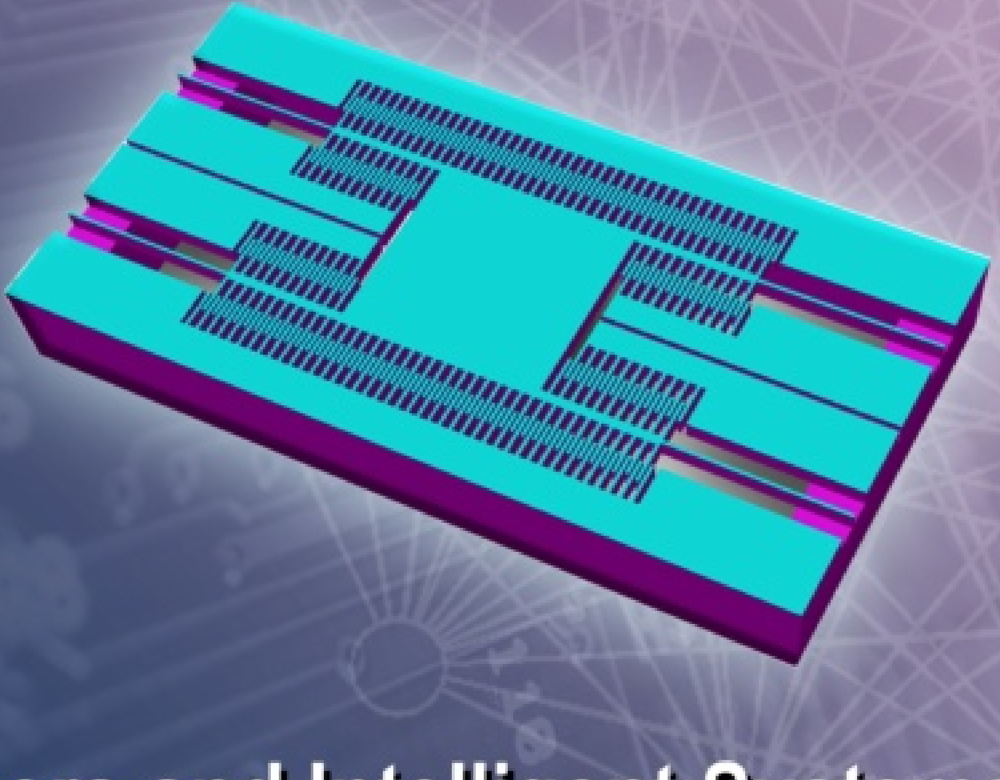
ISSN 1726-5479

SENSORS & TRANSDUCERS

12 vol. 17 Special /12



Sensors and Intelligent Systems

International Frequency Sensor Association Publishing

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Sensors & Transducers

Volume 17, Special Issue
December 2012
www.sensorsportal.com
ISSN 1726-5479

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Sensors & Transducers Journal

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Special Issue
December 2012

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ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 17, Special Issue, December 2012, pp. 50-59

Sensors & Transducers

ISSN 1726-5479

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Artificial Neural Network-based Electronic Nose for the Detection of Sulfate-reducing Bacteria

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Received: 29 September 2012 /Accepted: 29 October 2012 /Published: 18 December 2012

Abstract: The paper demonstrates a method for the implementation of an olfactory system for the detection of sulfate-reducing bacteria. The unchecked growth of sulfate-reducing bacteria causes serious microbiologically-influenced corrosion problems in various industrial systems. Conventional techniques or instruments used to detect the presence of bacteria are time consuming and require a high degree of profession skill. This work examines the potential of using an electronic nose, equipped with a metal oxide semiconductor and temperature sensors, combined with an artificial neural network, to measure and evaluate the presence of the bacteria. The input values for the neural network are represented by sensors' data set, whereas the output values indicate the presence of bacteria. This study also demonstrates the modeling techniques of a trained neural network using a Xilinx System Generator toolbox in a Matlab environment, so that the system can be implemented in a field programmable gate array for portable electronic nose applications. The preliminary design of the electronic nose and artificial neural network data processing promise a successful technique and has the potential to be an effective means of detecting the presence of sulfate-reducing bacteria. *Copyright © 2012 IFSA.*

Keywords: Electronic nose, Sulfate-reducing bacteria, Artificial neural network.

