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Microcontroller Based E-Nose for Gas Classification without Using ADC

Lachit DUTTA, Anil HAZARIKA and Manabendra BHUYAN
Department of Electronics and Communication Engineering, Tezpur University,
Napaam, Assam-784028, India
E-mail: lachit@tezu.ernet.in

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Abstract: This paper illustrates a technique that facilitate direct-interfacing (DI) a sensor array to a microcontroller for analog output voltage measurement without the use of an ADC (Analog-to-digital Converter). Even though all earlier reports on direct interface is successfully implemented for a single sensor, it provided a gateway for interfacing a sensor array. We successfully demonstrate the direct-interfacing of MOS (metal oxide semiconductor) based gas sensor array to an inexpensive 8-bit microcontroller. Further to accentuate the discriminative capability of the system two pattern classification paradigms- FFBP (feed forward back propagation) ANN (artificial neural network) and LDA (linear discriminant analysis) are associated with the direct interface circuit. We also corroborate gas identification in the microcontroller by implementing FFBP ANN which shows an accuracy of 98.75 %. The effectiveness of DI methodology established will serve as a viable tool for online gas monitoring applications. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Direct-interface, Sensor array.

1. Introduction

Typically when analog output of a sensor is fed to a microcontroller, the voltage is digitized using an ADC. The output of the ADC is then processed in the microcontroller unit (MCU) for further analysis. But the analog output measurement system can be minimized by directly interfacing the sensors to the MCU without using the intermediate ADC. Various studies on DI based circuits are reported in literature for measurement of different sensor parameters like resistance [1-15], capacitance [16-21], inductance [22] etc. Such analog voltage measurement circuits are simple and remarkable in terms of performance which was first demonstrated by Peter, *et al*. [3] in a PIC 16CXX microcontroller. Further, DI circuit has advantages in terms of both cost and power consumption [23-24]. Due to this, the system was later replicated in different microcontrollers for wide variety of sensors for measurement of analog voltage. Among them the most prominent designs were implemented in HC9S08Rx microcontroller [7]; ST7FLITE05 (09) microcontroller to study passive infrared (PIR) sensor responses [9]; and MSP430 microcontroller by interfacing a separate sigma-delta modulator-AD 7400 [10]. The analog voltage in [3, 7, 9-10] is measured by realizing a sigma delta ADC using simple local hardware (capacitor and resistors) by proper sequencing of the built-in timer and comparator module of the MCU. Although this approach does not require any ADC, the quintessential need of comparator and timer modules to measure the analog voltage demands for a relatively advanced and expensive microcontroller. Bengtsson [12] demonstrated that by using only two I/O pins of the microcontroller an RC circuit based DI circuit can effectively measure analog voltage. The DI circuit requires only two resistances, a capacitor and the microcontroller digital I/O pins to have Tri-state capability. The analog voltage (simulated signal from Agilent 33220A) is measured based on the charging/discharging time of a RC circuit. A counter value is assigned in the MCU and the counter is incremented or decremented based on the voltage to be measured. The counter output generated is proportional to the applied analog voltage.

Although DI technique is adopted by various researchers to interface sensor analog output to the MCU, it is mainly concentrated on a single sensor. While sensor array interface by DI approach remains unexplored. This paper presents a technique for interfacing an E-Nose array consisting of three numbers of MOS gas sensors to a microcontroller without using the ADC. Furthermore, we analyze the accuracy of the system to discriminate different gases by implementing pattern recognition paradigms in the microcontroller. Although microcontroller based pattern classification are popular and extensively used, this study presents the first approach of a DI based ADC less MOS gas sensor response pattern analysis and classification of gases. We demonstrate two types of classification –first software based classification using a PC in which we measure the sensor responses by DI method and store it and then extract the feature and analyze it in MATLAB for pattern recognition. Next we implement the ANN in the microcontroller where the sensor responses measurement, features extraction and pattern recognition are incorporated within the microcontroller. Finally the gas analyte identified is displayed in an alphanumeric liquid crystal display of the microcontroller. We successfully demonstrated online classification of gases by using a DI based MOS gas sensor array without using an ADC, comparator or timers modules. Thus the proposed method results in a low cost solution which can be useful for various measurement systems. The proposed methodology shed new light to DI method, presenting a promising solution for interfacing a sensor array producing analog voltage.

