GAS ANALYSIS SYSTEM BASED ON ARTIFICIAL NEURAL NETWORKS

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Abstract - *The paper presents the design and implementation of an automated system for the analysis of gas mixtures. Using low-cost, non-selective gas sensors in combination with signal processing algorithm based on artificial neural networks, the prototype system is able to correctly classify three combustible gases (methane, isobutane, and hydrogen) and to indicate when the total gas concentration in the air exceeds a preset alarm point. The system is designed using LabVIEW and virtual instrumentation concept and is capable of performing on-line analysis of gas mixtures.*

Keywords – gas recognition, gas sensors, artificial neural networks, LabVIEW

1. INTRODUCTION

Compact, automated systems capable to determine gas components in the atmosphere, be it individual gases or gas mixtures, are of great importance in a wide variety of applications [1,2]. Very often is not necessary a complete analysis in terms of exactly quantifying gas components in the analyzed atmosphere, but rather the detection, the identification and approximate quantification of a gas present in the air.

Since such a system is capable to "smell" and recognize different vapors or odors, it is generally called an "electronic nose". There are various applications in which an electronic nose may be used, from the product and process control, analysis of fuel mixtures through to the environmental monitoring of pollutants and diagnosis of medical complaints [3].

A gas analysis system can be regarded as a modular system, comprising two main components: sensing system and automated pattern recognition system (Fig.1). The sensing system can be an array of several different sensing elements (chemical sensors) which detect the vapor and transduce the chemical quantity into electrical signals.

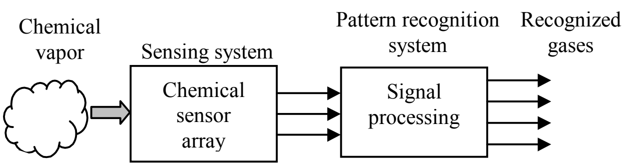

Fig.1 – Block diagram of a gas analysis system

When each sensor in the array is designed to respond only to a specific analyte, the number of sensors must be at least as great as the number of gases being monitored. Also, it is both expensive and difficult to build highly selective chemical sensors. A solution is to use low cost metal oxide semiconductor sensors, "broad range" devices designed to respond to the widest possible range of toxic and combustible gases. The principle of detection of these sensors, based on the change of sensing element conductivity with ambient atmosphere, offers only little selectivity. Therefore, a metal oxide gas sensor can detect various chemicals with different sensitivities. An array of several different sensors can yield more information than single measurements. Indeed, the low selectivity of the individual sensor turns into an advantage because, contrary to gas specific sensors, more gases can be detected than there are sensors in the array.

When a gas is presented to the sensor array, a signal pattern typical of the gas is obtained. By presenting many different chemicals to the sensor array, a database of labeled patterns can be built up. These sets of data allow the detection and recognition of gas components in gas mixtures.

The quantity and complexity of the signal generated by the sensor array can make conventional analysis difficult. Various parametric and non-parametric pattern analysis techniques have been used to process these data. These include linear and non-linear techniques, such as discriminant function analysis, principal component analysis, artificial neural networks, and fuzzy logic.

Our laboratory is currently involved in the research and development of automated gas analysis systems. The gas detection elements used in our experiments are tin-dioxide sensors (Taguchi type) obtained from Figaro Engineering Inc. As data processing technique for data analysis and pattern recognition we use artificial neural networks (ANN). One advantage of the neural algorithms is that most of the intense computation takes place during the training process. Once the ANN is trained for a specific task, operation is relatively fast and unknown chemicals can be rapidly identified. The association of these signal processing techniques with the virtual instrumentation concept are showing promising results in gas analysis.

In this paper we present a prototype gas analysis system developed in our laboratory to identify and quantify analytes in mixtures of gas.

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2. ARCHITECTURE OF GAS ANALYSIS STATION

A PC-based platform was implemented to develop and test gas analysis applications. Based on the virtual instrumentation design, the system is constructed in modular way that permits to test various types of sensors and to be easily extended for more sensors. The idea has been to implement a system that enables to investigate the most significant phenomena in gas analysis: non-linearity, cross-sensitivity, temperature and humidity influence, and stability.

As shown in Fig.2, the main components of the gas analysis station are:

- sensing devices
- gas mixing equipment
- sensor interface
- PC monitoring system.

