

Mobile Robot Multi-sensor Unit for Unsupervised Gas Discrimination in Uncontrolled Environments

Yuxin Xing, Timothy A. Vincent, Marina Cole, Julian W. Gardner
School of Engineering
University of Warwick
Coventry, UK
J.W.Gardner@warwick.ac.uk

Han Fan, Victor Hernandez Bennetts, Erik Schaffernicht, Achim J. Lilienthal
AASS Research Center
Örebro University
Örebro, Sweden
han.fan@oru.se

Abstract— In this work we present a novel multi-sensor unit to detect and discriminate unknown gases in uncontrolled environments. The unit includes three metal oxide (MOX) sensors with CMOS micro heaters, a plasmonic enhanced non-dispersive infra-red (NDIR) sensor, a commercial temperature humidity sensor, and a flow sensor. The proposed sensing unit was evaluated with plumes of gases (propanol, ethanol and acetone) in both, a laboratory setup on a gas testing bench and on-board a mobile robot operating in an indoor workshop. It offers significantly improved performance compared to commercial systems, in terms of power consumption, response time and physical size. We verified the ability to discriminate gases in an unsupervised manner, with data collected on the robot and high accuracy was obtained in the classification of propanol versus acetone (96%), and ethanol versus acetone (90%).

Keywords— gas sensor, mobile robot, MOX, open sampling system, gas discrimination

I. INTRODUCTION

Mobile robots have been widely used by authorities to investigate hazardous areas, explore harsh environments, manage and monitor air quality, etc. [1]. To avoid risks to personnel in rescue missions, particularly in areas with extreme contaminations or unknown gas substances, it is important that the conditions in such environments are assessed prior to the deployment of human teams. The integration of an electronic nose (a multi-sensor gas detection module) onto a mobile robot, which is already equipped for exploration, is of great interest, in order to discriminate and identify different gases. Gas discrimination, especially outside a laboratory setup is considered challenging due to uncontrolled variables, such as air flow, temperature and humidity, and the movement of the device when used on a robot. In addition, unknown gas interferences are often present in the environment. Previous reports have attempted to address gas discrimination in such conditions, but performance has been limited due to the slow response and poor selectivity of the current generation of commercial sensors [2]. In this work, we have developed a gas sensing unit (GSU) with multiple sensors as an Open Sampling System (OSS), which can distinguish at least three different gases under dynamic, uncontrolled conditions.

The current generation of commercially available gas sensors, such as those based on electrochemical, catalytic or

semiconductor principles, are not ideal to use on a mobile robot due to their bulky size and poor selectivity. Furthermore, such devices are not robust (susceptible to poisoning) and are costly to replace. Therefore new sensors need to be developed with high sensitivity, high selectivity and fast response at a low cost. We have developed new MOX and NDIR sensors that are suitable for a mobile robot. The MOX devices are based on CMOS compatible micro heaters (1.2×1.2 mm) for high sensitivity and low power consumption (23 mA). The NDIR sensor system uses an innovative CMOS compatible IR emitter with a plasmonic structure for high selectivity and sensitivity. The gas sensors are integrated along with commercial sensors for a comprehensive environment monitoring unit (pressure, temperature humidity and particles).

II. GAS SENSING UNIT

A. System Design

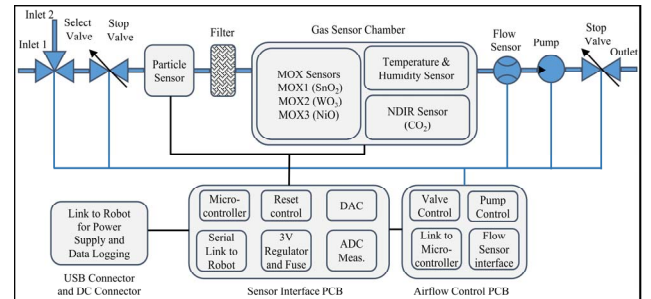


Figure 1: Block diagram of the new GSU.

