Estimating Gas-Source Location in Outdoor Environment Using Mobile Robot Equipped with Gas Sensors and Anemometer

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***Abstract*—This paper investigates the applicability of a gas-source localization method in outdoor environment. In the proposed method, a mobile robot is used to scan the area under consideration and to collect data on gas concentration and airflow velocity at various locations. The location of the gas source is estimated by applying a turbulent diffusion model of a gas plume to the data obtained by partial observation of the gas distribution in the given area. Discussion is made on the adjustment of the turbulent diffusion coefficient in the plume model to achieve successful estimation under various airflow conditions.**

I. INTRODUCTION

Currently, extensive research work is being done to develop mobile robots that can detect gas molecules and find their source location [1]. It is expected that these robots will be applied to search for hazardous materials, e.g. explosives, by tracking aerial trails of gaseous substances leaking from such hazardous materials. Automating the search process by using autonomous mobile robots will be especially useful if the robots are successfully applied to the search in a large space, e.g., in an airport and in a train station. In addition, gas-source localization robots are expected to be applied to the detection of land mines buried underground. Even now, demining is mostly done by human workers with metal detectors or with mine detection dogs that use their highly sensitive olfaction to detect the smell of chemical substances evaporated from the land mines [2]. However, training of mine detection dogs require significant amount of time and cost, and demining workers are always put at risk. Therefore, it is of great significance to realize autonomous robots with land mine detection capability.

Gas molecules released from their source are transported mainly by airflow since molecular diffusion is almost always much slower than the airflow. An aerial trail of gas molecules, i.e., a plume, is thus formed in the downwind direction from the source location. A mobile robot equipped with gas sensors and anemometer can theoretically track the gas plume in the upwind direction to find the source location [1]. However, successful demonstrations were so far mostly given in simplified small-scale environments [3]. Test areas of the scale of a few square meters were generally prepared in indoor environments without any obstacles. Gas plumes with well-defined shapes were generated in uniform airflow fields. On the other hand, the robots must be able to cope with much more complicated environments in real-life scenarios. For example, the gas distribution and the airflow field are sometimes modified because of the existence of obstacles. The uniformity of the airflow field may not be assumed in large-scale environments. Moreover, the scale of the turbulence in the airflow generally increases with the scale of the environment. Therefore, in large-scale environments, the gas concentration and the airflow direction show large fluctuations.

In our previous paper [4], a new method for estimating the gas source location from the gas concentrations and airflow directions measured at several locations was proposed. A turbulent diffusion model of the gas distribution was assumed, and the source location was estimated by finding the best match between the model and the observed gas distribution and the airflow velocity. Although successful demonstrations were presented for gas-source localization in an indoor environment, the applicability of the proposed method in a range of different environments was not investigated so far.

In this paper, we investigate the applicability of the proposed method in an outdoor environment. A robot equipped with gas sensors and an anemometer was used to scan the area of interest in an outdoor environment. The proposed method was applied to the gas concentration data and the airflow directions observed in the partial scans of the area of interest. The results of estimating the source location was affected by the value set to the turbulent diffusion coefficient in the plume model. The turbulent diffusion coefficient defines the growth rate of the plume width, and its

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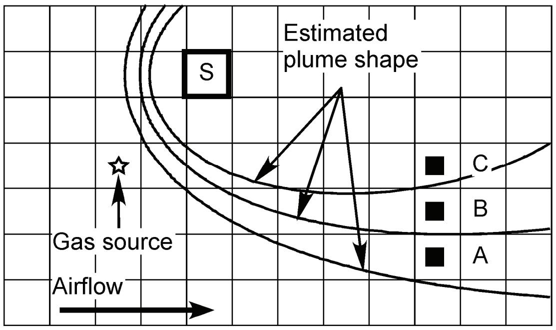

Figure 1. Illustration of the plume shapes estimated at measurement points A, B, and C.

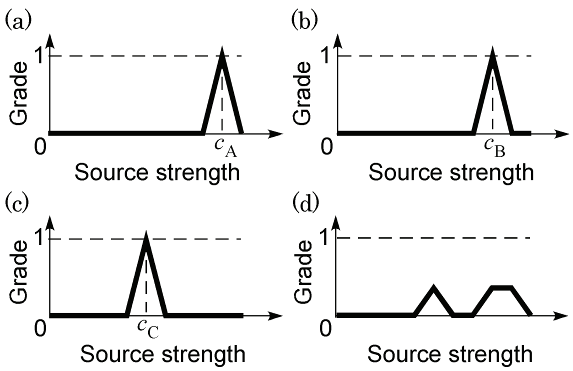

Figure 2. Source strengths calculated for the cell different from the true gas-source location. (a), (b), and (c) are the source strengths calculated from the values of the gas concentrations measured at cells A, B, and C in Fig. 1, respectively. (d) is obtained by averaging the membership functions obtained from all three measurements.

value is different for different airflow conditions. In the previous paper [4], its optimal value for the environment under consideration was simply given a priori. Discussion is made in this paper on the adjustment of the value for the turbulent diffusion coefficient in the plume model to achieve successful estimation of the gas source location under various airflow conditions.

