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IPNOSE: A PORTABLE ELECTRONIC NOSE BASED ON EMBEDDED TECHNOLOGY FOR INTENSIVE COMPUTATION AND TIME DEPENDENT SIGNAL PROCESSING

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ABSTRACT

Recent developments in computer technology have made possible low-cost integration of powerful computers in small volumes. Here we suggest the integration of a small form factor computer for an electronic nose system. This concept allows us to seamlessly implement arbitrary temperature modulation for tin-oxide sensors, remote connectivity, large data storage, and complex signal processing.

1 INTRODUCTION

Gas sensors used in electronic noses are based on broad selectivity profiles, mimicking the responses of olfactory receptors in the biological olfactory system [1]. The basic building blocks of a generic electronic-nose systems include sample delivery, sensor chamber, signal transduction and acquisition, data preprocessing, feature extraction and feature classification. In conventional systems, the processing module is a personal computer separated from the remaining parts of the system. This module is responsible for data preprocessing, feature extraction and classification. Significant efforts are required to improve the overall performance of the instrument, and every component mush be given careful consideration.

An alternative and effective approach to large sensor arrays is to modulate the operating temperature of a small number of tin oxide sensors. Excitation of the sensor at multiple temperatures during exposure to the analytes is asymptotically equivalent to having a large number of virtual sensors with different selectivities [2-4]. However, this solution is not convenient for portable systems, as it requires large memory allocation for each temperature-modulated waveform. In addition, feature extraction becomes more involved than in isothermal DC measurements, increasing the computational load of the computer system.

In terms of signal-processing requirements, all the available options summarized in Table 1 have to be analyzed when designing a temperature-modulated electronic nose system. Considering recent trends in portable computing, the use of embedded systems at reasonably low cost and size is the most effective solution. This type of systems can be applied not only for portable devices but also for at-line analyzers, significantly improving the capabilities of the instrument. In this article we present a portable

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electronic-nose system based on two design requirements: (1) signal-processing capabilities for temperature-modulation of metal oxide sensors and (2) remote operation through network connectivity.

Table 1. Summary of available architectures

Architecture	bits / speed / RAM	Pros/cons	Programming	Appropriate Processing
Sensor Array + µC (PIC)	8 bit / 10 MHz / kbytes	Easy, small, low power, Cheaper	ASM / C	Easy algorithms, k-NN, easy NN, mostly trained off-system. Linear classifiers.
SA + µP or DSP	16-32 bit / 20-100 MHz / Mb	Fast Portable RealTime Oriented	ASM / C / C++	Linear matrix ops, (PCA, LDA, PCR, PLS), k-NN, small NN and FIS. Standard Feature Extraction/Selection
SA + Embedded PC	32 bit / 80-233 MHz / Mb	Fast, medium size, Portable, Huge data capacity	Any	Complex Learning algorithms (GA, NeuroFuzzy Systems, Mixture Models, APR). Adv. Feature Extraction/Selection
SA + Desktop PC	32-64 bit / 700MHz /Mb	Fast, medium size, Huge data capacity, Not portable	Any/ Visual	Any

2 INSTRUMENT DESCRIPTION

The use of embedded technology provides several interesting benefits: availability of an abstraction layer for signal acquisition and control via an operating system, high level programming of the signal processing algorithms, large data storage in solid state disks, commercial-off-the-shelf hardware for Ethernet connectivity, serial ports, hardware for interfacing various types of displays, etc. Our implementation uses an embedded computer system based on the PC/104 standard [5]. This consortium defines compact size self-stacking modules (3.6 x 3.8 in) and a PCI bus across the stack. A small data-acquisition and relay board provides sufficient I/O to control the e-nose and acquire the signals. The Single Board Computer (SBC) is based on an Intel-code-compatible processor, allowing code development, debugging and testing to be easily done on a desktop personal computer. Various operating systems are available, including Microsoft NT embedded, Windows CE, or open source UNIX-clone Operating system (e.g., FreeBSD, GNU/Linux [6]). The open source option was selected due to the availability of the source code, which allows the developer to customize the operating system to meet hardware constraints.

