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Wireless electronic nose system for real-time quantitative analysis of gas mixtures using micro-gas sensor array and neuro-fuzzy network

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ABSTRACT

A wireless electronic nose system (WENS) is designed for the real-time quantification of ammonia (NH_3), hydrogen sulfide (H_2S), and their mixtures. The WENS hardware consists of a microcontroller for obtaining measurement data from a micro-gas sensor array, and an RF transceiver for transmitting the data sets to a master sensor node. Meanwhile, the WENS software analyses the binary gas mixtures using a fuzzy ARTMAP classifier and a fuzzy ART-based concentration estimator with multiplicative drift correction based on reference gases. A virtual instrument is developed in the LabVIEW environment for monitoring the analyzed gas mixtures. The performance of the proposed WENS is also assessed and compared with the minimum and product inference methods. The proposed WENS adopting the weighted inference method produces the best concentration estimations as regards the root mean square error.

1. Introduction

The design of a wireless electronic nose comprised of gas sensor arrays and a pattern recognition tool is an exciting topic. Since a semiconductor-type electronic nose can be designed using low-cost, small-sized, and easy-handling devices with a fast response time compared to traditional gas chromatography methods, this opens a wide variety of applications in such fields as medicine, food, and environmental monitoring. Depending on the field of application, various design techniques for an electronic nose can be considered. When combined with embedded technology, the recent appearance of handheld instruments has made on-site chemical compound analysis a reality [1,2]. However, such handheld instruments are not suitable when a real-time analysis of chemical compounds is continuously required or the location is inaccessible. Thus, to cope with these requirements, an electronic nose should also include wireless hardware platforms and optimized functioning to maximize its qualitative and quantitative recognition capability.

Nonetheless, despite the potential benefits of being wireless, there are few reported examples of the wireless electronic nose comprised of gas sensor arrays and a pattern recognition tool. A small number of studies have attempted to combine chemical sensors with wireless sensor networks, for example, a remote system for monitoring indoor air quality using a CO_2 gas sensor [3] and a wireless chemical sensor network for the detection and tracking of an acetic acid plume using LED chemical sensors [4]. However, these reports have only dealt with the detection of a single gas and not presented a real-time qualitative and quantitative analysis of the target gases.

To classify a single gas or gas mixtures, multilayer perceptron (MLP) neural networks have been widely used in electronic noses. Yet, according to the results of recent research [5], a fuzzy ARTMAP can outperform a multilayer perceptron on the classification accuracy and training time. Meanwhile, for quantitative gas analyses, MLP neural networks and neuro-fuzzy networks (NFNs) have both been developed [6–8], and NFNs shown to be more powerful than MLP neural networks as regards the estimation results. However, NFNs involve complex learning methods when training the membership function parameters. Thus, due to the intricacy of their training algorithms and difficult mathematical operations, MLP networks and NFNs are both limited as regards real-time quantitative gas mixture analyses and the implementation of an electronic nose into wireless hardware platforms.

In previous work by the present authors [9], a fuzzy ART-based network was proposed to estimate the concentrations of gas mixtures and demonstrated a good performance as regards the concentration estimation with less training time than other estimators using NFNs or MLP networks. The fuzzy ART-based concentration estimator employs the fuzzy ART proposed by Carpenter et al. [10]

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to perform fuzzy clustering in the input spaces and find proper fuzzy logic rules dynamically by associating the input clusters with the output clusters. The fuzzy ART learning creates clusters of concentrations of a single gas or gas mixtures. Using the regions formed for each concentration, corresponding membership functions are then designed and fuzzy rules extracted. Finally, fuzzy inference and defuzzification are used to estimate the concentrations for a given input.

Accordingly, this paper presents a wireless electronic nose system (WENS) that can classify ammonia (NH_3), hydrogen sulfide (H_2S), and their mixtures, plus estimate the concentrations of these gases, the main malodors in several environments. The proposed WENS consists of wireless sensor nodes and pattern recognition software. Each wireless sensor node is implemented using an ultra-low power microcontroller, MSP430F1611, a micro-gas sensor array with SnO_2–CuO and SnO_2–Pt sensing films for detecting the gases, and an RF transceiver for wireless communication between the sensor nodes. The software for analyzing gas mixtures, a fuzzy ARTMAP classifier and a fuzzy ART-based concentration estimator, is implemented on a desktop PC using MATLAB language. The performance of the fuzzy ART-based concentration estimator is also improved using the weighted inference method, which is inspired by the weighted fuzzy min–max neural network [11]. Plus, a virtual instrument is developed in the LabVIEW environment for monitoring the results in real-time and setting pre-determined parameters, such as the response to reference air and drift correction factors. Finally, for reproducibility and reliability, the multiplicative drift correction method [12], which is currently used in commercial electronic noses, is incorporated in the WENS design. The main contribution of this paper is that the weighted inference method is devised for the proposed WENS and it has improved the performance of the concentration estimator in the sense of the root mean square error. The unique feature of the weighted inference method is the weighting vector containing the variances of the input variables to the neuro-fuzzy network, which helps produce the best concentration estimation.

