Section V. Finally, in Section VI, we give some concluding remarks about the system.

II. RELATED WORKS

Using a mobile robot to track or locate an odor source has generated a variety of different approaches. Some approaches include detecting an odor source fixed at a distance [2], following an odor source by tracking the odor [12], representing the spread of odor throughout a given environment or attempting to replicate biological approaches found in nature [4] [7].

In these systems several common factors have been found which affect the performance of the odor detection. One factor is the surrounding airflow which may be turbulent and cause the odor to distribute unevenly. To cope with this, some studies use anemometers and wind sensors [5] in conjunction with the gas sensors. Meanwhile, other studies have conducted tests in controlled environments where the air speed and direction were known constants. In this work, we address the situation where the mobile agent is to rely solely on its gas sensors for perception of the odor and no explicit efforts are made to compensate for a changing environment.

Another factor is the olfactory mechanisms and the different technologies available. Perhaps the most widely used sensors in mobile odor detection is the tin dioxide sensor [1] although polymer sensors [12] [11] and even a real antennae from a silworm moth as described in [6] have also been used. The disadvantage with the later is that the sensor cannot be changed or adapted. As for the manufactured gas sensors, they can exhibit varying dynamics depending on temperature, humidity and the nature of the odor [9].

A final factor which has attracted much focus is the actual tracking strategy. Some strategies offer a system where the robot first examines the entire environment and makes an offline judgement about the odor source location [8]. One method outlined in [2] turns the mobile device in a 360° rotation and then points towards the direction of the odor emission. While these techniques use the sensing mechanisms and the mobility of the robot simultaneously, the odor sensing and the motion of the robot function independently. It is the focus of this work to create an adaptive odor tracking method with specific consideration of the dynamics of the gas sensors.

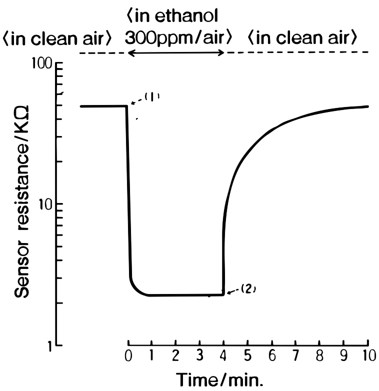

Fig. 1. Typical response of the TGS 822 sensor when the atmosphere changes from clean air to 300ppm ethanol vapor (1), and reverts back to clean air (2)

III. OLFACTORY AGENT

A. Odor Sensing Mechanism

In the design of an odor sensing system for a mobile agent a pair of tin oxide gas sensors were used [1]. The type of sensor chosen for the experiments was the Figaro TGS 822, particularly sensitive to organic solvent vapors such as methane, acetone and ethanol. The sensors are relatively small and easy to integrate on a mobile platform. The sensors can also maintain a steady state value under constant conditions. Figure 1 shows an example of a typical sensor response.

A beneficial feature of the sensors is their change in resistance as a function of the concentration of the molecules of gas. Figure 2 illustrates that as the concentration of gas is increased there is a greater drop in the resistance across the sensor. The ability to differentiate between different concentrations or intensities of the same gas is vital in a mobile robot application. If the representation of odor concentration is present then the robot is able to move towards an increasing intensity of odor to find the maximum point of concentration.

A drawback to the sensors is their tendency to become saturated under one odorant. Saturation occurs when the sensor has been exposed for too long a time to a highly concentrated odor. Once the sensor's resistance has dropped its maximum value (approaches 0Ω), it is unable to exhibit any further detection of an increase in odor intensity. The only possible way to detect the presence of a gas is to allow the sensor to at least partially recover in cleaner air (i.e. lower concentration of the odor). The saturation effect introduces a serious problem concerning the tracking strategy. If the sensors on the mobile robot become saturated before the robot has reached the odor source then any subsequent movement towards an increased concentration of that odor will be undetected. In other words, the robot will perceive the odor source to be located much earlier than it is in reality.