II. Method

If the gas concentration is measured in all places in the given area, the location of the gas source can be estimated by generating a gas distribution map. However, scanning the entire area is an extremely time-consuming process. In the proposed method, the gas-source location is estimated from the partial observation of the gas concentration distribution and the airflow velocity vectors.

A steady and uniform turbulent airflow field is assumed in the environment. When a gas source releasing gas molecules at the rate of q is placed on the ground, the time-averaged gas concentration on the ground is given by the turbulent diffusion theory [5] as

$$\bar{c}(x, y) = \frac{q}{2\pi K}\frac{1}{x}\exp\left[-\frac{U}{2Kx}(d-x)\right] \tag{1}$$

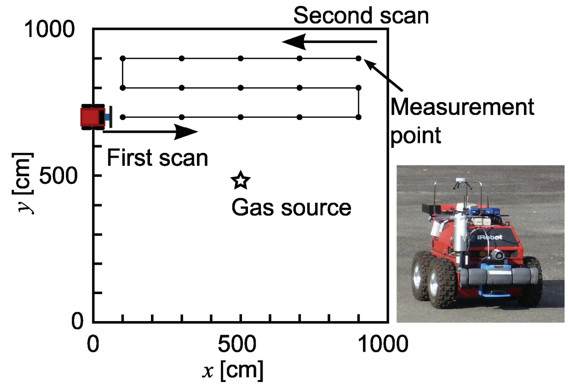

Figure 3. Experimental setup. The mobile robot performed two scans in the open outdoor environment. The robot made a stop for 10 s at each location indicated by a dot. Four sets of data named outdoor 1–4 were collected [5].

where K is the turbulent diffusion coefficient, U the wind speed, and $d = (x^2 + y^2)^{1/2}$. For this equation, a Cartesian coordinate system is taken on the ground and the x-axis is taken as the downwind direction. The origin of the coordinate system is set to the location of the gas source. The gas distribution for an arbitrary gas-source location and an arbitrary airflow direction can be calculated using the same equation after appropriate coordinate transformation.

In the proposed method, the area under consideration is divided into cells, and a certainty of containing a gas source is calculated for each cell. Assume that a robot equipped with a gas sensor and an anemometer has measured the gas concentration and airflow velocity at points A, B, and C in Fig. 1. Moreover, cell S is assumed to contain a gas source. If the value of K is known, the strength of the imaginal source in cell S is calculated to be c_A by taking the gas concentration measured at cell A and the relative displacement of cell A from cell S into (1). Since the obtained c_A contains a certain amount of errors, a fuzzy membership function having a peak at c_A is generated for cell S (Fig. 2a). The same calculation is repeated for the gas concentrations measured at cells B and C (Figs. 2b and 2c). In order to aggregate the results obtained from such multiple measurement points, the average of the membership functions obtained from all the measurement points is calculated as shown in Fig. 2d. Since cell S is not the true gas-source location, the source strengths calculated based on this wrong assumption do not coincide with each other. Therefore, the aggregated membership function has no significant peak as shown in Fig. 2d.

In contrast, a different result is obtained for the cell containing the true gas-source location. If a plume with an ideal shape is formed, similar source strengths should be obtained from the gas concentrations measured at points A, B, and C although the measured gas concentration contains some errors. Therefore, a high peak remains after averaging the membership functions for the cell containing the true gas-source location after averaging.