An overview of the design is shown in Figure 1. The instrument can control up to three sensor modules. Each module consists of four metal oxide sensors, one temperature sensor, and signal conditioning/excitation electronics on a custom printed circuit board (PCB). The sensors and a stainless steel chamber are mounted directly onto the PCB. The electronics can interface various commercial sensors, including FIS, FIGARO, MICROSENS, MICS or CAPTEUR via configuration jumpers, although in the current prototype only FIS sensors are used. These sensors (SB series) present an internal structure based on a micro-bead of sensing material deposited over a coil. This structure provides the sensors with a fast thermal response to a modulating heater voltage, a very practical feature for the purpose of increasing sample throughput.

The flow injection system consists of a multi-channel manifold with one electro-valve for each intake port. The software controls both the order and the aperture time of each valve and the pump, as defined in a configuration file. The reference channel includes a zero-filter for air cleaning. The output of the manifold connects directly to the sensor chamber. The system operates in a vacuum mode by means of a miniature pump connected downstream for the sensor chamber. A check valve is placed between the chamber and the pump to prevent backflow.

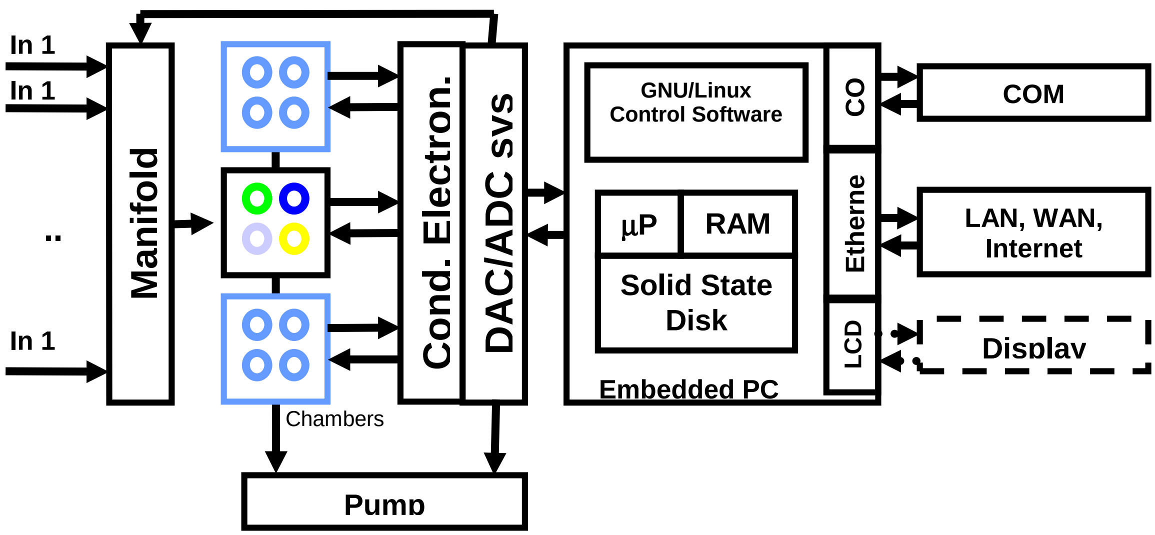

Figure 1. ipNose system overview

The embedded computer represents the core of the system. A PC/104 data-acquisition module is used for acquiring the signals of the sensors and generate excitation waveforms. A separate relay module is responsible for driving the pump and the solenoid valves. The use of a Linux open source operating system provides the instrument with classical UNIX features like multitasking, shared libraries, TCP/IP networking or even multi-user capabilities. Configuration parameters for the instrument are stored in text files. These configuration files allow the user to define various parameters, including the number and duration of the cycles, sampling rates, cycle configuration (pumps, valves, PWM channels...), and arbitrary heating profiles. The use of high-end computing hardware allows complex multivariate analysis of high-dimensional patterns such as those typical of temperature-modulated metal-oxide sensors. Arbitrary temperature profiles can be easily programmed or uploaded into the system as text files (e.g., generated with MATLAB). The use of solid-state hard drives allows the system to be used as a portable intelligent volatile detector, as well as a data-acquisition instrument for processing data in the laboratory. Remote connectivity provides additional functionality for distributed sensing and control applications.