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1. Introduction

For the past few decades, experts have focused on issues related to microbiologically-influenced corrosion (MIC), which refers to the influence of microorganisms involved in the deterioration of metals. Sulfate-reducing bacteria (SRB) are among the nonpathogenic and anaerobic microorganisms that contribute to MIC problems. The metabolic activity of SRB involves the chemically reducing of sulfate to sulfide and producing compounds such as hydrogen sulfide (H_2S) (or iron sulfide (Fe_2S) in the case of ferrous metals) [1]. Previous studies on SRB show that these bacteria cause corrosion and cracking in metals and alloys used in various industrial systems. Moreover, the metabolism of SRB contributes to the biological formation of H_2S, which results in the degradation of water quality and the suppression of marine life in affected areas [2]. Table 1 lists negative effects of SRB, whereas Fig. 1 shows illustrations of such problems.

Table 1. MIC Problems at Various Industrial Systems [3].

Industry/Application	Problem Components/Area
Pipelines/storage tanks (gas, oil, water, wastewater)	- Low points in long-distance pipes
	- Dead-ends and stagnant areas
	- Exterior of buried pipelines in wet clay environments
Chemical process industry	- Heat exchangers, condensers, and storage tanks
	- Water distribution systems
Cooling water systems	- Cooling towers
	- Welded area of heat exchangers
	- Sludge build-up area of storage tanks
Docks, piers, and other aquatic structures	- Splash zones
	- Just below the low-tide line
Pulp and paper	- Rotating cylinder machines
	- Whitewater clarifiers


(a) (b)

Fig. 1. (a) Corrosion of metal at sea [4], (b) Corrosion of heating oil tank [5].

Early detection of SRB prior to further treatment is crucial to the prevention of equipment failure and costly maintenance expenses. Two fundamental techniques, namely, culturing and direct techniques, are generally used as detection methods of SRB. SRB are known to grow slowly and are generally not easy to notice [6]. Researchers have developed different growth media, such as API-RP 38, Postgate B, Starkey, and Baar's, for used in SRB sample culturing. SRB reproduce quickly in these media, such that three to seven days is enough for a sample to be dark enough to be observed with the naked eye.

Typical, culturing methods are time consuming. However, direct methods, which detect the presence of SRB cells or compounds, do not require SRB growth during testing and require less time to obtain results. However, they usually require highly profession skills or special equipment found only in laboratories. These direct methods include the APS reductase antibody method, ATP assay system, and the epifluorescene/cell surface antibody method [2]. Field test kits currently in the market usually include transparent dip slides with an SRB's growth medium. The dip slides are placed in an incubator set at a temperature between 25 °C to 30 °C. The SRB traces can be seen after one to two days. The level of SRB's growth can be seen from the SRB colony traces, as shown in Fig. 2.

The present study introduces the implementation of an electronic nose, a high sensitive instrument that provides data closely linked to results obtained from sensory panels [7]. Electronic noses are used in many applications, such as agriculture, food quality analysis, and bacteria detection. Because electronic noses devices are cost-effective, easy to build, and can provide faster analysis, these devices are widely used as an objective-automated, nondestructive means of object characterization in research and industrial applications [8].

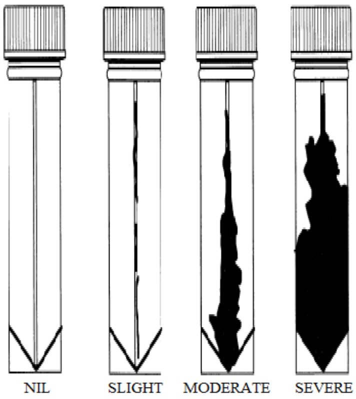


Fig. 2. Level of SRB growth in dip slides [9].

2. Materials and Methods

2.1. Sample Preparation

Sample preparation of SRB is a fundamental part of data collection in this study for the development of electronic nose. The SRB samples are enriched from sludge collected from a pond in Universiti Sains Malaysia (USM) and undergo the process of isolation and inoculation. This process takes place in the Industrial Biotechnology Research Laboratory, School of Biological Science, USM and last nearly two months. The samples are then cultured and incubated for the current research. Difco Nutrient Agar (NaCl) is used as the culture medium to enhance SRB growth. The bacteria cultures of are streaked onto the surface of the media, which are slated at a certain angle in a glass vial. The illustration of sample prepared is shown in Fig. 3.

