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A rapid discreteness correction scheme for reproducibility enhancement among a batch of MOS gas sensors

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ABSTRACT

Metal oxide semiconductor (MOS) gas sensors have been widely reported in machine olfaction system (i.e. electronic nose/tongue) for rapid detection of gas mixture components due to their positive characteristics of cross-sensitivity, broad spectrum response and low-cost. However, the discreteness of MOS gas sensors caused by inherent sensor variability during the manufacturing process results in the failure of the batch-oriented applications of MOS gas sensors due to their weak reproducibility. Certainly, it will also cause negative influence to the development of electronic nose/tongue based on MOS gas sensors (e.g. accuracy and consistency during electronic nose/tongue detections). Therefore, the contribution of this paper is to solve the discreteness and improve the reproducibility of sensors by designing an effective and easily realized scheme for large-scale calibration. Experimental results demonstrate that the proposed scheme can effectively and rapidly realize the calibration of the sensors' discreteness in batch of electronic noses production and the proposed scheme have also been used in industry. Besides, this paper also proves that one sensor's discreteness is constant and keeps unchanged when the sensor is exposed to different kinds of gas components.

1. Introduction

Electronic nose (E-nose), as an artificial olfaction system, is an instrument comprised of a chemical sensor array with partial specificity and an appropriate pattern recognition algorithm [1,2]. Metal oxide semiconductor (MOS) gas sensors have been widely reported in E-nose for detection of chemicals [3–12]. MOS sensors have also been used in odor-discrimination system for fruit detection [13]. Recently, a variety of algorithms have been proposed for dealing with the sensor drift problem [14–18]. Fonollosa et al. also studied the sensor failures in discrimination of chemical substances [19]. However, most of the research in E-nose based on MOS gas sensor array focus on the pattern recognition analysis using one fixed sensor array, and without considering the problem of sensor's reproducibility that will result in the difference of electrical signal between two sensor arrays of the same type [9]. In other words, other sensor arrays with completely the same type may not be appropriate with the learned pattern recognition model (i.e. artificial neural network) due to the weak reproducibility [20]. MOS gas sensors are operated with the principle that volatile odor components can produce a reaction inside the sensor in contact with a catalytic metal, changing the electrical resistance of the sensor device and producing some voltage signal [21]. Generally, the sensing material is metal oxide, most typically SnO_2 [1]. The principles can be described as follows.

When the metal oxide crystal is heated at a certain high temperature in air, oxygen is adsorbed on the crystal surface with a negative charge. In the presence of a deoxidizing gas, the surface density of the negatively charged oxygen will decrease so that the barrier height is reduced which will decrease the sensor resistance. The detection principle of MOS gas sensors is based on the chemical adsorption and desorption of chemicals on the sensor's surface. Besides, the ambient temperature and humidity will also affect the sensitivity characteristics of sensor by changing the rate of chemical reaction [22]. Therefore, from the complex sensing principle and the various factors related in sensing, the reproducibility of MOS gas sensors should be taken into consideration in the industrial production of MOS gas sensors based instruments.

In batch of E-nose production, the homogeneity of multiple electronic noses' predictions when exposed to the same gas component is very important and the week reproducibility would

Abbreviations: MOS, metal oxide semiconductor; FPGA, field programmable gate array; DC, Direct current; RH, Relative humidity; JTAG, joint test action group; CPU, central processing unit; SDRAM, synchronous dynamic random access memory; LCD, liquid crystal display; CO, carbon monoxide; NH_3, ammonia; NO_2, nitrogen dioxide.

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seriously degrade the homogeneity [23]. The homogeneity completely depends on the MOS gas sensor array embedded in E-nose, because the pattern recognition module used internally is identical among E-noses and different inputs from sensors would lead to different predictions. Unfortunately, the MOS gas sensor array of identical type reflects diverse responses to the same chemical in the same experimental condition due to the inherent sensor variability and discreteness during the manufacturing process [9]. The kind of sensor discreteness must cause the reduction of E-nose prediction accuracy and reproducibility. To solve the problem of sensor discreteness, specific correction methods have been studied in previous publications [23,24]. Comparatively, the GAT–RWLS method proposed in [23], for its simplification of algorithm, is easier to implement for calibration in real-time E-nose detection. However, in large-scale sensors application (i.e. production of E-nose instruments), a rapid discreteness correction scheme is very necessary to reduce the complexity and also promise the accuracy, especially for regular calibration. The problems of sensor's discreteness and reproducibility in large-scale application of MOS gas sensors have been mentioned and fully solved in this work.

Therefore, the contribution of this paper is to present an effective implementation scheme of sensors' discreteness correction coupled with GAT–RWLS method for batch-oriented instruments production. In addition, this paper also reveals that the sensors' discreteness has little relation with the type of measured gas.

