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High-precision intelligent interface for a hybrid electronic nose

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Abstract

At present all commercial electronic noses may be described as monotype, that is, they rely on a single class of sensing material and transduction principle such as conducting polymers or semiconducting oxides chemoresistors. However, in order to meet the emerging needs of the industry, we need to design superior instruments and to this end we have developed a multitype programmable electronic instrument. First, it can handle a wide range of sensor baseline values (e.g., three orders of magnitude of resistance). Secondly, it has a high resolution and stability with, if desired, embedded numerical temperature compensation. Thirdly, sensor signals can be mathematically pre-processed in order to enhance the discrimination power of the electronic nose. The instrument can employ resistive and piezoelectric sensors in arrays, either paired or on integrated devices, to make a multitype or hybrid electronic nose with improved dynamic characteristics.

Keywords: Conducting polymers; Electronic noses; Intelligent interfaces

1. Introduction

There has been considerable interest in the use of thin conducting polymer films as gas sensors [1], and more recently in their application to electronic noses [2]. It is highly desirable to measure ppm and sub-ppm concentrations of gases using conducting-polymer technology, but these materials tend to exhibit a relatively low sensitivity when compared with metal oxides [3], showing typical changes in resistance of 1% at ppm concentrations. This lack of material sensitivity is often coupled with a long-term drift in the sensor output and so it is necessary to design an interface circuit that has high precision and may be readily calibrated. The circuit must also cope with the wide range of polymer baseline values observed (50 Ω to 50 kΩ) yet retain a high resolution.

In addition, we believe there is some advantage in using piezoelectric conducting-polymer sensors within electronic noses [4]. At present, all three of the major commercial manufacturers (Alpha MOS, Aromascan Plc, Neotronics Scientific Ltd.) use chemoresistive sensors in a monotype nose. The inclusion of an array of piezoelectric sensors to produce a multitype or hybrid nose has a number of advantages, such as extending the olfactory range of the nose and improving its discrimination power. Again, we need to have a stable circuit that can detect changes in frequency of a few hertz in many megahertz over long periods of time.

In this paper we present a new circuit design for a hybrid electronic nose that can both measure the signals from an array of chemoresistive and piezoelectric odour sensors and implement numerical pre-processing algorithms, which render it suitable for the next generation of electronic noses.

2. Design details

Our design philosophy has been to develop a fully programmable precision interface circuit with the physical and electrical (galvanic) separation of the analogue, digital and communications parts of the circuitry, achieved by independent power supplies, and opto-isolation of critical signals. Fig. 1 shows the block schematic of the circuit, which uses a combination of standard and recently introduced analogue and digital components. It has been laid out on a two-layer printed circuit board (PCB) with plated through holes, with special attention to the relative position of all components so as to minimize unwanted cross-talk without the extra cost of using a four-layer board with ground planes and interlayer shields. The circuit has been set up to interface either two banks of sensors (six chemoresistive and six piezoelectric) or six pairs of sensors, each pair on a remote, detachable and miniature PCB. The latter configuration is aimed at using a dual resistance–mass sensor described elsewhere [5], which permits simultaneous measurements on the same polymer film. Further expansion of the number of sensors is possible in a variety of ways.