2. Materials and Methods

2.1. 12-bit ADC Using Direct Interface to Microcontroller

In order to measure analog voltage by DI methodology without using an ADC, we used a circuit comprising of two resistances (R_1 and R_2) and a capacitor (C). The analog voltage (V_{in}) to be measured is applied to the microcontroller (PIC-18F45k22) through the RC circuit as shown in Fig. 1. The analog voltage (V_{in}) is directly proportional to the time of charging the capacitor, and is calculated by measuring the charging/discharging of the RC circuit by the MCU [12]. A precise DI measurement system needs precise measurement of resistances (R_1 and R_2), capacitor (C), supply voltage (V_{DD}), input logic low (V_{IL}), input logic high (V_{IH}), and oscillator frequency (F_0). A precision multimeter (Keithley-2110) is used to measure the values of local hardware components and are found as: $C = 2.256\ \mu\text{F}$, $R_1 = 3.2059\,\text{k}\Omega$ and $R_2 = 9.9519\,\text{k}\Omega$. Next, we measure the low and high input/output logic levels of the MCU by the multimeter and the values are found as- $V_{IH} = 1.962\text{ V}$, $V_{IL} = 1.880\text{ V}$ when $V_{DD} = 4.65\text{ V}$. Further the local oscillator frequency (F_0) of the PIC MCU is measured using DSO3202A digital storage oscilloscope from Agilent Technologies and was found to be 20 MHz.

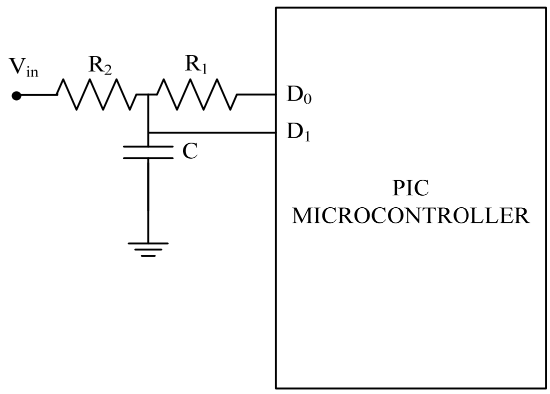

Fig. 1. Basic direct-interfacing circuit.

We have calculated the parameters representing the analog voltage of the DI circuit using equations available in [12]. The range of charging and discharging time of the capacitor is predicted by expressions (1) and (2) respectively [12].

$$t_c = -\frac{1}{(1/C)((1/R_1)+(1/R_2))} \cdot \ln\{(\frac{V_H(R_1+R_2)-R_2V_{DD}-R_1(V_{RL})}{R_2\cdot((V_{RL})-V_{DD}})\} \quad (1)$$

$$t_d = -\frac{1}{(1/C)((1/R_1)+(1/R_2))} \cdot \ln\{\frac{1}{R_2}(\frac{V_{IL}(R_1+R_2)}{(V_{RL})} - R_1)\} \quad (2)$$

Our primary goal is to measure the maximum charging time ($t_{c,\max}$) and maximum discharging time ($t_{d,\max}$) of the capacitor by setting $V_{in} = V_{DD}$ in (1) and $V_{in} = 0$ in (2) [12]. The values were calculated to be $t_{c,\max} = 84.74$ ms and $t_{d,\max} = 44.64$ ms respectively. The starting counter value (N_0) is calculated using the following equation, and is found as $N_0 = 1413$.

