Sensor Systems for Detecting Gas Plumes – Robots and Sensor Network

Toyosaka Moriizumi* Member

Hiroshi Ishida** Member

Two kinds of sensor systems for detecting gas trail (so-called plume) are discussed. One is the mobile robot with several kinds of sensors which can track the gas plume to search for a gas source. The other is the sensor network which can reveal the spatial and temporal behaviors of air-pollutant plumes in detail. The sensor network can also perform an automatic calibration to achieve a maintenance-free operation.

Keywords : robot, plume tracking, air-pollution monitoring, metal-oxide gas sensor, sensor network

1. Introduction

There exist two kinds of sensors, physical sensors and chemical ones. The former deals with wave information (i.e., light or sound waves), and its technology has been well established due to the sophisticated theoretical treatments. Even cheap photodiodes are designed and prepared in combination with lens, reflectors and anti-reflection coating for collecting and/or guiding the wave energy efficiently onto the sensors.

In contrast, chemical sensors are usually designed, paying little attention to how to collect gas/odor information. Engineer's concerns are usually the sensing materials, principles and device structures. Since gas/odor is carried by an aerial trail called a plume⁽¹⁾, the efficient sensing can be realized utilizing the method to collect gas/odor information from the plume as much as possible. Animals are quite smart at how to collect the information and keep the total olfactory capability extremely higher than a human. Dogs are famous for their ability to track trace scents. Male moths can follow the pheromone plume over a long distance to reach the mates. If we could mimic their behaviors, efficient gas or odor sensing systems could be realized.

Authors' group have been developing several types of systems for tracking or observing gas plumes⁽¹⁾. Their potential applications include fire alarming and searching for gas leaks, hazardous chemicals and pollutant sources. The present paper is concerned with review on the recent developments on gas/odor tracking robots and the sensor network for air-pollution monitoring.

2. Plume-Tracking Robot

2.1 Robot with Gas and Airflow Sensors Since the diffusion rate of molecules released from a gas source in conventional environments is much slower than the velocity of convective airflow, the plume extends in the downwind direction from its source. Airflows are almost always turbulent, and a number of eddies stretch and twist the plume. Hence, the development of plume tracking systems is not trivial tasks.

Both the first version⁽²⁾ and the second version⁽³⁾ of our robots had plural gas sensors and airflow sensors. With the aid of those sensors, the robots can track a gas/odor plume. The basic strategy in the search for a gas source was developed by mimicking animal olfactory behaviors. The robot moved upwind when it is in contact with a plume using the airflow sensors. The plural metal-oxide gas sensors are arrayed like on the antennae of insects. The left and right gas sensors are used in the upwind progress to steer the heading of the robot to the centerline of the plume. When the contact with the plume is lost, the robot performs local search to regain contact with the plume. The basis of the algorithm was constructed in the study of the first version⁽²⁾.

The development of the second version realized the drastic (about seven times) speedup of the plume tracking⁽³⁾. In order to overcome the slow recovery time of tin-oxide gas sensors, we avoided using the absolute levels of the gas sensor outputs for the control of the robot. Instead, the controller detected the relative changes in the sensor outputs to allow the robot to take appropriate actions immediately when the outputs start changing from one state to another. It took about half a minute to track the plume from the starting point (outside of the plume) to the gas source.

2.2 Robot with Cooperation of Vision, Olfaction and Flow Sensing

The successful results on upwind plume tracking demonstrated by the first and second versions had been mostly obtained under simplified experimental conditions. Ventilation systems and/or electric fans were usually used to create unidirectional wind fields. Gas plumes with well-defined structures were given and therefore, the robots were able to track the plumes easily with airflow sensors. Upwind plume tracking is not always feasible with current sensor and robotic technologies in general indoor environments. The velocities of air currents are often too small to be detected with airflow sensors on the robots.