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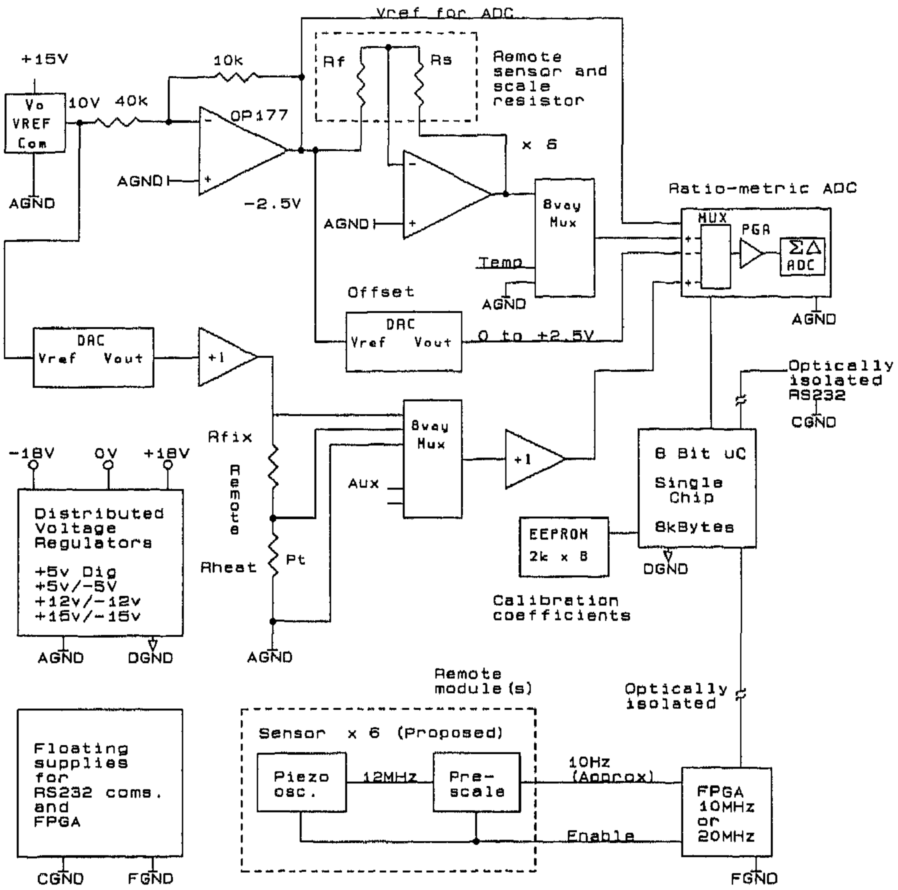

Fig. 1. Block schematic of the precision interface circuitry for a hybrid electronic nose.

During the design careful attention was given to the distribution of power supplies. Many local voltage regulators have been incorporated, since nowadays this is a cost-effective approach.

2.1. Analogue circuit for resistive sensors

A single miniature precision resistor is selected and mounted next to the remote conducting-polymer sensors so that a fixed current is injected into the conducting-polymer resistive sensor. The resultant voltage drop across the sensor is limited in this way to about 0.2 V because unwanted non-linear *I–V* characteristics have been observed in some polymers at higher voltages. To achieve the current-to-voltage conversion, a variation of a virtual earth amplifier is used which incorporates a low-pass filter. The low-pass filter (50 kHz–3 dB) is necessary to eliminate high-frequency cross-talk from piezoelectric sensors oscillating at about 10 MHz in close proximity to the conducting-polymer sensors. A 12-bit digital-to-analogue converter (DAC) provides a programmable offset to the differential amplifier incorporated within the ADC. The signals are multiplexed to sample an array of six polymers, leaving additional lines in the eight-way MUX for a temperature sensor and, say, a humidity sensor.

The common output of the multiplexer is passed to a sigma–delta charge-balancing ADC (type AD7712) with a differential input, programmable gain input amplifier and digital filter, giving a practical resolution of over 16 bits. The voltage reference used for the sensors is also used for the ADC and a ratiometric design has been achieved. This means that the absolute stability of the shared voltage reference is of no practical consequence; however, a low-drift device is used in the present design.

In addition, two temperature sensors are present (one measures the circuit temperature and the other the sensing head for compensation).

2.2. Field programmable gate array for piezoelectric sensors

A field programmable gate array (FPGA) operating at 20 MHz has been programmed to measure the time period of the output from each piezoelectric sensor to a resolution of better than one part in a million. In normal operation, the piezoelectric crystal and resistive sensing elements are situated in the flow-stream of the gas or odour and are held at a constant temperature (ideally to within ±0.1°C). The crystal oscillator circuit resides close to the coated crystal and a binary counter prescales the frequency to about 10 Hz. This low-frequency signal is received by the FPGA, which has been