$$N_0 = \frac{t_{c,\max}}{t_{c,\max} + t_{d,\max}} \times 2^{12} \quad (3)$$

The delay values needed for up or down counting of the counters are set as- $1413\,(N_0)$ to 4095 when $V_{in} = V_{DD}$; 0 to $1413\,(N_0)$ when $V_{in} = 0$. The delay value to be used in the microcontroller firmware while up counting (D_c) and down counting (D_d) were both found to be 7 instruction cycles using Equations (4) and (5) [12].

$$D_d = \frac{F_0 \cdot t_{d,\max}}{4 \cdot (2^{12} - N_0)} - 9 \quad (4)$$

$$D_c = \frac{F_0 \cdot t_{c,\max}}{4 \cdot N_0} - 9 \quad (5)$$

Before implementation of the DI based E-Nose, the circuit was tested with analog voltage and corresponding counter values were obtained.

2.2. Experimental Setup

We have developed an E-Nose set up for conducting experiments on DI based E-Nose, which comprises of power supply circuits, sample chamber, pumps, relays, valve, sensor chamber, mass flow controller (MFC), data acquisition (DAQ) card and microcontroller board all fitted together. Fig. 2 shows the pictorial representation of the developed experimental setup. The sensor chamber consists of three MOS gas sensors obtained from Figaro Inc. namely -TGS 2201, TGS 2620, and TGS 832. The versatility of these sensors lies in the fact that although they are highly sensitive to a particular gas they are cross sensitive to a wide spectrum of gases. The cross sensitive property of these sensors makes them the most prominent device for developing an E-Nose [25]. The analog voltage outputs from the sensors are connected via DI technique to the MCU.

We first examine the change in counter value due to the change in the corresponding output voltage level of the sensors on exposure to different gases. In order to evaluate the effect of counter value on the gas sensing properties of the sensor array four high purity chemicals (acetone, acetic acid, methanol and 2-propanol) were collected to conduct the experiments. The sensor array is exposed to a high concentration of the chemical analyte for which we inject 300 μL of each chemical samples into the sample vial.

The samples require about 15 minutes to completely vaporize and develop the required headspace. The gas concentration was calculated in parts per million (PPM) by using standard method and was found as-Methanol-316.82 PPM, Acetic Acid-223.9 PPM, 2-Propanol- 174.6 PPM, and Acetone-167.6 PPM. The gas was then fluxed to the sensing chamber by a pump at a flow rate of 1.2 SLPM to facilitate exposing to the sensor array. The flow rate was controlled and regulated by a mass flow controller (Alicat MC-05 SLPM-D). The electronic control and real time data acquisition is implemented by a PC using Lab VIEW software and in case of DI circuit it was done using a microcontroller.

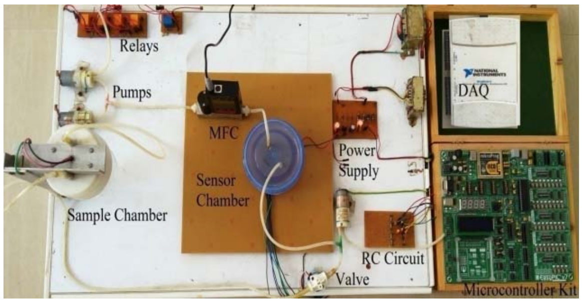

Fig. 2. Pictorial representation of the Experimental E-Nose setup.

2.3. MOS Gas Sensor Array Interface and Data Acquisition

The typical MOS gas sensor circuit for Figaro MOS gas sensors is a simple voltage divider circuit as shown in Fig. 3 with a load resistance of 470 Ω, supply voltage (V_C) and heater voltage (V_H) of +5V DC.