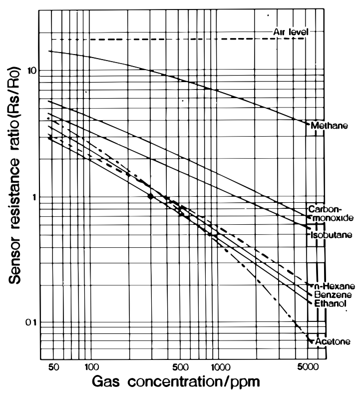

Fig. 2. Sensitivity characteristics of the TGS822 sensor to ethanol vapor and other various gases and vapors. The ordinate is the ratio of the sensor's resistances measured at various concentrations of gases compared to the sensor resistance at 300 ppm ethanol vapor

B. Mobile Robot interface

The odor sensors are mounted on the koala mobile robot shown in Figure 3 and 4. The gas sensors are placed in two separate units. The units are oriented 180° from each other, one at the front of the robot and one at the rear, creating a bi-directional olfactory detection system. Each unit consists of a sealed capsule approximately 10 cm in length and a small fan used to draw air into the capsule. Initial experiments reflected the odor detection range of the sensors, without the fan, to be approximately $1m$ when the odor source is placed in direct line with the sensor. With the addition of the fan, that range increased to $1.5m$. Also the fan is instrumental in accelerating the recovery process of the sensors once the odor is removed. Each unit contained one TGS 822 sensor and is placed on the underside of the robot.

The incoming signal for data processing is the two corresponding responses from the spatially separated sensors, the front sensor and the rear sensor. The sensor readings are transferred to a host computer via a common data acquisition card. The input into the card is the voltage across each sensor which is proportional to the respective resistance. Meanwhile, the mobile robot interfaces with a host computer via an RS232 interface.

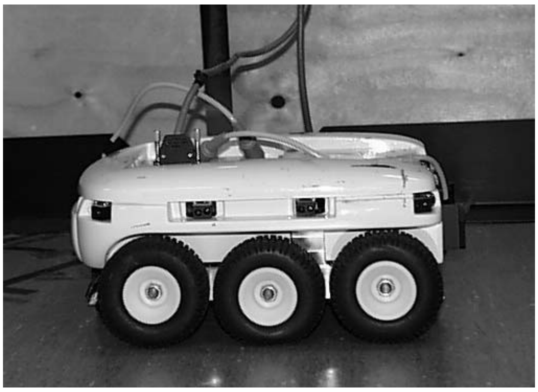

Fig. 3. Side view of the koala robot showing the IR sensors.

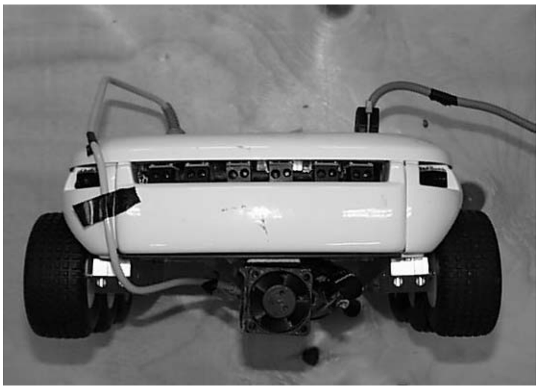

Fig. 4. The front view of the koala robot showing the gas sensing unit placed on the underside.

IV. ODOR TRACKING STRATEGY

The odor tracking strategy is summarized in Figure 5. There are two sensors on the robot, one at the front and one at the rear. At the beginning of an experiment, the robot is placed at a starting point and remains there until the sensor values stabilize (Figure **??**). The mobile robot is programmed to use a basic obstacle avoidance algorithm which contains a wall following algorithm that guides the robot through the pipeline environment. As the robot is moving forward it is simultaneously collecting samples of data and analyzing these samples from the front and rear sensors. If the reaction in the front sensor is greater than that in the rear sensor, then the odor source is determined to be ahead of the robot. At this point, the robot turns around $180°$. The robot moves forward again and collects another sample. Each time the sensor in the front position detects a reaction, the robot turns $180°$. In case the sensor at the rear of the robot exhibits a stronger reaction, the robot is considered to have passed the odor source. If neither of the sensors detect an odor, the default action is to move forward.