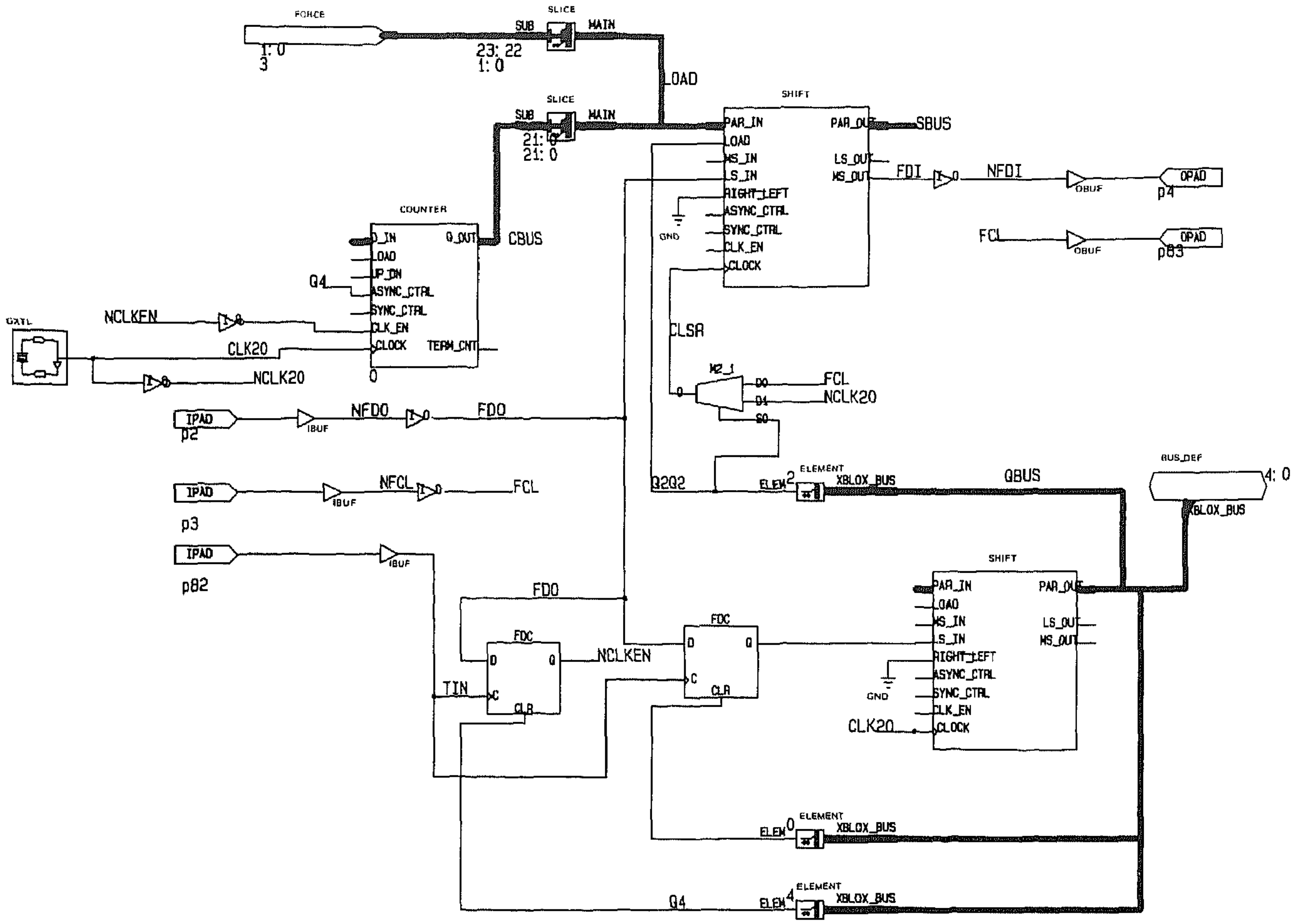

Fig. 2. Diagram showing the internal representation of the field programmable gate array.

configured to determine the period of the signal with a resolution of 50 ns. Internally a 22-bit counter accumulates the number of 50 ns periods in about 0.1 s, giving a resolution of better than 1 ppm. This approach was used rather than the more obvious method of direct frequency measurement as it means that no high-frequency signals are passed along interconnecting cables, which may result in unwanted interference with analogue stages. The FPGA is part of the logic cell array (LCA) family by Xilinx and is part XC3042A-7. The schematic diagram was created using the Foundation Active CAD software tools together with XBLOX utilities and is shown in Fig. 2.

2.3. *Microcontroller function*

The activity of the analogue and digital subsystems is determined by a single-chip microcontroller (type MC68HC705C8A). The microcontroller was programmed in assembly language to monitor an array of six resistive sensors and six piezoelectric sensors. The pin-out configuration of the 37-way D-connector is arranged so that the sensor cables can be paired and measurements made every 100 ms on dual sensors described by Ingleby et al. [5] every 0.1 s. This relatively high sampling rate allows an analysis of the transients of the sensors signals, which are influenced by the type of analyte under test and its concentration. Individual sensors can be sampled at rates of up to 100 Hz with some loss of resolution. Commands are usually issued by a host PC via an RS-232 link; however, facilities have been incorporated which permit modular construction with up to eight such PCBs in a rack-based instrument with a local host. The microcontroller has a floating-point maths package (24-bit mantissa, 8-bit exponent) and all manner of calibration coefficients can be stored in non-volatile memory (EEPROM). This allows the microcontroller to pre-process the voltage signals and compute, for example, the fractional change in resistance that is commonly used for resistive sensors [6] or the frequency shift for piezoelectric sensors.