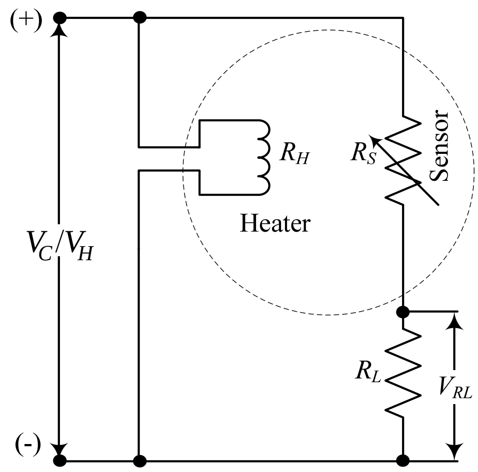

Fig. 3. MOS gas sensor circuit.

The basic working principle of the MOS gas sensor is that its conductivity changes when it is exposed to a gas. The gas sensing operation is performed in two phases. In the first phase the gas is applied to the sensor till the response voltage reaches an equilibrium condition. When the peak steady state voltage is achieved, in the second phase the gas molecules from the sensor chamber are removed by applying fresh air to recover the sensor response to its original (baseline) value.

2.4. Direct Interface E-Nose

To calculate the output response (V_{in}) at the two response conditions- baseline and peak steady state, we measure the counter value using the circuit interfaced to the PIC microcontroller (Fig.4).

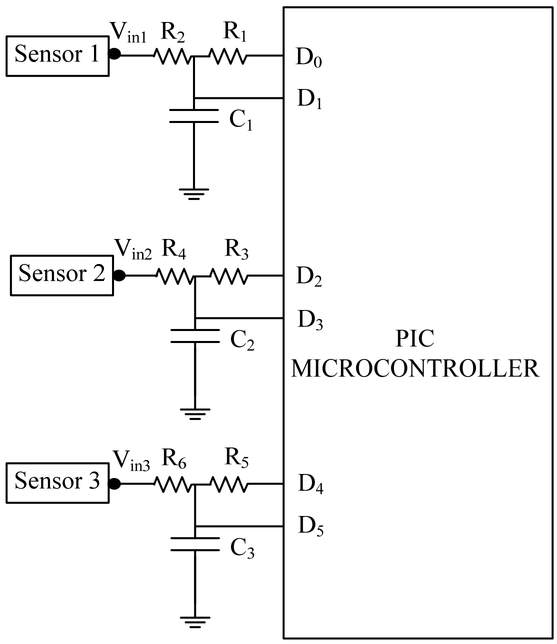

Fig. 4. Sensor array interfaced to MCU through DI circuit.

Before interfacing the E-Nose to the DI circuit, we have calibrated the counter values in terms of the input analog voltage by applying analog voltage from a precision power supply. In case of interfacing sensor array digital I/O-pins (D_0, D_1), (D_2, D_3) and (D_4, D_5) of the MCU were used to measure the counter value for the output voltages to V_{in1}, V_{in2} and V_{in3} of the sensor array.

In our measurement the sensor output response voltages at baseline (V_b) and peak (V_p) are always found to be less than digital logic high (V_{IH}) of the MCU. On refreshing the sensor (Fig. 5) it produces a baseline voltage (V_b) and the capacitor charges to V_b. Accordingly, the baseline counter value N_B is measured by charging the capacitor from V_b to V_{IH} and decrementing the counter value from N_0. The capacitor is then fully discharged. When a gas is applied the response reaches an equilibrium steady state peak value (V_p). Similarly, the capacitor charges to V_p and the counter value N_P is determined. For refreshing the sensors air is used when the responses comes down from V_p to V_b again the capacitor also discharges as shown in Fig. 5. At this point the counter value is also decremented from N_P to N_B again. The two counter values N_B and N_P are stored in the microcontroller and a PC for calibrating in terms of the change in response voltage $(V_p - V_b \approx N_P - N_B)$ which is proportional to the change in conductance of the gas sensors.

This process of determining the differential counter value is repeated for the three gas sensors (TGS 2201, TGS 2620, and TGS 832) for four chemical gases (acetone, acetic acid, methanol and 2-propanol) to generate a database for gas classification using two classification paradigms- Linear Discriminant Analysis (LDA) and ANN. A total of 50 feature data were generated for the three gas sensors and four gases $(3\times4\times50)$.