A leap from purely olfactory-guided navigation has been achieved by exploiting visual information as an aid to locate a gas source⁽⁴⁾. The third version of robot with cooperation of vision, olfaction and airflow sensing is shown in Fig. 1. A CMOS digital camera (EyeCam-1, Joker Robotics) was mounted on the front side of the robot. The field of view is 48 degrees horizontally and 36 degrees vertically, which covers the floor up to 1.5 m in front of the robot. An onboard microprocessor (Eyebot controller M4, Joker Robots) performs all data acquisition,

* Graduate School of Science and Engineering, Tokyo Institute of Technology,

2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552

** Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology,
2-24-1 Nakacho, Koganei, Tokyo 184-8588

Fig. 1. Robot equipped with gas sensors, airflow sensors, and a camera

signal processing, and motor control. The relatively slow locomotion speed is set to 5 cm/s considering the slow recovery time of the gas sensor response. The slow speed is also required for the visual navigation described later since the image processing speed is approximately one frame per second with the onboard Motorola MC68332 processor.

As in the former two versions, the third one is equipped with four tin oxide semiconductor gas sensors (TGS2602, Figaro Engineering) and thermister airflow sensors (F6201-1, Shibaura Electronics). One of the gas sensors is sticking out from the front side of the robot and used to check its smell, when the robot approaches an object.

Although plumes of gases are generally invisible, their sources, e.g., open bottles of chemicals, gas valve, etc., are often visible. If the target gas source has distinctive visual feature, it would be easier to navigate the robot visually than to try olfactory-guided navigation. Though many animals are using visual cues as an aid in their olfactory search behavior, how they achieve the fusion of different sensory information is still a big open question. Taking human behavior into consideration, however, it seems that the following behavioral strategies could be used for a robotic searcher to find a gas source.

- a) When a salient object is found in the visual field, the searcher approaches it and checks its smell.
- b) When the searcher smells an airborne scent, it turns to the upwind direction and looks for any visible object.

Here we propose behavior-based navigation algorithm shown in Fig. 2. It consists of three or four reflexive behaviors that are activated under certain conditions. A fixed priority level is assigned to each reflexive behavior as in the subsumption architecture⁽⁵⁾. The scheduler in Fig. 2 picks up the behavior with the highest priority among those activated and transmits the commands to the motors.

A typical path of the robot with the algorithm of Fig. 2 is shown in Fig. 3. There were four colored bottles on the floor (squares in Fig. 2), one of which (black square) was emanating ethanol vapor and three of which were odorless. Although no artificial airflow was used, a stable convective airflow (3–6 cm/s) existed along the positive x direction. The robot was placed at the starting position with the head pointing to the negative x direction. The random search was first activated, and then the robot drove toward the wall soon after the start. The color of the floor was taught to it, but intentionally that of the wall was not given. Therefore, the robot mistook the wall as a salient object laid on the floor. After

Fig. 2. Behavior-based algorithm with cooperation of vision, olfaction and airflow sensing

Fig. 3. Robot path with the behavior-based algorithm. Airflow sensing was not cooperated in this experiment for simplicity

checking the smell of the wall (A) several times, the robot found an empty bottle (B). Since no gas was detected from the bottle, the search was continued and the bottle leaking gas was found (C). The search time was 126 seconds.

3. Sensor Network for Monitoring Air Pollution

We do not know any modern cities free from air pollution. Tokyo is heavily polluted especially by NO_2 , SPM (suspended particulate matter) and sometimes oxidant. The pollutant distribution is now being monitored by the cumbersome and costly chemical analyzers, which are installed at the stations placed sparsely (only about 80 in Tokyo metropolitan area). If gas sensors are introduced, the small and economical monitoring system could be realized and placed with a considerably higher density (even within our home!). Their outputs could be collected efficiently by the modern network technology and the movement of pollutant plumes might be revealed.