2. Wireless electronic nose system

2.1. Silicon bridge-type micro-gas sensor array

A silicon bridge-type micro-gas sensor array is employed to allow the fabricated WENS to detect hydrogen sulfide and ammonia gases simultaneously. Thus, anisotropic wet-etching of silicon in a 25 wt% KOH solution at 80 °C and silicon reactive-ion etching are applied to achieve a bridge-type sensor for low power consumption. The micro-gas sensor array is consisting of two sensing films; one is Pt-added tin oxide sensing film, SnO_2–Pt and the other is CuO-added one, SnO_2–CuO. Fig. 1 shows the photograph of the micro-gas sensor array in which each sensing membrane has a bridge-type micro-heater. The size of the fabricated device and active region is 2 mm × 2 mm and 85 μm × 75 μm, respectively.

When measured on the dominant sensing film, the response time to reach 90% of the steady-state value of the sensor to NH_3 and H_2S is 0.5 and 0.2 s, respectively, and has shown good reversibility. This experiment was conducted in an 800 cm^3 chamber at 25 °C with 40% humidity. After the chamber was saturated by the gas with a desired concentration using a mass flow controller (MFC), the response was measured at every 62.5 ms by the ADC module of an MSP430 microcontroller with applying repeatedly a periodic control signal consisting of 6 s on and 4 s off the micro-heater. From the measurement at several concentrations of NH_3 and H_2S, it is presumably assured that the detection limit is far below 2 ppm of NH_3 and 0.05 ppm of H_2S. Further details on the fabrication process can be found elsewhere [13], while the packaged micro-gas sensor array is shown in Fig. 2.

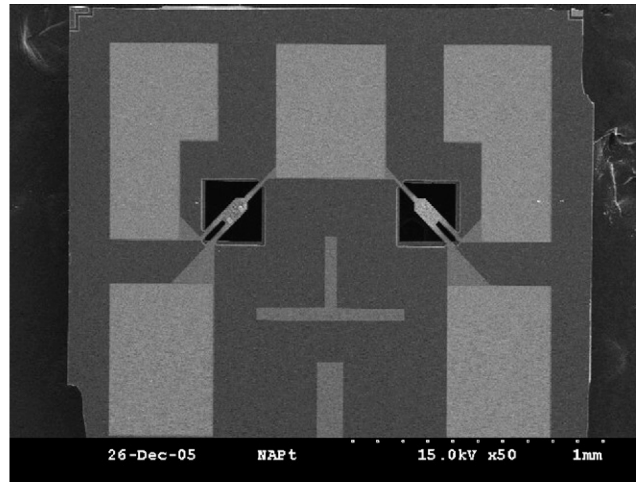

Fig. 1. Photograph of the micro-gas sensor array: CuO-added tin oxide sensing film (left) and Pt-added tin oxide sensing film (right).

2.2. Hardware of wireless sensor node

As shown in Fig. 3, the proposed WENS has two wireless sensor nodes—a slave sensor node and a master sensor node, where the former measures the target gases at a particular location and transmits the measured data sets to the master sensor node via an RF transceiver. The master sensor node then sends the received data to the host computer through a USB interface for final processing using a MATLAB programming language.

The top of the board of the implemented wireless sensor node includes a silicon bridge-type micro-gas sensor array with SnO_2–CuO and SnO_2–Pt sensing films, a single-chip relative humidity and temperature multi-sensor module comprising a calibrated digital output, Sensirion SHT1x, and a single-chip 2.4 GHz IEEE 802.15.4 compliant RF transceiver, Chipcon CC2420. Meanwhile, the bottom contains an ultra-low power microcontroller, Texas Instruments MSP430F1611, with a built-in 12-bit A/D converter and 48k-byte flash memory. The devices are all connected to and controlled by the microcontroller. To sense the sensor resistance changes in the presence of the target gases, a load resistor is connected to each sensing film in series along with a dc voltage supplier. An operational amplifier, TLC271, with a high input impedance

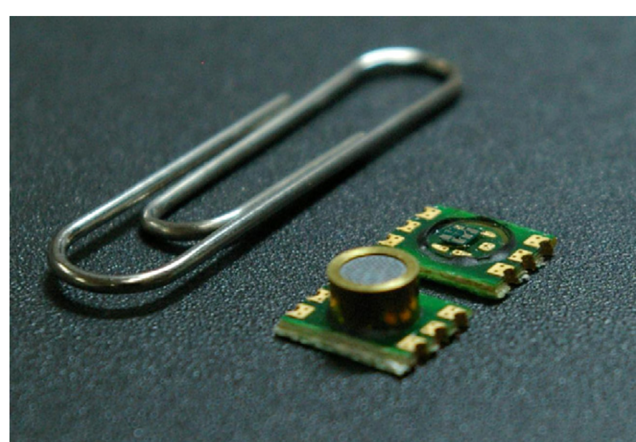

Fig. 2. Packaged silicon bridge-type micro-gas sensor array with compact size, 6.3 mm (W) × 8.0 mm (L).