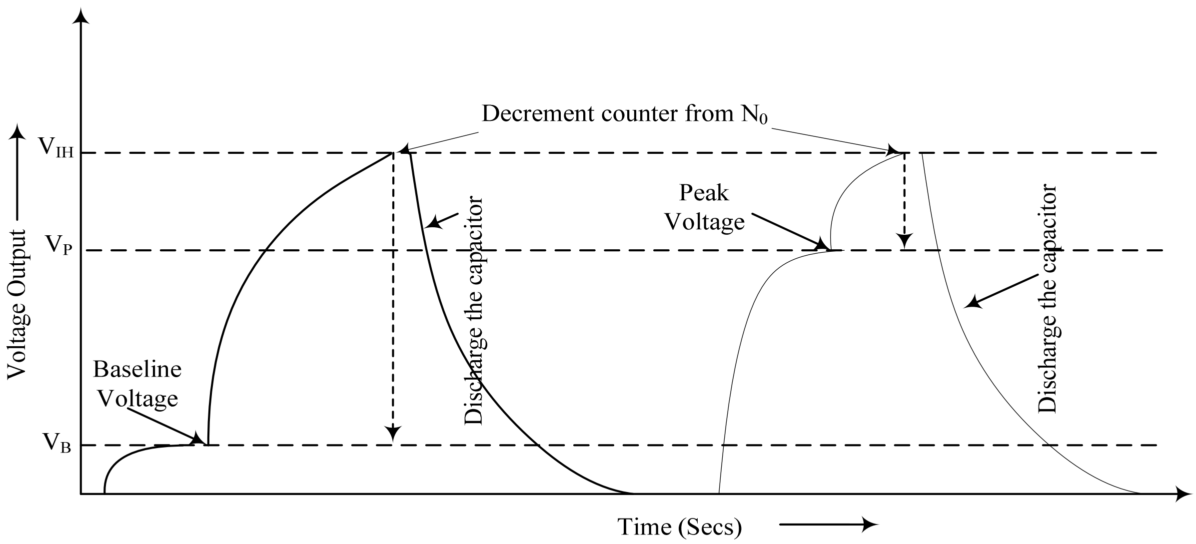

Fig. 5. Capacitor charging-discharging.

2.5. Classification Paradigms

To demonstrate the discriminative capability of the measured data of the DI circuit we have used pattern classification algorithms are used. The feature data is used in an unsupervised classification algorithm- LDA where it models the difference between data class by maximizing the ratio of intra-class variance to the inter-class variance. The LDA based transformation of the feature data is used to generate a graphical 2-D plot to examine the cluster separation. Since LDA is used only as a graphical aid to observe the cluster existence, the main objective to recognize gas samples is demonstrated by a supervised pattern recognition model- Feed Forward Back Propagation (FFBP).

The network is trained prior in MATLAB to obtain the optimum performance parameters such as weights, biases, number of hidden neurons etc. The ANN is modeled in the microcontroller using the parameters through embedded C programming to identify different gases.

3. Results and Discussion

As mentioned in section 2.1 DI circuit was calibrated by measuring the counter value produced for a varying analog voltage. Fig. 7 shows the counter values generated in the MCU for analog input from 0 - 1.7 V and compared with the ideal values of a 12 bit ADC. The counter value is measured up to the maximum voltage approximately equal to that generated by the sensors on exposure to gases.

To perform real time gas classification, the DI circuit based gas sensor array was interfaced to the MCU and counter values were produced for four chemical gas samples. A spider plot of counter value from the gas sensor responses is shown in Fig. 8, which depicts the sensors behavior to the four tested gases.

The features from each sensor are used to design the LDA algorithm, which forms four none overlapping and distinctive clusters of the four tested gases. The plot of LDA shown in Fig. 9 illustrates the relationship and trends of the E-Nose array to different gases. The LDA analysis elucidate that the DI method of counter value measurement can be effectively used for gas classification analysis.