A custom-made incubator is prepared for the cultivation of SRB. The temperature of the incubator is maintained by a heater and a cooling fan at around 32 °C, which is suitable for bacterial growth. The collected samples are placed inside the incubator and incubated for three hours for electronic nose analyses.

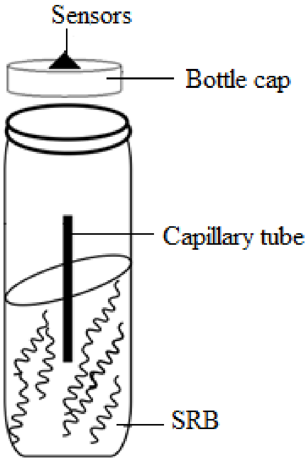


Fig. 3. Diagram of SRB samples prepared.

2.2. Electronic Nose Analysis

The samples are analyzed as follows: the vials are sealed with a suitable lid equipped with a gas and temperature sensor on the bottom surface of the cap. Three samples are placed inside the incubator and tested under the same conditions for 180 min at different time; the average signal outputs from the sensors are collected and recorded at 10-minute intervals. Preliminary experiments are carried to obtain signals of suitable intensity and good reproducibility for analyses.

The architecture of the electronic nose prototype is shown in Fig. 4. It composed of a gas sensor, (Figaro TGS 825) and a temperature sensor, (Sensirion SHT 75). The TGS 825 is a metal oxide gas sensor that uses a tin dioxide (SNO_2) semiconductor as its sensing element. This sensor has high sensitivity and selectivity to H_2S, and is capable of detecting concentrations as low as 10 ppm [10]. The resistivity of the sensor changes based on the influences of gasses: when a target gas comes in contact with the sensor surface, the sensor resistance decreases in accordance with the present gas concentration. The sensor response is expressed as analog voltage level with time. A simple voltage divider circuit, associated with TGS 825 (shown in Fig. 5) converts the variations in sensor resistance into variations in voltage. The main function of the ADC 0804 is to convert the output voltage level from the sensor device to a digital form with 8-bit resolution for field programmable gate array (FPGA) processing.

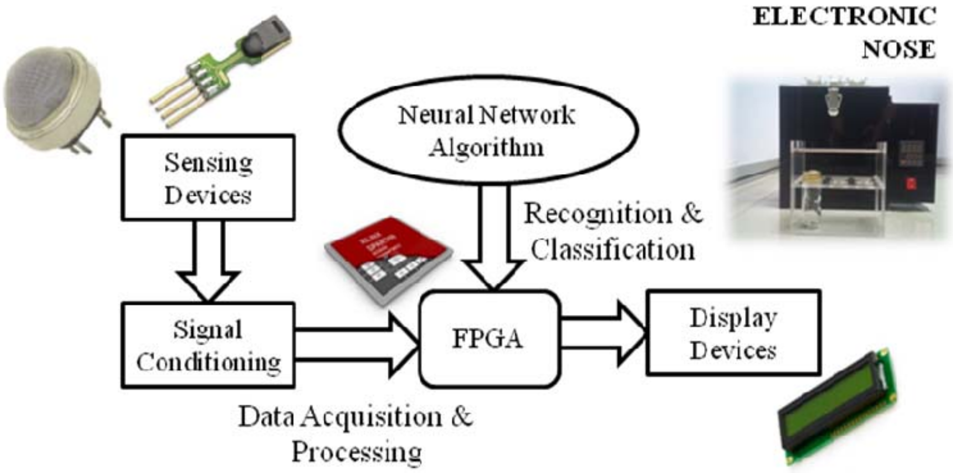


Fig. 4. Overview of the SRB detection system.