The above-mentioned calculation is repeated for all cells and all measurement points. A map showing the possible gas-source location is obtained by plotting the value of the highest

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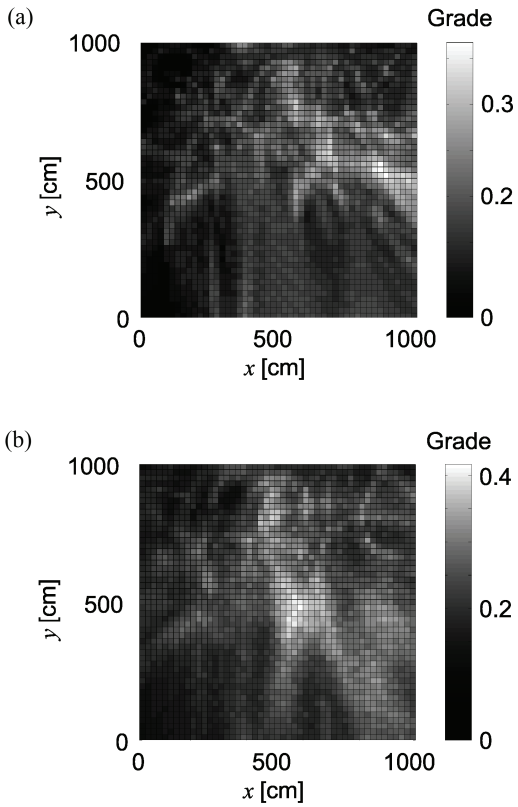

Figure 4. Result of applying the proposed gas-source localization method to the data, outdoor 3. The turbulent diffusion coefficient, K, was set to 1585 in (a) and 3981 in (b), respectively.

peak of the aggregated membership function for each cell. A gas source is estimated to be in the bright region in the gray-scale map.

III. Experimental Setup

The proposed method was tested using the experimental data obtained by the researchers in Örebro University, Sweden [6]. The picture of the robot and the illustration of the measurement path of the robot are shown in Fig. 3. The robot is equipped with a semiconductor gas sensor (TGS2620, Figaro Engineering), a three-dimensional ultrasonic anemometer (Model 81000, Young), and a laser scanner (LMS200, SICK). The robot has a self-localization capability based on the odometry and the laser scanner. The map of the environment was given a priori. The global and local path planning functions are also implemented in the robot.

The experiments were done in an 8 m by 8 m area taken in an open outdoor environment. The gas source used was a small cup filled with ethanol and was placed in the middle of this area. The mobile robot was programmed to perform two entire scans of the environment. Along the path, the robot was stopped at the predefined measurement points, and the readings of the gas sensor and the anemometer were recorded for 10 s. The measurement points were taken with a 2 m interval in x-direction and a 1 m interval in y-direction. The robot was driven at a maximum speed of 5 m/s, and the measurements were recorded at a frequency of 1 Hz. The proposed method was applied to four sets of data named outdoor 1–4, which were obtained at different dates and time. Only the partial data collected at the downstream end of the test area were used (Fig. 3). The time average of the gas sensor reading and the airflow velocity at each measurement point was calculated and provided to the proposed method.

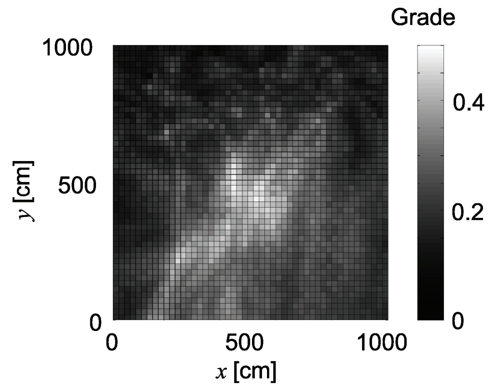

Figure 5. Result of applying the proposed gas-source localization method to the data, outdoor 4. The turbulent diffusion coefficient, K, was set to 1585.

IV. Results

The results of applying the proposed method to the dataset, outdoor 3, are shown in Fig. 4. In Fig. 4a, the value set to K was too small. The bright regions are scattered and not corresponding to the actual gas-source location, i.e., the middle of the square area. In Fig. 4b, the bright regions are gathering around the actual gas-source location since the value set to K was appropriate. Fig. 5 shows the result of applying the proposed method to a different dataset, outdoor 4. The source location was again successfully estimated if the value of K was appropriate.

These results indicated that the performance of the proposed method depends largely on the value of K. To determine the optimum value of K for each experimental condition, the root-mean-square distance, σ, is evaluated as

$$\sigma = \sqrt{\frac{1}{N}\sum_{i}^{N}\left(d_i\right)^2} \qquad (2)$$

where d_i is the distance of cell i from the actual source location. N is the number of cells with high grade values (over 80% of the maximum). The summation is taken only for the cells with high grade values.

The correlation between the value of K and the value of σ was shown in Fig. 6. The smaller value of σ means that the cells with high grade values are converged well around the actual gas-source location, which in turn means that the estimation of the gas-source location is carried out more accurately. Therefore, the optimum value of K for each dataset is the one that minimizes the value of σ. Fig. 6 shows that the reasonably good accuracy is attained for the estimation of the gas-source location by adjusting the value of K.