To analyze a wide variety of chemicals, several types of Taguchi gas sensors from Figaro Co. are used in our applications: TGS813, TGS842, TGS2610, TGS2611, TGS109 (for combustible gas detection), TGS821 (high selectivity to hydrogen), TGS203, TGS2442 (for carbon monoxide detection), TGS822 (for solvent vapor), TGS 826 (high selectivity to ammonia), AMS800 (air quality control) [4,5].

As presented in [6], the detection principle of Taguchi type sensors is based on the increase of sensor's conductivity depending on the gas concentration in the air. A simple electrical circuit can convert the change in conductivity to an output signal, which corresponds to the gas concentration.

Because of this principle of operation, the sensor sensitivity is altered by the change of the ambient temperature and humidity. To monitor and compensate these influences, temperature and humidity sensors are used in our experiments (5KD-5, 8KD-5 termistor from Ishizuka Elec. Co and NH-2 humidity sensor from Figaro Co.).

A static method is used for calibration and testing of devices. The sensors are placed in a special designed gas chamber, 5.4 liters volume. The analyzed chemicals are injected in the gas chamber using a standard syringe that enables to set with precision a certain concentration of gas. High purity gases from Sigma-Aldrich Co. are used in experiments. A mixing fan improves the quality of the mixture in the gas chamber. The main advantage of this static calibration method is the avoiding direct gas flow onto the sensor, which would cause a false high reading.

A sensor interface performs the conditioning of signals obtained from gas, temperature and humidity sensors, converting the change in sensors resistances to output voltages.

These signals are then digitized and fed into the computer (laptop) using a data acquisition board (DAQ), National Instruments DAQCard-AI-16E-4 type. The DC voltage source (+5V) accessible to 8 and 14 pins of DAQ is used to supply the gas sensors heaters and the conditioning circuits.

LabVIEW5.1 software is used in interfacing, acquisition controlling, and data processing [7,8]. With the capabilities of the LabVIEW environment, the gas analysis station has an open architecture, giving the possibility to expand data acquisition, control, and processing needs easily, and in this way to develop and test various applications of gas analysis.

3. PROTOTYPE GAS ANALYSIS SYSTEM

A prototype gas analysis system developed with the experimental platform presented above is described in this section. Three combustible gases have been considered as pollutants in our application: methane, isobutane, and hydrogen. Since explosions of such gases have been the cause of many disasters (e.g., in mines), their detection and identification is a very important task.

Our system was designed to detect and recognize these gases and to indicate the exceeding of a preset concentration level. It not performs a precise quantification of gas concentration, but signals any deviation from a critical level or from the usual ambiance of a process. The main task is to analyze mixtures of air with these three gases and to perform a correct classification especially when two or three components are present in the mixture.

An initial four-sensor array was simplified to three sensors after first experiments: TGS813, TGS842, and TGS2610 offer enough information for analysis. All sensors can detect the three analyzed gases, but have specific sensitivity characteristics.

When a chemical vapor is blown over the sensor array, the three sensors respond with an unique pattern (signature). A data analysis algorithm based on artificial neural networks (ANN) was designed and used to analyze the sensor array patterns in parallel in order to identify the gas components.

The first step in the development of the gas analysis system was to establish a data set for ANN training. For this

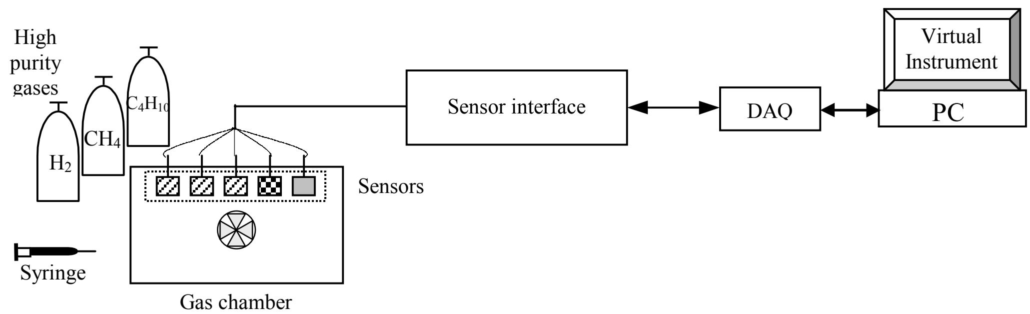

Fig.2 – Architecture of the gas analysis station

purpose, various mixtures of the three gases with concentrations in the range 500ppm-10000ppm were presented to the sensor array. A LabVIEW5.1 virtual instrument (VI) with two operation modes was developed to perform this calibration process.