Since the main objective is to identify the four gases correctly by using the DI based E-Nose, FFBP ANN classifier was used. The classifier uses a total of 50 feature sets (N_f) that were measured using DI method by the three sensors (N_s) for the four gases (N_g) forming a total data set of size $N_f \times N_s \times N_g$ $(50\times3\times4)$.

The dataset was divided for training and testing in the ratio of $60:40$ and a three layer FFBP model was designed in MATLAB (Fig.6) with one hidden layer. The performance of the ANN was evaluated changing the number of hidden neurons.

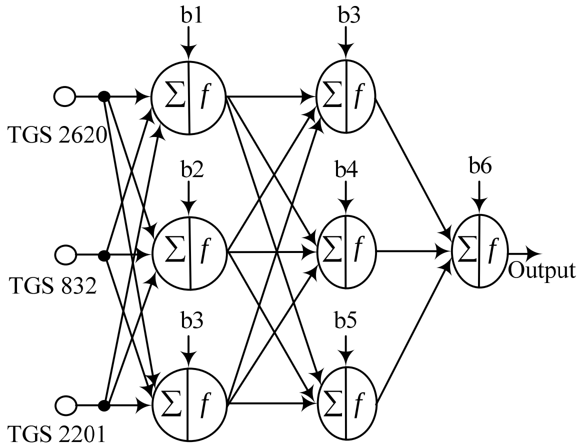

Fig. 6. FFBP ANN model used.

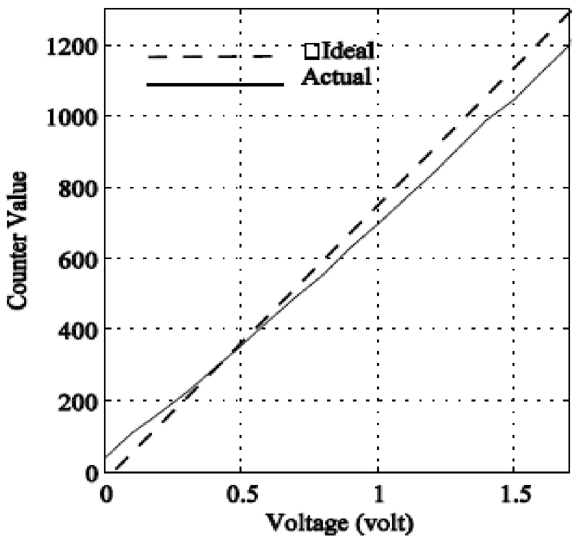

Fig. 7. Counter output of DI circuit in Fig. 1.

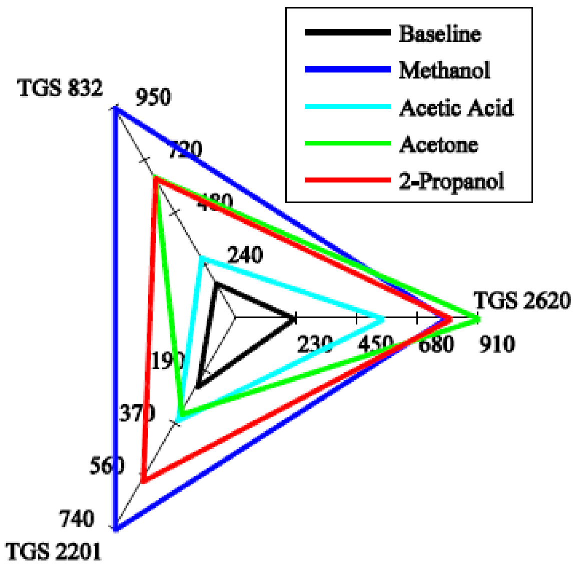

Fig. 8. Spider plot of sensors responses when exposed to different gases.