The new generation GSU, presented in this work, was designed to significantly improve the performance of the sensor unit that we originally presented in [3] with enhanced signal processing capabilities, sensors response time and reduced module physical size. The new module (Fig.1) incorporates three MOX sensors for VOC detection and a plasmonic NDIR sensor system tuned for CO₂ detection at 4.26 μ m wavelength. All sensors are driven by high frequency PWM to lower power consumption (NDIR power consumption reduced from 75 mA to 50 mA by using AC drive).

Both types of sensors demonstrate fast response times, 10 s for the MOX and 30 ms for the NDIR, as compared to the commercial available devices (typically, 30 s for MOX and

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~5 s [4]) for high quality NDIR. Commercial sensors are included to monitor flow rate (Honeywell HAFBLF0750), particle density (Isocom H21A3), humidity, ambient temperature and pressure (Bosch BME280). The unit has an adaptable modular design, which can be easily customised for a particular exploration application (e.g. sensors can be interchanged as required, or prototype sensors trialled).

A pump (Micropumps D250) enables continuous sampling of ambient gas at 380 ml/min. If the environmental conditions risk damages to the module, two valves (Gem M-Series, normally closed) can automatically isolate the sensors. The unit, shown in Fig. 2, allows gas sampling from two different locations, selected via a third valve. This aids the detection of gases regardless of their density, so gases with higher or lower density of air can both be detected (i.e. air density is 1.225 kg/m³ [5], CO is lighter than air with density of 1.14 kg/m³ [6] and NO₂ is heavier than air with density of 1.45 kg/m³ [6]).

A stacked PCB design is employed to greatly reduce the physical size of the unit to fit inside a 100×100×100 mm enclosure. The stacked layout enables the 5V components (e.g. pump, valves) and sensors to be individually tested. A high performance microcontroller (Teensy 3.6) is included to allow preliminary signal processing to be performed in real time: digital filtering, peak detection and fast Fourier transform. The on-board microSD card module records the raw sensor data at 100 Hz, and the processed data is transmitted to the robot via micro USB connection at 10 Hz for further processing.

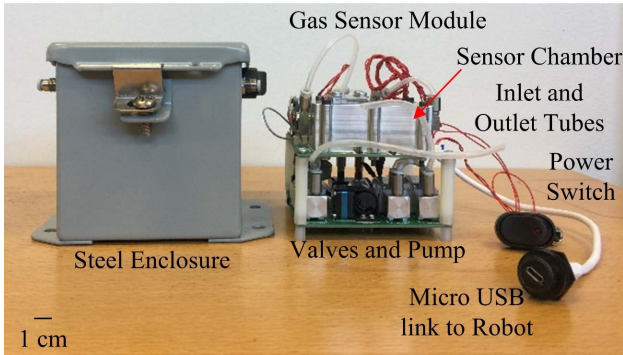


Figure 2: Assembled GSU and internal components. Steel enclosure (100×100×100 mm) provides secure and robust housing for the module.

B. Multi-sensor Unit Testing in Laboratory Setup

The three MOX sensors within the unit, targeting CO, NO₂ and acetone, are coated with tin oxide (SnO₂), tungsten oxide (WO₃) and nickel oxide (NiO), respectively.

The unit was tested with innocuous propanol, ethanol and acetone VOCs under laboratory conditions on a gas testing bench. A maximum of 200 ppm of acetone in synthetic air was introduced in 5-minute steps (returning to a baseline of synthetic air between acetone pulses). The results for the WO₃ coated MOX and NiO coated MOX are shown in Fig.3. The NiO coated MOX sensor demonstrates excellent selectivity to acetone; the WO₃ coated device produces a lower response.