The microcontroller not only monitors the resistance of an integrated platinum heater in a hex resistance sensor array device [7] but also permits the control of its temperature (up to 600°C) via the second DAC. The circuit is designed to run an integrated resistance heater directly.

3. Results

Fig. 3 shows a photograph of the circuit which was laid out using Cadstar version 7. At the top left is a 37-pin D-

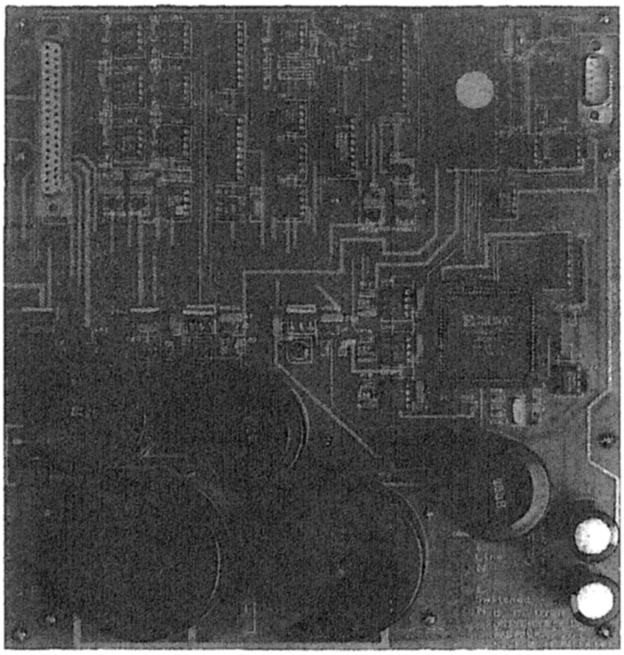

Fig. 3. Photograph of the interface.

connector to sensors and analogue resistance circuitry. At the top right is the microcontroller with a RS-232C serial communication port. Bottom left are the independent voltage supplies to the analogue and digital circuitry, and centre right the digital circuitry with FPGA.

3.1. Noise and stability of interface electronics

Fig. 4 shows the intrinsic noise recorded for a 330 Ω metal film resistor with a scaling resistor of 1 kΩ. A voltage of about 0.08 V falls across the resistor and the signal is sampled every 0.1 s. It is clear that the resistance signal is stable over a short period of time and that simultaneously digital sampling at first 4 Hz and then 400 Hz has no appreciable effect on the reading. The signals and noise levels are given for each of the three regions in Table 1.

The stability of the resistance-measuring circuitry was measured over a 17 h period at a sampling rate of 0.05 Hz to assess its long-term stability. As shown in Fig. 5, the voltage signal is stable and the noise levels are constant. The ambient temperature is also plotted and can be seen to fall by about 2°C. If desired, the microcontroller can compensate the sensor signals for the shift in ambient temperature using a polynomial equation and thus further improve upon the accuracy of the instrument.

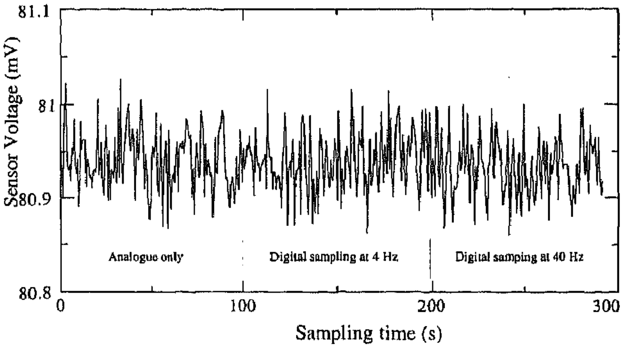

Fig. 4. Intrinsic noise of the analogue circuitry when monitoring the resistance of a 330 Ω precision metal film resistor at the end of a 1.0 m wire cable (scale resistor is 1.0 kΩ, sampling rate is 10 Hz). The plot shows that the simultaneous operation of the digital circuitry has no discernible effect on the analogue signal at 4 Hz and 400 Hz.