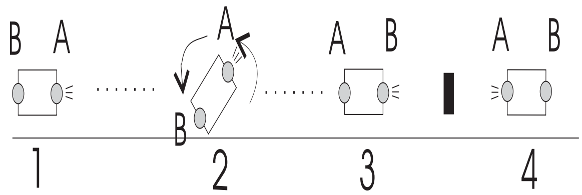

Fig. 5. An example of the localization strategy showing the mobile robot and the two sensors A and B. At 1. Sensor A detects the odor 2. the robot turn $180°$ and continues to move forward. At 3. the location of the odor is confirmed from the Sensor B's reaction. Finally at 4. the odor is localized by detecting when the robot has past the maximum intensity point.

There are two main reasons why it is advantageous to turn the robot around $180°$ each time one of the sensors detects an odor. Firstly, this method prevents any one sensor from unwanted saturation. As soon as one sensor detects the odor, it is subsequently turned away from the odor allowing it to recover. This was confirmed by conducting simple tests in a straight line without using the presented odor tracking strategy. In these tests the robot was to move directly towards an odor source and as expected the point of maximum intensity was detected before the actual source was reached. Secondly, if both sensors detect the odor to be in the same direction, then the location of the odor source is determined with a higher level of confidence. The bi-directional configuration of the sensors on the robot contributes to the odor tracking strategy by allowing the robot to interpret odors in two opposite directions simultaneously.

The movement of the robot and the sampling of the sensors occur simultaneously. First, the command is sent to the robot to move forward, as the robot is moving at a constant speed it is reading the sensor values at continuous intervals of 1 reading per 0.17 seconds. These values are the voltage readings across each of the sensors. To know if an odor is being detected, one must examine the change in voltage values over a period of time. Hence, the robot collects samples of readings where each sample contains 60 readings. After the analysis of each sample, the robot determines the next course of action but at no point does it stop its motion. It is important that the robot take these samples as it moves rather than move a fixed distance then sample the air. This is due to the fact that moving the robot creates certain air currents [8]. Therefore, moving the robot at a constant speed while collecting data reduces the amount of turbulence in these currents.

To determine whether a sensor is reacting to an odor source a comparison is done between the sample taken from the front sensor and the rear sensor. There are 60 readings per sample so a simple median filter is used to reduce the noise and smooth the data. This was done by sorting the window of 5 consecutive values and taking the middle value. Once the sample from each sensor is filtered, the change in voltage values with respect to the readings is approximated. This is done by finding the coefficients of a polynomial of degree 1 which fits the data in a least-squares sense. From the linear approximation, the slope of the line, m, is obtained.

Since the detected odor is a source of ethanol, we know by Figure **??** that there should be a drop in voltage values when measuring from a low concentration to high concentration of ethanol. Therefore, for either of the sensors to recognize a reaction, the slope, has to be in the downward direction and secondly, the magnitude of the slope , must be greater than a pre-determined threshold. The determination of this threshold depends on the substance being detected and the preferences of the user. If one wants to detect only the regions containing an intense odor emission then the threshold is set at a higher value. To determine the direction of the odor source, the difference in slope between the front and rear sensor is examined. If both sensors exceed the threshold, T, and the front sensor exhibits a greater drop in voltage values than the rear, then the robot interprets the odor location to be ahead.

Once the direction of the odor source is determined, the robot turns $180°$ and while it is turning it does not collect any readings from the sensors. Once it has turned, the robot begins to move forward at a constant speed and collects another sample. Since it takes time to collect a sample, approximately 10 seconds, there is a displacement of the robot's location between turns. This prevents the robot from turning on the same point continuously when it approaches the odor. When the robot detects that it has passed the odor source (i.e. stronger reaction from the rear sensor), it signals the host computer and stops.