3 REMOTE OPERATION

Recent trends in industrial automation and process control show a progressive increase of embedded computing technology, indicating a migration from proprietary instrumentation networks towards standard Ethernet networks. The idea of providing remote connectivity to an electronic nose is geared towards expanding the market for these instruments for industrial applications and distributed sensing.

Our design provides a versatile, re-programmable platform for remote operation. Incoming remote connections are processed with a daemon (a background process), denoted by ***smelld*** in the current implementation. Once a connection is established, commands can be sent to the instrument to perform sampling or training, obtain current sensors values, change heater voltages, control pump and valves, or even re-program the instrument. As illustrated in **Figure 2**, these features allow the user to perform log analysis, extract or modify internal database parameters, or change signal processing software of a distributed system of ipNoses from any workstation. Although the e-nose system is remotely operated via TCP/IP under a client/server architecture, it can also be configured to send active signals to external systems (e.g., e-mail the user when samples do not match specifications).

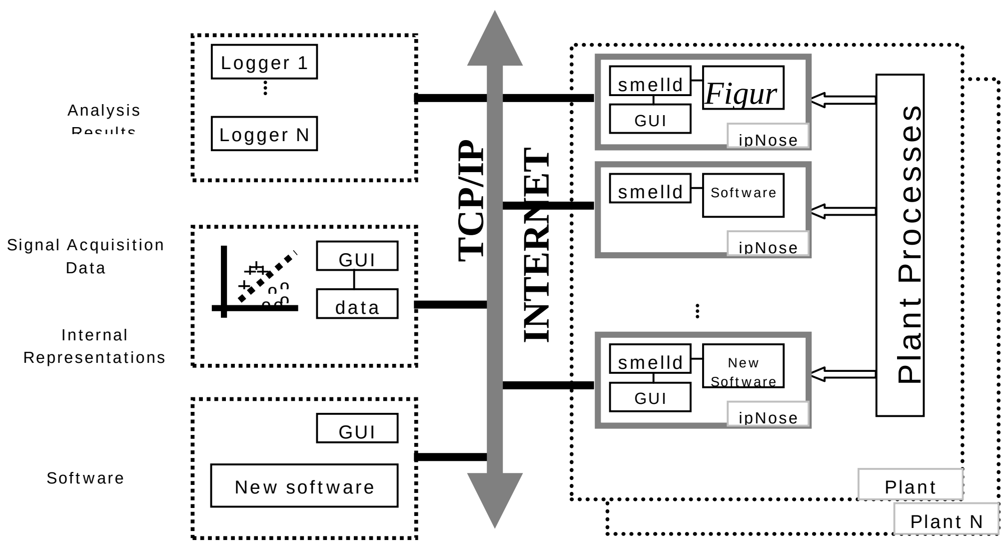

Figure 2. Schematic model for remote connectivity

4 FUNCTIONAL EXAMPLE

In this section we illustrate the pattern-recognition capabilities of the ipNose. Shown in Figure 3, a database with four odors was collected using a pulsed heater profile on four FIS sensors. Each sample consisted of five cycles, as defined in a sampling-protocol configuration file. A cleaning cycle (e.g., a washing analyte) was first applied to remove volatile compounds from the chamber, followed by two reference cycles (e.g., a zero-filter). The reference waveform may be used to compensate for sensor drift. In the remaining cycles, the target odor was introduced into the chamber and the system was finally purged with filtered air. The database used for this experiment defined a sampling frequency of 8Hz and a 40-second cycle, yielding a 1600-dimensional vector per sensor.