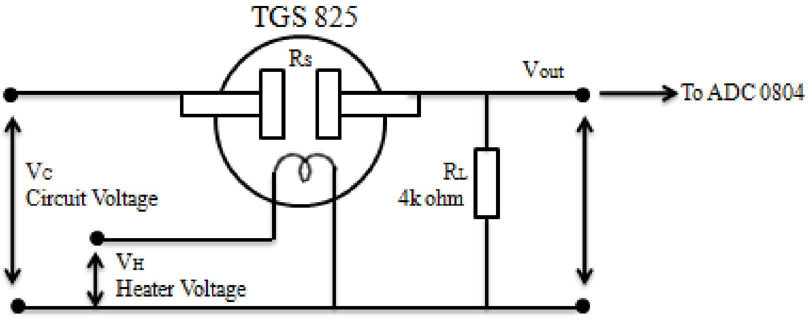


Fig. 5. Detection circuit for TGS 825 Figaro Gas Sensor.

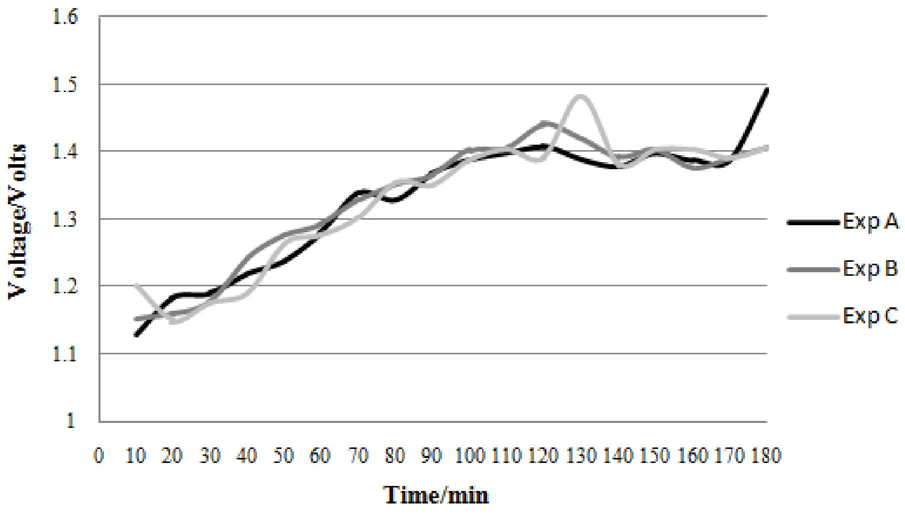
The Sensirion SHT 75, measuring temperature and relative humidity, and provides precise output as fully-calibrated digital readout data. Temperature is measured using a band-gap sensor [11]. The required signal conditioning, analog-to-digital conversion and digital interface circuitries are all integrated in the package of the sensor chip. The sensor consumes 3 mW power during measurement operations and has a temperature measurement tolerance of ±0.3 °C. All the sensor response values are used in prediction and classification studies via artificial neural network (ANN) techniques.

The responses of the electronic nose sensors obtained from the tested samples over 180 min are illustrated in Fig. 6. The analog voltage level and temperature value taken from the TGS 825 and SHT 75 sensors are displayed as increments over time. The output voltage of the gas sensor increases because of the presence of H_2S, whereas the rising temperature could be the result of heat released during the respiration process of the bacteria [12]. The obtained results undergo statistical analysis to measure the significant effects of SRB growth on output voltage and temperature. In this analysis, time is taken as controlled independent variable, and the sensor response is taken as the response variable.