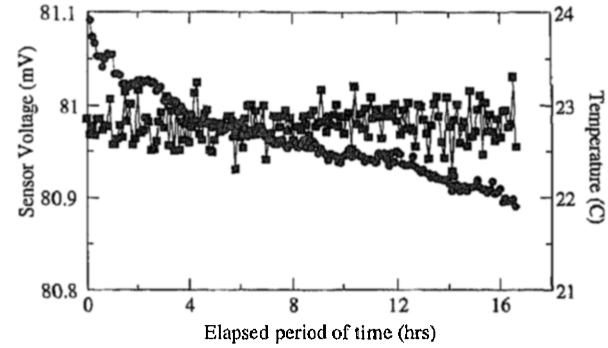

Fig. 5. Long-term stability of the analogue circuitry: the resistance is sampled at 0.05 Hz and a temperature IC (LM35DZ) shows the stability of the air temperature overnight.

The FPGA was tested using a crystal-controlled 4 Hz signal and an accuracy of one count in 2.4 × 10^6 was achieved with a 10 MHz internal circuit oscillator. The FPGA was then reconfigured to run at 20 MHz.

3.2. Response of sensors to organic vapours

Fig. 6 shows the response of a conducting-polymer resistance sensor and a polymer-coated 10 MHz crystal to 10% of the saturated vapour pressure of ethanol in air. The sensor temperature was maintained at 31 ± 0.1°C using a commer-

Table 1
Performance of resistance circuitry (voltage gain set to 1)

Parameter	Condition		
	Analogue only	Digital sampling at 4 Hz	Digital sampling at 400 Hz
Mean level (mV)	80.941	80.940	80.934
Standard deviation (mV)	0.034	0.034	0.033
Bit resolution [a]	16	16	16
Noise (% of FSD)	0.12	0.12	0.12

[a] Full-scale deflection is +0.25 V d.c.

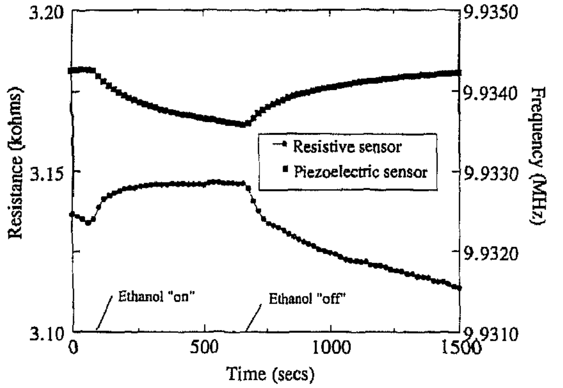

Fig. 6. Response of conducting-polymer resistive and piezoelectric sensors to a pulse of 10% saturated vapour pressure of ethanol in air at 31°C. The response and decay times are an artifact of the flow-injection system used.

cial Dri-Bloc heater and the humidity of the carrier air is controlled to ≈ ±1%. A 0.65% increase in resistance was observed and a 670 Hz fall in frequency. The plot shows that the circuit is capable of measuring sensor resistance with an accuracy of better than 0.1% and frequency shifts equivalent to 0.07% ethanol vapour (or 0.007% at a reduced sampling rate).

4. Conclusions and discussion

We have developed a high-precision programmable interface circuit for a hybrid electronic nose. The circuit is capable of measuring the response from an array of six chemoresistors with a resolution of 0.05% and an array of six piezoelectric sensors with a 50 ns resolution of the FPGA in 100 ms, i.e., less than 1 ppm. The embedded microcontroller can not only pre-process sensor signals and provide control of integrated resistive heaters in sensor array devices, but also compensate for fluctuations in the ambient temperature.

The analogue components are available in surface mount form and so, excluding the power supply, the entire circuitry can be produced on a small PCB of approximately 10 cm × 10 cm. The physical layout of our circuit permits the rapid creation of either smaller instruments of only resistive sensors or piezoelectric sensors, or large instruments containing up to 24 sensors.

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Biographies

David Dyer is a lecturer in the Department of Engineering at the University of Warwick. He has academic and industrial experience of a wide range of analogue instrumentation with digital sub-systems, and especially micropowered devices. His current research interests include the application of field programmable logic arrays and microprocessors in intelligent instrumentation.

Julian Gardner was awarded a B.Sc. (first class) in physics from Birmingham University (1979), a Ph.D. in physical electronics from Cambridge University (1983) and a D.Sc. in engineering from Warwick University (1997). He is currently a reader in the Department of Engineering at the University of Warwick and director of the Centre for Nanotechnology and Microengineering. He is an author of over 200 papers and has research interests in chemical silicon sensors, electronic noses, intelligent sensor systems and pattern-recognition techniques.