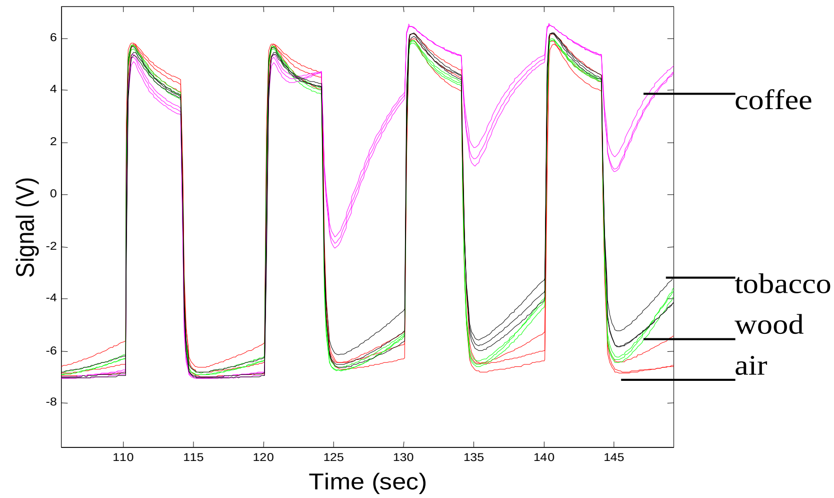

Figure 3. Detail of sample cycle

The data set was collected for three days using random presentation of the analytes. Rather than using sampling vials, the analytes were "sniffed" directly from their plastic bags by placing the intake close to the surface (3-5cm) without any additional control. In this situation concentration levels may have high variability. Pattern recognition should therefore focus on the shape of the transients rather than their DC offset. For this reason, each waveform was autoscaled. Due to the high dimensionality of the waveforms, a dimensionality-reduction procedure was used. First, principal component analysis (PCA) was used to project the data from the last pulsed cycle (320 samples/sensor x 4 sensors) onto a lower dimensionality feature space (10 dimensions). Linear discriminant analysis (LDA) was subsequently used to project onto a three-dimensional space, resulting in the scatter plot shown in **Figure 4**. The k Nearest Neighbors voting rule (k=3) was used as a classifier. Since only 17 samples per class were available, predictive accuracy was estimated though leave one out cross-validation. A classification rate of 99% was obtained on the LDA subspace, as opposed to 82% in the original signal space.

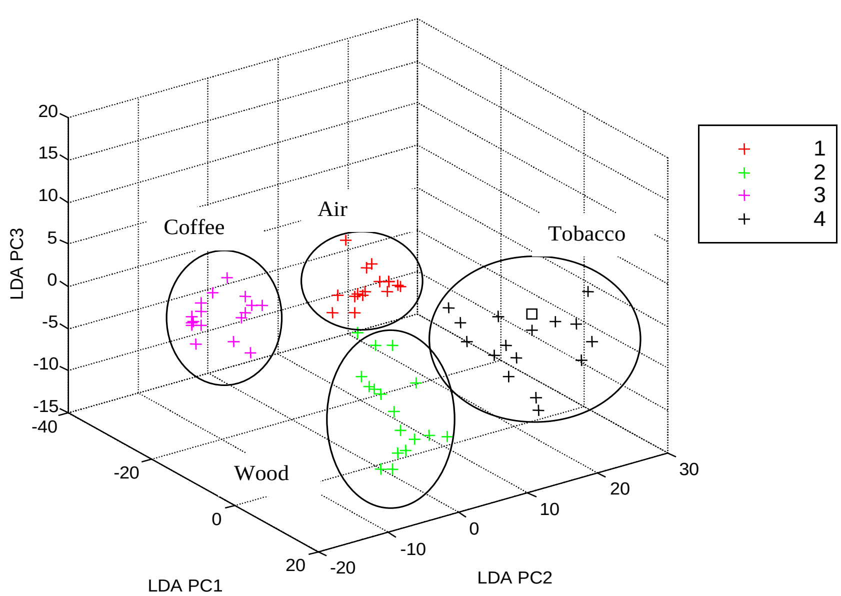

Figure 4. The first three LDA components

5 FUTURE WORK

Various aspects of the instrument are still under development. The first step is to augment the signal-processing engine, which presently includes LDA feature extraction and kNN classification. Special emphasis will be made to feature generation procedures for temperature-modulated waveforms such as windowed time slicing [7] and feature subset selection [8]. As shown in Figure 5, a PDA can be used in field tests to control the instrument, for which a graphic user interface is underway. Existing software and hardware are ready for the addition of conditioning modules such as PWM-driven temperature controllers for the sensor chamber and Tenax-traps for thermal desorption.

Figure 5. ipNose electronic nose

6 ACKNOWLEDGEMENTS

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