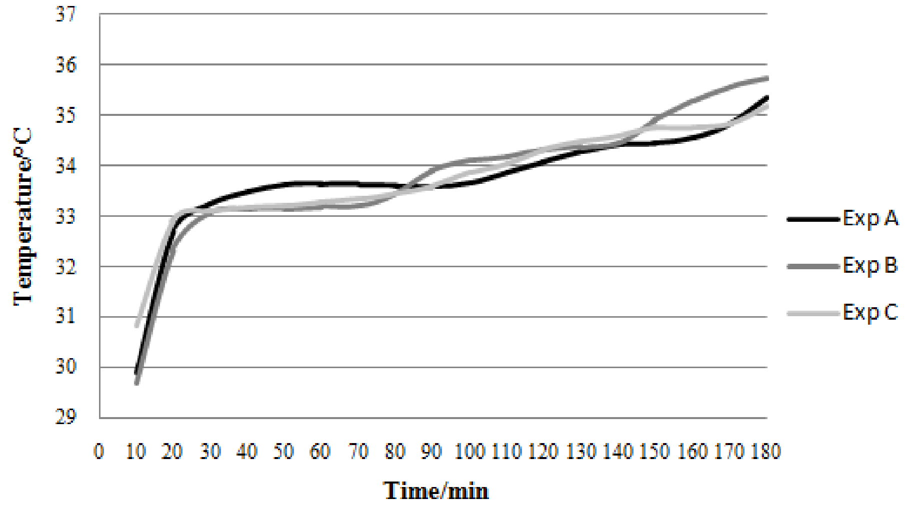
2.4. Artificial Neural Network Model

ANN is a mathematical and computational model composed of a large number of simple processors, called neurons that are highly interconnected and operate in parallel sequence. Neural network systems are capable of learning and reasoning by providing meaningful solutions for high-level complex and non-linear problems. Neural networks have been applied across a diverse range of problem domains in various engineering fields, such as pattern recognition, classification, identification, fault diagnosis, and intelligent control system.

In the present study, a multi-layer perceptron neural network is trained using the back propagation algorithm in Matlab, based on the data collected from the experiments. In the training tasks, the neural network is trained with numerous data to adjust the network weights and biases for each connection link between the neurons based on the error, until the minimum error in the predicted data sets is achieved. For the multi-layer neural network, the input layers are composed on two neurons, corresponding to the two parameters previously investigated, whereas the output layer contains only one neuron. A numerical value of one generated by the output neuron indicates the presence of SRB in the tested sample. Otherwise, the sample tested is free of SRB. A sigmoid transfer function, which is common used to reduce the possibility of overtraining [7], is used in the hidden layer of the multi-layer neural network as the neuron's activation function. This activation function transforms the input, which can have any value between plus and minus infinity, into a reasonable value between 0 and 1 [13].



(a)



(b)

Fig. 6. (a) Plot of output load voltage of gas sensor versus time,
(b) Plot of temperature sensor response versus time.

The data set for the multi-layer neural network is randomly divided into training data (70 %), testing data (15 %) and validation data (15 %). The training data is used to compute the gradient and to update the values of the weights and biases of the neural network. The validation data sets are used to minimize over-fitting and to stop the training in case of over-learning. Finally the neural network is tested using the testing data, and the detection accuracy is recorded.

2.5. Hardware Implementation of Neural Network

This study proposes an FPGA-based portable electronic nose used to perform on-site measurement. The parallel processing, computing power, and flexible interface of FPGA are expected to provide rapid results. The flow of the hardware implementation of the neural network on FPGA is illustrated in Fig. 7. Details regarding the FPGA implementation of the sigmoid transfer functions are also provided.