The WO₃ coated sensor demonstrates good selectivity with significant response observed only for a target gas (e.g. NO₂,

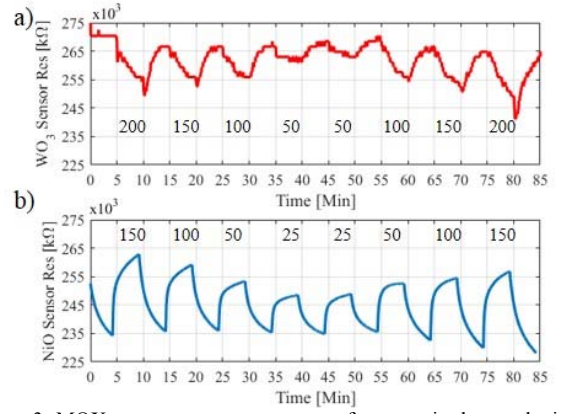


Figure 3: MOX sensors response to steps of acetone in dry synthetic air using (a) WO₃ coated device in concentration from 50 ppm to 200 ppm, and (b) NiO coated device in concentration from 25 ppm to 150 ppm.

previously reported [3]). The SnO₂ doped sensor (data in [3]), demonstrated selectivity to CO, with a lower response to other compounds (i.e. acetone). The selectivity from our MOX devices is found to be far greater than that of commercial sensors (e.g. SGX Sensortech), as the customised chemical coatings on the sensors are trialled for optimum performance for each gas. These enhancements make our novel sensor system suitable for gas discrimination and identification.

III. GAS DISCRIMINATION WITH AN OPEN SAMPLING SYSTEM

A. Experimental Setup

To validate the proposed sensor unit, we conducted a performance test with respect to gas discrimination accuracy. The performance test aims to verify the instrument's suitability for its desired gas sensing application, i.e., gas detection and identification in uncontrolled environments [7].

In this experiment, three gas sources, propanol, ethanol and acetone were placed at different positions in an indoor workshop, where the environmental conditions, e.g., airflow, temperature, and humidity, are uncontrolled. Each gas was released from an open plastic container using a bubbler and a fan to facilitate evaporation (see Fig. 4). For the sample collection procedure, a robot equipped with the proposed sensor unit was remotely controlled to carry out an inspection tour, approaching the gas sources one by one. The robot stayed in the vicinity of each gas sources for 3 to 5 minutes approx. 0.5 metres away to ensure the sensor unit was sufficiently exposed to the analytes.

B. Results

In order to prepare the test sets for the gas discrimination experiment, we divided the data collected by the robot into three parts, which correspond to propanol, ethanol, and acetone respectively. Given in total three test sets, we present results from two discrimination tasks, namely propanol vs. acetone and ethanol vs. acetone. The measurements are processed using the algorithm presented in [2], which was developed for gas discrimination in open environments. The algorithm used is an unsupervised approach that does not require training data of target analytes. The only free parameter is chosen following the suggestion in [2], any other parameter is learned from the data.

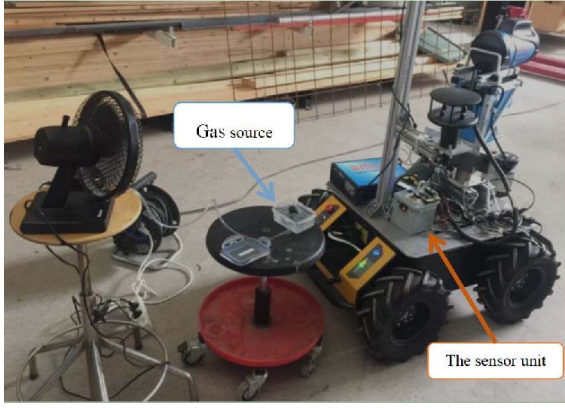


Figure 4: The experimental scenario of the gas discrimination experiment.