Finally, the wall-following routine needs to also operate in conjunction with the odor tracking strategy. The routine is programmed by reading the IR sensors located on the perimeter of the robot. The IR sensors are capable of emitting an integer value relating to the proximity an object. The program is set to continuously follow the wall along the robot's right side. The robot checks its IR sensors by taking four different averages of the sensors, one average for each side of the robot (front, back, right, left). It is able to make small adjustments if it finds it is too far away from the wall or too close to the wall. Again this is determined by another threshold set by the user. The robot is also able to turn corners. The robot performs these checks between each reading of the gas sensors.

V. EXPERIMENTS

To test the odor tracking strategy two separate environments were used, detection in a linear environment and detection in a complex environment. In all the experiments, the robot collected odor samples while moving at a speed of $0.035m/s$. The odor source was chosen to be a $5cmx5cm$ cloth soaked with ethanol and taped to the floor. This prevents the robot from detecting the source with the IR sensors and treating it as an obstacle. A total of 20 experiments were conducted on each environment and no precautions were taken to control the temperature, humidity or air currents.

In the first environment the robot was to move in a straight line collecting odor samples and tracking the distance moved. An odor source was placed at various locations along the line. Although the robot is to be applied in a pipeline situation an actual pipe was not used. Instead a small corridor of width $1m$ made of wall panels was created. The purpose for this experiment is to obtain an understanding of the change in the sensor results as a function of the distance traveled by the robot as shown in Figure **??**. This figure shows an example of where an odor source is located at $2.45m$ to $2.50m$ from a starting point labeled D_0. The graph reflects the sensor readings of the front and rear sensor as the robot travels a total of $4.1m$ in a straight line. Since the starting point D_0 is measured at the back of the robot, the forward sensor begins at $D_0 + 0.31m$ where the robot length is $0.31m$. In the case shown in the graph, the maximum point was detected by the forward sensor to be at $2.37m$ and by the rear sensor to be at $2.47m$. From the graph, it can be seen that the sensor results are capable of correctly representing the location of the odor source by indicating the point of maximum intensity. Notice that the saturation effect was also eliminated by turning the robot and thus preventing any one sensor from extended exposure to the ethanol.

The second test environment was created using the same wall paneling but in different complex configurations as examplified in Figure **??**. The robot was taking samples of odors as well as autonomously following the wall-panels and avoiding obstacles. Due to the fact that the robot may have to make small adjustments and turn corners as it is moving, it is difficult to keep track of the exact distance traveled. So instead, the robot is to stop and signal to a host computer when it has detected to have passed the odor source. A total of 20 tests were performed in 4 different complex configurations (denoted A to D). The results summarized in Table I show the average distance from the source to the back of the robot once the robot stopped.

VI. CONCLUSION

In this paper we have presented a method to localize an odor source using a mobile robot integrated with an electronic nose. We focused on an environment where the agent was following

TABLE I

THE RESULTS FROM TESTING IN A COMPLEX ENVIRONMENT

Configuration	Number of Runs	Average dist from source and stand. deviations (cm)
A	5	10.5 ± 1.5
B	5	12.5 ± 2.7
C	5	8.5 ± 1.6
D	5	13.3 ± 3.3

a pipeline using a simple wall-following algorithm. The agent used its sensors to detect an ethanol leak in the pipeline. In all the tests performed the agent was able to detect the leak within a reasonable distance. One of the advantages of this method is that the agent acts completely autonomously and could therefore be used in an environment that is unreachable for humans. The main feature is the presented odor tracking strategy which is motivated from the sensor dynamics. Future work will concentrate on expanding the applicability of the mobile odor device to more complex environments and perhaps the creation of a omni-directional sensing mechanism capable of perceiving odors in several directions simultaneously.

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