In the first operation mode, the VI acquires continuously the signals obtained from gas, temperature, and humidity sensors. Characteristic parameters of TGS813, TGS842, and TGS2610 gas sensors are calculated for each settled concentration of gas and the results are saved in data files. In the second operation mode, the VI displays the sensors sensitivity characteristics for each gas or mixture of gases. The front panel of the VI in characteristics view mode is presented in Fig.3. Since they are linear on a logarithmic scale, each sensitivity characteristic was obtained with a minimal number of points. Using the LabVIEW graphical analysis tools we can extract from these characteristics a large number of training pairs, with a minimal number of gas mixtures in the calibration process. In this way, the number of known gas mixtures used in experiments was reduced from several thousands to 320 for the same training set.

Once the training data set was established, we developed the gas identification algorithm. A multilayer perceptron (MLP) neural network was designed in Matlab5.3 to perform the role of gas recognition and classification [9]. The choice of the number of neurons in each layer was an important point in defining the ANN. The size of the input layer is dictated by the number of sensors (N=3) and the size of the output layer is determined by the number of analyzed gases (M=3). The sensor responses have been normalized to the measured range. Thus the numerical values of ANN input and output signals are restricted to the range (0,1). To obtain the best accuracy of classification, we have explored different structures of ANN and the number of hidden neurons has been adjusted experimentally.

The network has been trained with Levenberg-Marquardt backpropagation algorithm using a large training data set obtained from the sensor array characteristics. The experiments have shown that in our case the optimal structure of ANN is 3-11-3, with 0.01 learning rate and 0.9 momentum constant.

The ANN has been tested on 25 samples with different concentrations and different mixtures of the three gases. The temperature and humidity compensation functions were not included in the neural processing algorithm. This allowed the ANN to generalize well on the test data set. In Fig.4 several examples are presented with sensor array responses and the ANN classification for some test gas mixtures.

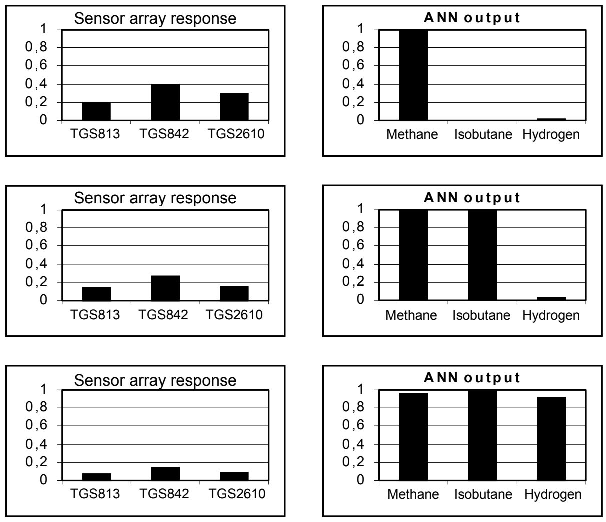

Fig.4 – ANN classification examples for different gas mixtures

Once the ANN is trained, the obtained parameters (weights and biases) are frozen and saved in data files. The neural processing algorithm has been implemented into a LabVIEW VI. This solution has given us the possibility to perform real-time processing of the acquired data. Using this method, most of the intense computation takes place during the training process. Once the ANN is designed for gas component recognition, operation consists of propagating the