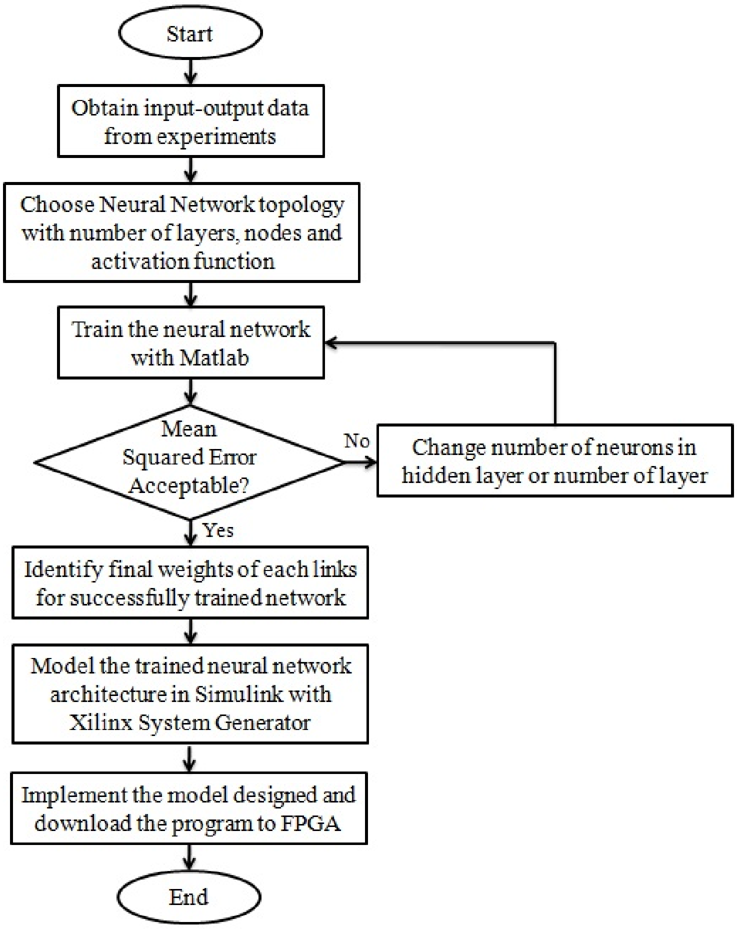


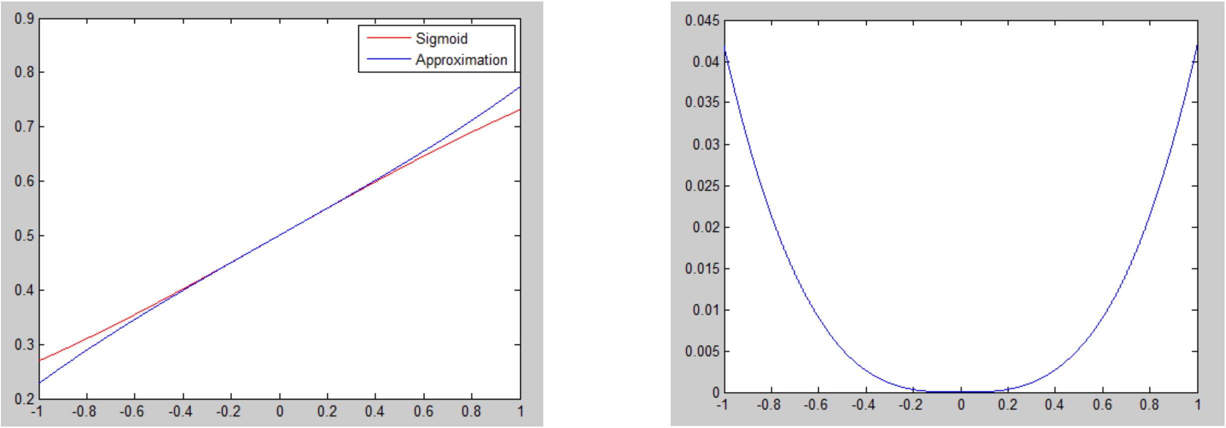
Fig. 7. Flow diagram of the FPGA neural network implementation.

The Xilinx System Generator is a high level tool that bridges model-based designs in Simulink and hardware realizations in Xilinx FPGA [14]. The Xilinx System Generator also converts models designed in a Simulink environment to a hardware description language code that can be imported into a Xilinx FPGA.

The connection weights and biases of neuron for the 2-2-1 multi-layer neural network system for SRB detection is implemented using adder and gain multiplier blocks, similar to the model design in Simulink. However, the block sets provided by the Xilinx System Generator do not have the sigmoid transfer function. Thus, the sigmoid function is modeled through the expansion of the Maclaurin power series, the infinite expansion of which can be represented as follows:

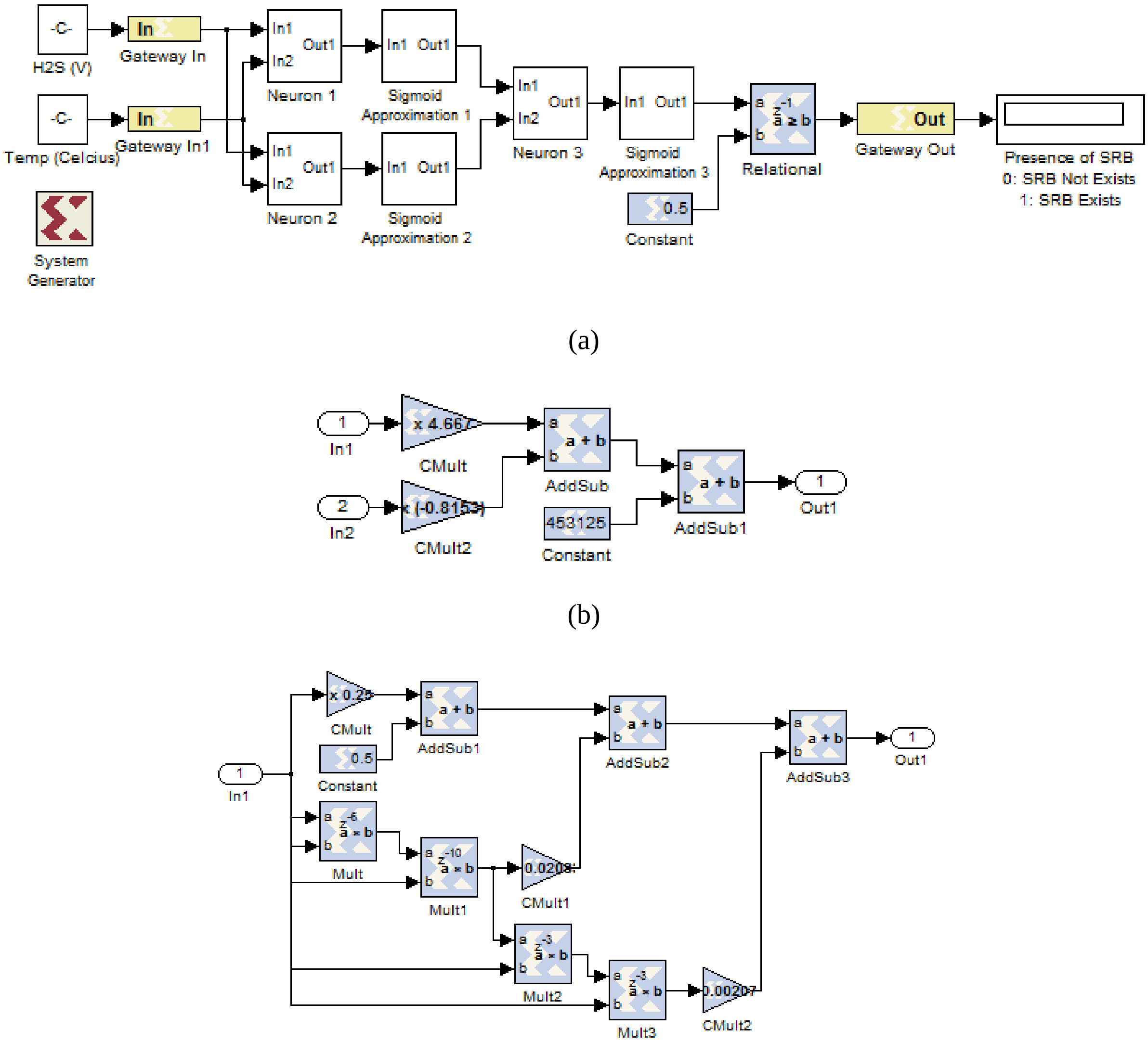
$$f(x) \approx f(0) + f'(0)x + \frac{f''(0)}{2!}x^2 + \frac{f'''(0)}{3!}x^3 \ldots. \qquad (1)$$

Typically, the expansion of power series, such as the Taylor series approximation, is able to express a function as a polynomial equation in the region where the value of x is close to a specific value. In the current study, the Maclaurin power series approximates the function of $f(x)$ when x approaches zero. The comparison between the real sigmoid function and the approximation function is illustrated in Fig. 8. Based on the plot, the approximation equation shows precise result when the value of x falls between the range of -0.5 and 0.5. In this case, the input value of each neuron in the trained neural network falls between these ranges. Thus, the Maclaurin power series expansion is found to be an accurate approximation in this study. Fig. 9 shows the modeling of the resulting function using the Xilinx System Generator in a Simulink environment.



(a) (b)

Fig. 8. (a) Comparison of real sigmoid function and approximation function, (b) Plot of error between real and approximation function versus input value, *x*.



(a)

(b)

(c)

Fig. 9. (a) Top-level design of neural network model, (b) Design of a single neuron model, and (c) Design of sigmoid Approximation function model.