3.1 GASDAS Authors' group proposed the system called GASDAS (gas distribution analyzing system) and have been developing the monitoring system using both NO_2 and ozone sensors. The basic structure and characteristics of NO_2 system were reported in the previous paper⁽⁶⁾. The system showed the good capabilities of temperature and humidity compensations in a short term after careful calibration. However, the lack of the long-term stability is an inevitable problem of the gas sensor, which causes the deterioration of the measurement accuracy over time. The frequent recalibration of a number of individual

Fig. 4. Comparison of NO_2 concentration measured with gas sensor and NO_x analyzer immediately after beginning to use a calibrated gas sensor on September 28, 2003

Fig. 5. Comparison of NO_2 concentration measured with gas sensor and NO_x analyzer. Dashed line shows recalculated sensor value after adjusting the sensor baseline to the average reported from stations at 1276 hour

sensors in the network is a time-consuming and laborious task. We have reported a new calibration method to achieve maintenance-free operation of the sensing network⁽⁷⁾. The network can be used not only for collecting the sensor data but also for the calibration and diagnosis of the sensors by comparing the measured pollutant concentrations with those of nearby sensors and monitoring stations located by local governments.

3.2 System Setup and Case Study Our NO_2 measurement system consists of a metal oxide gas sensor (TGS2106, Figaro Engineering) and a flow system containing a gas sensor cell and a temperature and humidity sensor cell. Data acquisition, processing, and communication over the Internet is performed using a TINI microprocessor board (DSTINIm400, Dallas Semiconductor). NO_2 concentration is calculated using calibration curves obtained experimentally after temperature and humidity compensation. The error in the calculated concentration values for two-week measurement was less than 10 ppb.

A case study was performed in the area surrounding our university. The sensor system was placed in the laboratory room. There are four stations placed around the campus. The concentrations of SO_2 , NO_2 , NO , photochemical oxidant, suspended particulate matter (SPM) and CO are measured by using atmospheric monitoring instruments at the stations. Meteorological variables (temperature, humidity, wind direction, and wind speed) are also measured at the stations. We can obtain hourly mean values of those measured data reported from the Internet site⁽⁸⁾. They were compared with the sensor data.

3.3 Auto-calibration Method Among the various factors that influence the long-term stability of the gas sensor response, the baseline drift was found to be the major cause of the errors in the measured gas concentrations. The sensor system has to be occasionally recalibrated to keep the measurement accuracy at high levels.

If the level of pollutant gas concentration in the whole local area under study is almost uniform, similar values are reported from the surrounding stations, and the sensor output in that area can be adjusted to their average. Usually, NO_2 concentrations are different at different sites. The different concentrations would be monitored at the different sites when the formation of NO_2 is at

high levels. Therefore, it is difficult to estimate the concentration at the university from those reported at the monitoring stations. In a case where low levels of NO_2 concentration are reported at all four stations, a natural conclusion would be the small amount of NO_2 generation in the whole local area, and an uniform distribution of low level NO_2 concentration. The gas sensor output around the baseline can be calibrated in this special case.

3.4 Results To validate the concept of the proposed calibration method, both NO_2 concentration and meteorological data measured at four stations for one year (from 2002 to 2003) was statistically analyzed. The study showed that the above calibration concept is correct. The gas sensor output is adjusted to the average of the values measured at the surrounding stations when all the stations in the area simultaneously report concentrations less than 10 ppb. During the one year period, the above criterion was met at least once per month and satisfied during nighttime with a strong south wind. The amount of vehicle exhaust emission is small at night, and the south wind blowing from Tokyo bay contains little NO_2 gas since there is no source.

NO_2 concentration measured with the sensor system and the chemiluminescence-based NO_x analyzer (Model 42C, Thermo Environmental Instruments) are compared in Figs. 4 and 5. The analyzer which is the same type of instrument as those used in the stations was used as a reference for the sensor system. The sensor system and the analyzer were both placed at our laboratory in the university. The raw sensor data and the data reported at the environmental monitoring stations were collected for several months, and were reviewed to investigate the effect of the proposed calibration method.