The algorithm used is an unsupervised approach that does not require training data of the target analytes. The only free parameter is chosen following the method proposed in [2], the remaining parameters are learned from the data. The discrimination performance is evaluated using the index Exact Match Ratio E (Eq. 1), which is calculated as the ratio between the number of correct predictions and the total number of considered measurements. We compute the per-class exact match ratio (E_{class}) for each of the classes, and the exact match ratio, which is computed over the full dataset ($E_{overall}$).

$$E = \frac{\#correct\ predictions}{\#total\ measurements} \quad (1)$$

Table I shows the performance for the two discrimination tasks. In both cases, instantaneous MOX sensor responses are used as the features. Although the robot was stopped in front of the gas sources to acquire measurements, fluctuating gas concentrations are still observed and steady states were not reached (see the concentration indicators in Fig. 5). Nevertheless, we manage to determine that there are two analytes present, and classify them with high accuracy (above 85% in overall and per-call exact match ratios).

TABLE I. THE EVALUATION OF THE GAS DISCRIMINATION PERFORMANCE.

	propanol vs. acetone	ethanol vs. acetone
$E_{overall}$	95.91%	89.76%
E_{class1}	88.64% (propanol)	85.53% (ethanol)
E_{class2}	99.84%	92.90%

IV. CONCLUSIONS

In this paper, we have presented a gas sensing unit with novel sensors suitable for unsupervised gas discrimination on a mobile robot. The improved, and redesigned second generation gas unit has a physically compact size with two gas inlets for sampling at two different locations. It contains three micro-heater MOX sensors, a plasmonic NDIR sensor, and commercial environmental sensors to provide an extensive assessment of the gases present in the environment. The sensor unit was tested both in a laboratory setup and on a mobile robot platform. Propanol, ethanol and acetone were used as gas sources in the experiments, and data on the robot were

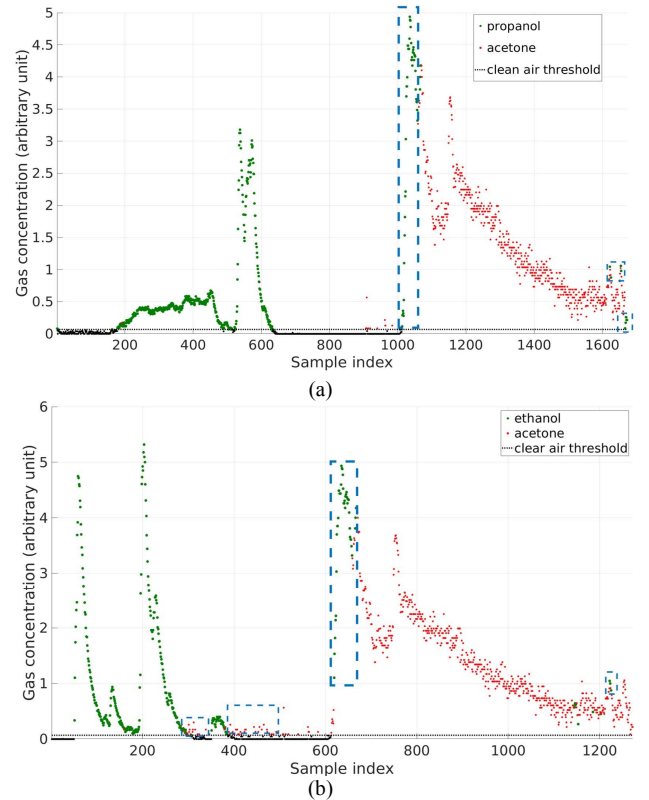


Figure 5: The discrimination results of (a) propanol vs. acetone and (b) Ethanol vs. acetone respectively. Green and red colours denote different class labels assigned by the KmP algorithm. Black denotes the measurements considered as clean air, which are determined by the clean air threshold estimated from the baseline responses of the GSU. Misclassifications are marked by the dashed blue boxes.

collected and processed by an unsupervised learning algorithm. The GSU can discriminate and classify propanol versus acetone, and ethanol versus acetone with high accuracy (over 85%). Our unit has the potential to discriminate three gases in real-time (online sampling), which is challenging with the current generation of commercial sensors. Future work will include improving the sensors stability on the robot, and compensation for temperature drift.

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