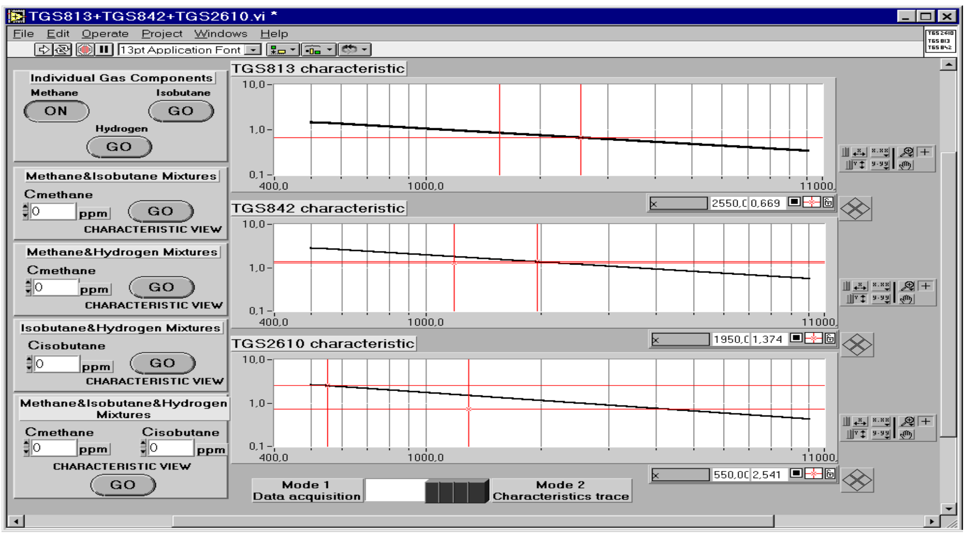

Fig.3 – Virtual instrument for sensors characteristics tracing

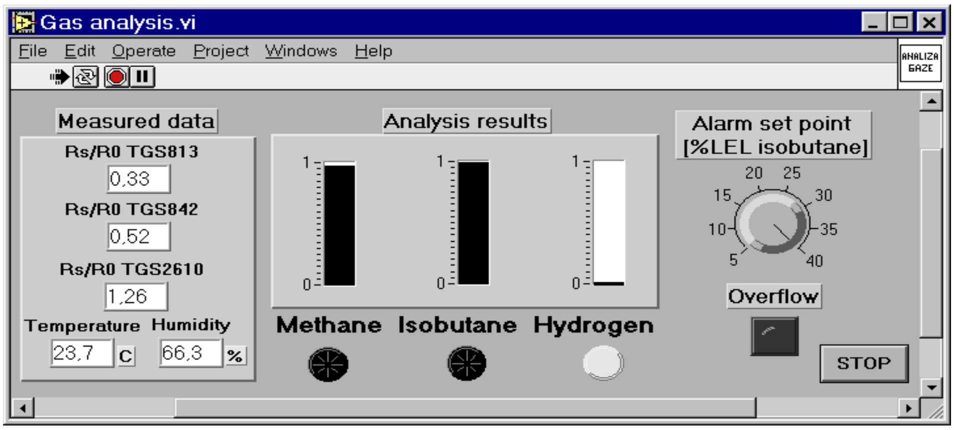

Fig.5 – Gas analysis virtual instrument

measured data through the network integrated in LabVIEW. Since this a simply series of vector-matrix multiplications, unknown gases can be rapidly identified.

Finally, a LabVIEW VI has been designed and implemented to perform the gas analysis functions: signal acquisition, gas identification, pollution level checking, and results display. Each function is realized by a module (subVI) that can be programmed and executed independently. This modular design concept simplifies the program debugging and facilitates its reusability. The front panel of the main VI is presented in Fig.5.

Besides the recognition of gas components in the analyzed mixture, the VI is designed to check the total gas concentration in the air and to indicate when the pollution level exceeds a preset value. User can set the critical threshold of gas concentration from the VI front panel. The alarm set point is expressed as percentage of isobutane lower explosive limit (%LEL).

A special module (subVI) has been implemented to compensate the influence of temperature and humidity on the gas sensors responses. The compensation algorithm was developed on the basis of dependency characteristics obtained in the calibration step.

The prototype gas analysis system has been tested in laboratory on a variety of known mixtures of the three gases (methane, isobutane, and hydrogen). The results are satisfactory from the practical point of view, the performance of the system being 98.7% correct identification on the test set.

4. CONCLUSION

The prototype gas analysis system proposed in the paper is capable of making the recognition of gas components in three gas mixtures and estimation of total gas concentration with good accuracy. The obtained results have shown that the combination of an array of three partially selective gas sensors with a signal processing algorithm based on MLP artificial neural network can be used to analyze three chemicals (methane, isobutane, and hydrogen). The virtual instrumentation design provides an open architecture for incorporating new analysis functions for future system expansion. LabVIEW graphical programming language offers powerful tools for data acquisition and processing needs and simplifies the ANN training process, by reducing the number of calibration points.

Further work will involve developing other neural processing algorithms in order to extend the gas analysis system for more gases and to perform a quantitative estimation of gas concentration.

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