As shown in Fig. 4, the error in the measured NO_2 concentration was relatively small after beginning to use a calibrated gas sensor. Two months after the gas sensor was calibrated, the measurement error was increased to 40 ppb. Figure 5 shows the occasion when the calibration criterion was met. Adjusting the gas sensor baseline to the average values of four stations decreased the measurement error from 40 ppb to 10 ppb. It was found that the new calibration method is quite promising for a gas sensor to keep a sufficient accuracy in an atmospheric environmental system.

4. Conclusion

The properties of gas sensors are governed by the trailing behavior of air, since the substances to be detected are carried by it. The two ways for detecting gas plumes have been studied by authors' group and reviewed in the present paper. One is to move the sensors in searching for the plumes and the other to place many sensors in the detection field. It is concluded that they are essential and promising for enhancing both sensitivity and reliability of gas sensing systems in various application fields such as security and air-pollution monitoring.

Acknowledgements

The authors appreciate the collaboration with Mr. W. Tsujita and other graduate students of the authors' Laboratory. We also thank Prof. T. Nakamoto for his constant support and valuable comments.

(Manuscript received July 26, 2005)

References

- (1) T. Nakamoto, H. Ishida, and T. Moriizumi : "A sensing system for odor plumes", *Analytical Chemistry*, Vol.71, No.15, pp. 531A-537A (1999)
- (2) H. Ishida, K. Kagawa, T. Nakamoto, and T. Moriizumi : "Odor source localization in the clean room by an autonomous mobile sensing system", *Sens. Actuators B*, Vol.33, pp. 115-121 (1996)
- (3) H. Ishida, G. Nakayama, T. Nakamoto, and T. Moriizumi : "Controlling a gas/odor plume-tracking robot based on transient responses of gas sensors", *IEEE Sensors Journal*, Vol.5, pp. 537-545 (2005)
- (4) H. Ishida, H. Tanaka, H. Taniguchi, and T. Moriizumi : "Mobile robot navigation using vision and olfaction to search for a gas/odor source", Proc. of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 313-318 (2004)
- (5) R. A. Brooks : "A robust layered control system for a mobile robot", *IEEE J. of Robot. Automat.*, Vol.2, pp.14-23 (1986)

- (6) W. Tsujita, S. Kaneko, T. Ueda, H. Ishida, and T. Moriizumi : "Sensor-based air-pollution measurement system for environmental monitoring network", Technical Digest of Papers, The 12th International Conference on Solid State Sensors, Actuators and Microsystems, pp. 544-547 (2003)
- (7) W. Tsujita, A. Yoshino, H. Ishida, and T. Moriizumi : "Sensor network for atmospheric environmental monitoring and its auto-calibration", Proc. of Asia-Pacific Conf. of Transducers and Micro-Nano Technology (Apcot-MNT) 2004, Vol.3-1, pp.132-135 (2004)
- (8) <http://www.env.go.jp/>

Toyosaka Moriizumi (Member) was born in Gumma Prefecture, Japan,

in 1942. He received the Ph.D. degree in electronics from Tokyo Institute of Technology, Tokyo, Japan, in 1969, and became an Emeritus Professor at Tokyo Institute of Technology in 2005. He has been engaged in research in the fields of semiconductor thin films, heterojunctions, and SAW devices. His present interest is bioelectronics and biomimetics; i.e., electronics noses and gas/odor plume-tracking systems. He is a member of IEEE and seven other academic societies.

Hiroshi Ishida

(Member) was born in Morgantown, WV, USA, in 1970. He received the Ph.D. degree in electrical and electronic engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1997. In 2004, he joined the Department of Mechanical Systems Engineering at Tokyo University of Agriculture and Technology, Tokyo, Japan, where he is currently an Associate Professor. His research interests are in biomimetic electronics with emphasis on chemical sensors and their applications in robotics. He is a member of IEEE and four other academic societies.