2. Materials and method

2.1. Sensors' discreteness and gases experiments

MOS gas sensors' discreteness will cause large difficulties in batch-oriented instruments development. Especially that the discreteness extremely lowers the accuracy of electronic nose instruments. The discreteness can be illustrated in two facets:

(1) Baseline difference: the sensitive resistance Ro of identical sensors in the standard environment (clean air) with temperature 20 °C and relative humidity (RH) 60% is variable which results in that the baseline of sensor with identical type is different in the same environment.
(2) Sensitivity difference: when exposed to some kind of pollutant gas, the MOS sensors with identical type also have different sensitivity which can be denoted as Rs/Ro (Rs is the sensitive resistance in the pollutant gas and Ro is the sensitive resistance in clean air). This will result in that the sensor responses with identical type are also different when exposed to the same type of gas with the same concentration in the same environment. That is, the same two sensors in the same environment have different outputs.

Therefore, it is not difficult to infer that the discreteness of MOS sensors can largely influence the accuracy of detective instruments, and rapid correction of the discreteness without changing the sensor circuits is very significant in improving the sensors' reproducibility and the performance of instruments, especially in batch-oriented application.

For studying of the sensor discreteness and its rapid correction in batch-oriented application, we have employed multiple kinds of gases experiments using 6 electronic nose systems embedded with identical sensor array. The electronic nose system based on Field Programmable Gate Array (FPGA) processor has been introduced in our previous publication [5]. For visualization, the picture of our E-nose has been illustrated in Fig. 1 (the left part in bottom). Considering the characteristics of broad spectrum and low-cost of metal oxide semiconductor gas sensors, four metal oxide semiconductor gas sensors from Figaro Inc. including TGS2602, TGS2620, TGS2201A and TGS2201B are used in the sensor array. The heating voltage of TGS2620 and TGS2602 is 4 V (Volt), and the heating voltage of TGS2201A/B is 7 V. The supplied power voltage of system is DC12 V. The experiments of electronic noses were employed in the climate chamber (LRH-150S). The experimental process including gas preparation, climate chamber, E-nose system and data collection is illustrated in Fig. 1. The typical response of an array of four gas sensors with four phases in the sampling process (1. baseline, 2. transient response, 3. steady state response, 4. recover process) can be observed in Fig. 1 (the top part). Totally, 126 formaldehyde samples, 72 benzene samples, 66 toluene samples, 58 carbon monoxide samples, 27 ammonia samples and 30 nitrogen dioxide samples were obtained. The experimental conditions and concentrations are different from each other. The discreteness of TGS2620, TGS2602, TGS2201A and TGS2201B sensors when exposed to the same concentration of formaldehyde gas has been illustrated in Fig. 2. Note that TGS2620 (1–6), TGS2602 (1–6), TGS2201A (1–6) and TGS2201B (1–6) represent six sensors with completely the same type, respectively. We can see from Fig. 2 that the discreteness of TGS2620 is weaker than other three MOS gas sensors. In other words, the reproducibility of TGS2620 is comparatively better. This phenomenon results from several facets. Though their sensing principles in detection are similar, their manufacturing process, electrical characteristics, and sensitivity will also influence the reproducibility. For instance, the sensor resistance (Rs) of TGS2620 is 1–5 kΩ, while 10k–100 kΩ is for TGS2602, 250 kΩ and 25 kΩ are for TGS2201A and TGS2201B, respectively. In our experiments, TGS2620 shows the best reproducibility and stability, while TGS2602 performs the worst.

2.2. Review of the previous GAT–RWLS method

GAT–RWLS method using reference formaldehyde gas for discreteness correction was proposed in our previous publication [23]. Through a large number of electronic nose experiments, we found that there exists a good linear relation between two sensors with the same type when exposed to the same environment and conditions. That is, the discreteness can be easily corrected in a linear way. For simplification, the calibration transfer model is shown by

$$y_{i,n} = a_i \cdot x_{i,n} + b_i, \quad i = 1, \ldots, k; \qquad n = 1, \ldots, N \tag{1}$$

where k denotes the number of sensors being calibrated, N denotes the number of calibration samples, x denotes the response of slave, y denotes the estimation of the master, a_i and b_i represent the calibration coefficients of the ith sensor obtained using reference gas (formaldehyde). In this model, a master should be determined as the standard electronic nose in advance, take other electronic nose as slaves, and calibrate the slaves to the master.

The proposal of model (1) is based on a global affine transform (GAT) with scaling and translation in a special way that the sensors in a sensor array influence each other in calibration. That is, the calibration is independent for each sensor. Also, considering the experimental error of a number of samples which will result in the inaccuracy of the calibration model, a robust weighted least square (RWLS) method was used for regression (1) and obtaining the parameters a and b. Experimental results of the formaldehyde samples correction demonstrate that the proposed method was very effective and easy to realize. We refer readers [23] for the details of the GAT–RWLS method.

In this paper, the calibration parameters obtained using formaldehyde as reference gas would also be validated for correction of the sensors' discreteness when exposed to other five kinds of gases in different conditions and concentrations.