3. Results and Discussions

3.1. Statistical Analysis of Investigated Parameters

Analysis of variance (ANOVA) was applied to conduct further analysis of the results from the preliminary experiment. The objective is to study the effect of a single factor on a response. In the analysis, time was taken as the factor and the output readings from the sensor were taken as the response. The results are tabulated in Table 2. The sensor response from the TGS 825 was 94.29 % influenced by time factor, as shown by the R-sq (adjusted) in the analysis, whereas the temperature was 94.80 % influenced by the time factor. In addition, the time factor or between-treatment mean square was several times larger than the within-treatment or error mean square, indicating that the treatment means were not likely to be equal. Formally, the value of P calculated for these two responses was less than 0.05 (95 % confidence level). Therefore, hypothesis H_0 was rejected. Moreover, a conclusion was drawn whereby the treatment means differ, that is, the time of incubation representing the level of bacterial growth, significantly affects the concentration of H_2S and temperature.

Table 2. Results of ANOVA analysis.

One-way ANOVA: TGS 825 Sensor Responses versus Time					
Source	DF	SS	MS	F	P
Time	17	0.454638	0.026743	52.51	0.00
Error	36	0.018334	0.000509		
Total	53	0.472972			
S = 0.02257		R-Sq = 96.12 %		R-Sq (adj) = 94.29 %	

One-way ANOVA: SHT 75 Sensor Responses versus Time					
Source	DF	SS	MS	F	P
Time	17	70.3810	4.1401	57.87	0.00
Error	36	2.5724	0.0715		
Total	53	72.9564			
S = 0.2675		R-Sq = 96.47 %		R-Sq (adj) = 94.80 %	

3.1. ANN Models Result

The simulated results of neural network system which trained using the back-propagation algorithm in Matlab is shown in Table 3. The modeling of the neural network using Xilinx System Generator toolbox indicated the success of the system in predicting and classifying the samples tested into groups, with and without SRB. The neural network system model achieved 100 % prediction accuracy.

Table 3. Simulated results of the neural network system.

Samples	**Predicted as samples**		**Success Rate**
	With SRB	**Without SRB**	
With SRB	20		100 %
Without SRB		20	100 %

4. Conclusions

The electronic nose and ANN data classification technique can be an effective means of monitoring and predicting the presence of SRB. The present study establishes the potential and possibility of using an olfactory system to detect the presence of bacteria. However, this study barely represents the first step toward creating an in-line system for monitoring and detecting SRB presences. Other factors such as pH and concentration of CO_2, can be taken into consideration to determine the presence of SRB for future development. For these, further research and calibration tests are required. Since the processing unit of the electronic nose is implemented using FPGA, it allows more complex and robust neural network system, which involve more parameters, to be developed.

Acknowledgements

This work was supported by the Ministry of Higher Education (MOHE) through a research grant (Grant No. PRGS 203/PCEDEC/6740004). The authors are grateful to the Universiti Sains Malaysia for allowing access to their facilities.

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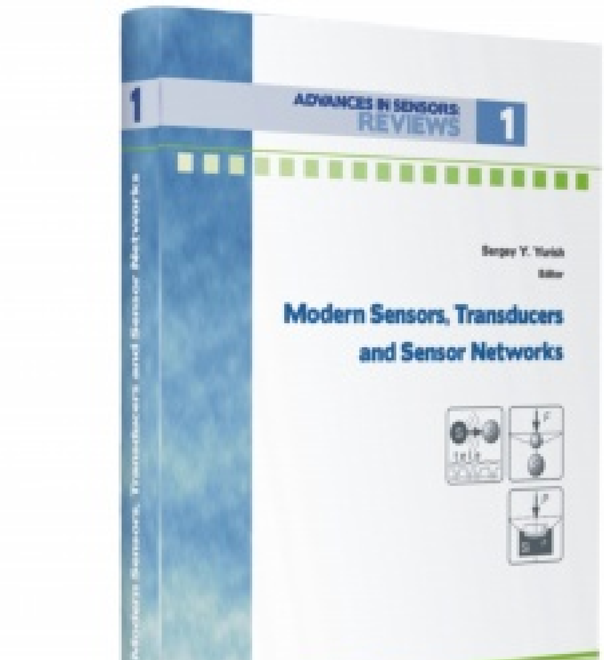

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