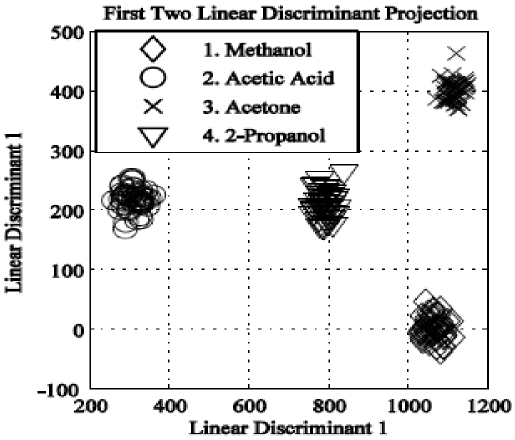

Fig. 9. LDA analysis.

Then the optimal number of hidden neurons were calculated and found to be $n = 3$ which gives classification accuracy up to 98.75 %. Table 1 shows the performance parameter of the FFBP ANN with n=1, 2 and 3. The algorithm of the optimal FFBP model with $n = 3$ is then coded in the microcontroller to perform on-line gas discrimination by the DI based E-Nose. Table 2 shows the counter value measured by the DI based E-nose circuit and the ANN output error produced by the microcontroller. The result shows that the errors are within the range of acceptable limits.

The confusion matrix of the test results of the DI E-Nose is shown in Fig. 10 which informs about the individual class accuracy as well as overall class accuracy.

Table 1. ANN performance parameters with n=1, 2 and 3.

Data Size	Hidden Neuron (n)	Computational time (s)	No. of Epochs	Percentage Accuracy (%)	Mean Squared Error (M.S.E.)
$4\times50\times3$	1	16.64	590	50	1.0701
	2	10.37	1000	75	0.1250
	3	1.61	19	98.75	5.3×10^{-7}

Table 2. ANN results for DI based E-Nose.

Gas	Sensors (TGS)	Peak Voltage	Measured Counter Value	Model Target Output	Predicted (in Microcontroller)	Error
Methanol	2620	1.1128	778	1	1.0003	+0.0003
	832	1.3575	954			
	2201	1.0591	741			
Acetic Acid	2620	0.8143	547	2	1.9999	-0.0001
	832	0.3883	276			
	2201	0.5405	357			
Acetone	2620	1.6127	1133	3	2.9999	-0.0001
	832	1.1578	809			
	2201	0.8596	600			
2-Propanol	2620	1.2429	800	4	3.9991	-0.0009
	832	0.9112	638			
	2201	0.8143	570			

		Predicted Output				
		Methanol	**Acetic Acid**	**Acetone**	**2-Propanol**	
Actual Output	**Methanol**	20	0	0	0	100 %
	Acetic Acid	0	20	0	0	100 %
	Acetone	0	0	20	0	100 %
	2-Propanol	1	0	0	19	95%
		95.23 %	100 %	100 %	100 %	98.75 %

Fig. 10. Confusion matrix.

Table 2 and Fig. 10 shows that the developed DI based E-Nose can successfully recognize the four tested gases. Moreover the microcontroller utilizes only 9 % RAM (142 bytes) and 27 % ROM (8782 bytes), which makes it feasible to adopt the proposed methodology for low cost microcontrollers.

4. Conclusions

A methodology for analog voltage measurement by DI based E-Nose was created, implemented, analyzed and tested. To check the distinctness of the system to classify different gases, feature sets were extracted and LDA is performed, which shows distinctive cluster formation of the four tested gases. The capability to efficiently classify different gases is validated through the FFBP ANN programmed in the microcontroller. These results shows that it is possible (without the need of an ADC) to effectively measure the analog voltage in form of counter value by the MCU and also the measured counter values can be used to model pattern recognition tools. The designed system showed a promising recognition rate up to 98.75 %. We have shown that the proposed DI based system will be useful for online gas monitoring and detection systems.

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