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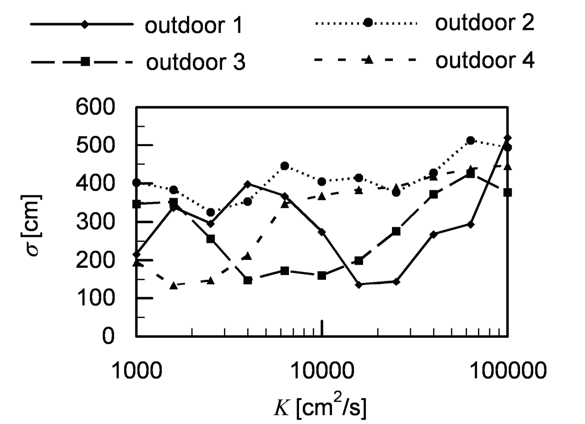

Figure 6. Change in the error in the estimated source location with *K*.

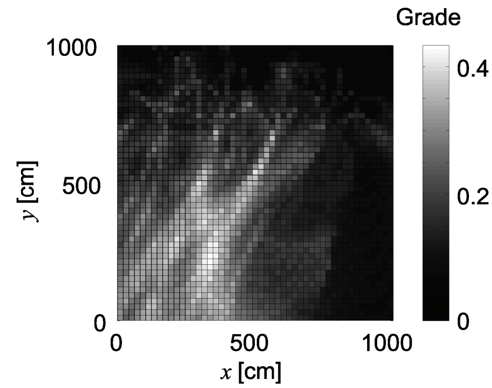

Figure 8. Result of applying the proposed gas-source localization method to the data, outdoor 2. The turbulent diffusion coefficient, *K*, was set to 2512.

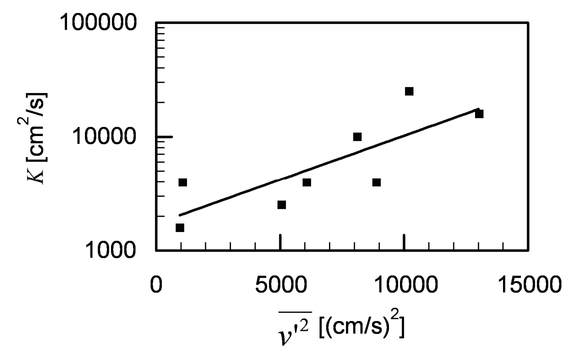

Figure 7. Optimum value of *K* with respect to the turbulent intensity.

If the actual gas-source location is unknown, however, this method cannot be applied since the value of σ cannot be determined. In order to adjust the value of *K* on the fly while the robot is performing the are scan, it is necessary to determine the optimum value of *K* autonomously from the airflow velocity data collected by the mobile robot. The turbulent diffusion coefficient is affected by *v*', the fluctuations in the instantaneous airflow velocity in the direction perpendicular to the mean airflow direction [7]. Therefore, its square-mean value, $\overline{v'^2}$, was calculated for each scan in each dataset. The correlation between the optimum value of *K* obtained from Fig. 6 and the value of $\overline{v'^2}$ is shown in Fig. 7. It is known that the value of *K* increases with the value of $\overline{v'^2}$ [7]. The result shown in Fig. 7 confirmed the positive correlation between *K* and $\overline{v'^2}$. This correlation allows us to estimate the optimum value of *K* from the value of $\overline{v'^2}$ measured with the ultrasonic anemometer on the robot.

V. Conclusions

Estimation of the gas-source location was tried by applying the turbulent plume model to the gas concentration and airflow velocity data collected by a mobile robot. As a result, the applicability of the proposed method was shown for the large outdoor environment. The gas source location was successfully estimated even from the data collected in one third of the whole area. This result is encouraging for attaining quick gas-source localization in a large-scale environment.

We then discussed the optimization of the turbulent diffusion coefficient, *K*, that must be given a priori to apply the proposed method. It was confirmed that there exists a positive correlation between the value of *K* and the value of $\overline{v'^2}$. A mobile robot will be able to determine the optimal value of *K* autonomously using the value of $\overline{v'^2}$ calculated using the measurement data of the airflow velocity vector.

Among the four sets of experiments, good convergence of the estimated gas source location was not obtained for outdoor 2 (Fig. 8) even though the value of *K* was changed from 10^3 to 10^5. Future work will be addressed to investigate the applicability of the proposed method to a wider variety of environments and to determine the necessary conditions to apply this method.

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