Available online at www.sciencedirect.com
ScienceDirect
Sensors and Actuators B 123 (2007) 336–343
SENSORS AND ACTUATORS B CHEMICAL
www.elsevier.com/locate/snb

An embedded system for portable electrochemical detection

Sylvia Kwakye, Antje Baeumner *

Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, United States

Received 20 June 2006; received in revised form 28 August 2006; accepted 28 August 2006
Available online 27 September 2006

Abstract

An embedded system designed to provide miniaturized electrochemical detection (miniEC) in a handheld package is described. The uniqueness of the system lies in the selection of off-the-shelf components that meet stringent requirements for high performance and low power at low cost. The design incorporates a microfabricated electrode sensor array, a potentiostat for electrochemical tests, a liquid crystal display, a four-key pushbutton interface for user input, memory for data storage and a serial connection for networking. An MSP430 microcontroller with its unparalleled low power capability is programmed to process, display and store the signal. It also transmits data to another input device such as a PC via the serial communication module using an RS232 protocol. The potentiostat applies a potential across the sensor and is also responsible for amplifying and converting the sensor current into a voltage range that the microcontroller can record. The four-button interface allows the user to cycle through the electrochemical test variables to view or change them prior to taking a measurement. The button interface also allows the user to start/stop a measurement, set the time and date, and to view a summary of archived data from previous measurements. A graphical user interface was developed so that the user can also perform these tasks from a PC over the serial communication link. The miniEC is compact (about 80 mm × 65 mm) and powered by a single 1.5 V battery (AAA or AA) and can run, for example on a single AAA battery rated at 1000 mAh continuously for 2 weeks. The design of both the hardware and software is modular, general and flexible such that differentiated products can easily be generated for applications in niche fields within a short development window.

Keywords: Potentiostat; Microcontrollers; Amperometry; Biosensors; Embedded systems

1. Introduction

Many successful miniaturized analysis systems for industrial and biomedical applications have been reported in literature over the last decade [1–5]. Apart from glucose sensors however, mass market production of miniaturized or “lab-on-chip” systems for portable applications has not proceeded as rapidly as expected. The first of such systems are just beginning to appear. Examples include the i-STAT portable analyzer [6] and Sandia’s MicroChemLab biotoxin detector [7]. The i-STAT performs a wide selection of blood tests using disposable microfluidic cartridges. MicroChemLab is in field use in the Boston subway transit system (Massachusetts, USA) and used for monitoring water systems in other parts of the United States. Another example notable in particular for its low cost is US$ 40 Pria Diagnostics male fertility kit [8].

The majority of portable systems reported use electrochemical detection [1–5,7].

The sensitivity and selectivity of electrochemical detection are comparable to spectroscopic detection methods [9]. In addition, electrochemical detection, particularly amperometry, offers key advantages in simplicity, smaller size and lower cost. In amperometry, a potential is applied by a potentiostat to an electrochemical cell to cause oxidation–reduction (redox) reactions of electrochemically active molecules at the electrodes. The redox activity generates a measurable current that is proportional to the concentration of the electrochemically active molecules. The simplicity of the setup is demonstrated by the wide range of sub US$ 100 amperometric glucose sensors available. Incidentally, the glucose sensor is the most abundant miniaturized test system in use today. Its success is attributed to the fact that the sensors are small, inexpensive, stable, easy to use and easy to produce [10].

Conventional potentiostats are designed for research and are capable of performing many different kinds of complex electrochemical analysis. As such they typically are bulky and

* Corresponding author. Tel.: +1 607 255 5433; fax: +1 607 255 4080.
E-mail address: ajb23@cornell.edu (A. Baeumner).

0925-4005/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.snb.2006.08.032

therefore unsuitable for integration with the microfluidic technology used to miniaturize liquid assays. Several groups have designed and fabricated miniaturized single chip potentiostats from silicon that can be integrated [11–13]. The advantage of this approach is that potentiostats can be made very small, of the order of millimeters, and customized at fabrication specifically for specific experimental requirements such as current magnitude and frequency. For specialized applications such as in vivo neurotransmitter monitoring, these integrated potentiostats may be the best option [14]. The setup and fabrication costs however, make this approach too expensive for the production of mass market analysis devices. The use of existing integrated circuits (IC) such as op-amps, microcontrollers and system-on-a-chip components is the least expensive way to achieve instrumentation miniaturization at minimum cost [15,16]. These components have already been optimized for microelectronic applications and are manufactured in so many different configurations that, with some research, suitable ones can be found to meet experimental requirements. When combined with microfabricated electrodes, devices with accuracy and sensitivity comparable to conventional bench top electrochemical analyzers can be realized [16,17].

The primary requirements of most portable battery-operated devices are low power consumption, low cost and small size [18]. Taking into consideration these and other business-driven factors such as long life-cycle and simple production, we have designed a robust customizable microcontroller-based miniaturized system (miniEC) for electrochemical detection. Like other biosensing systems such as the glucose sensor, the miniEC has two parts. It consists of a disposable microfluidic cartridge that houses the amperometric sensor and an embedded system to power the sensor and measure, display and store the sensor results. This paper focuses on the design of the embedded system and discusses the rational for various design choices.

2. Hardware design

2.1. Sensor

The sensor used in this publication was developed previously in our laboratory and consists of an interdigitated ultramicroelectrode array (IDUA) transducer embedded in a microfluidic channel [19,20]. An IDUA consists of a pair of microelectrode arrays that mesh with each other. Each array contains 420 microelectrodes. A microelectrode is 2.5 μm wide and 1000 μm long. The gap between a pair of microelectrodes is 4.5 μm wide.

In an amperometric setup, the IDUAs can be used as a two-electrode system due to a small iR drop, have enhanced signal to noise ratios due to the small dimensions and diffusion patterns, and are ideally suited for redox cycling reactions as described elsewhere [19].

2.2. Microcontroller unit

The microcontroller unit (MCU) in the system is a miniaturized computer that is programmed to execute the behavior that defines the miniEC. An MCU was chosen that would meet miniEC system requirements for computational speed, low power consumption, development tools, design flexibility and low cost. Four MCU family architectures, AVR, PICmicro, MSP430 and MC68HC11/12, were evaluated by comparison of the Atmega128L (ATMEL, San Jose, California), PICLF452 (Microchip Technology Inc., Chandler, Arizona), MSP430F449 (Texas Instruments, Dallas, Texas) and MC9S12C64 (Freescale Semiconductor, Austin, Texas) microcontrollers considered at the time to be representative of the features offered by each family. The MSP430F449 was selected because it had the best combination of low power consumption, low leakage current, event-driven capability and selection of integrated low power peripherals for portable battery powered operation. Table 1 shows the most important subset of the MCU features compared.

Table 1
Microcontroller unit comparison

MCU	AVR Atmega128L	MSP430 MSP430F449	PICmicro PIC18LF452	MC68HC12 MC9S12C64
Core architecture	8 bit	16 bit	8 bit	16 bit
Power supply (V)	2.7–5.5	1.8–3.6	2–5.5	3.2–5.5
Power modes	6	6	2	5
Active current (mA at 1 MHz)	8	0.30	1.6	2
Idle current (μA at 32 kHz)	22	1	25	700
Flash memory (kB)	128	60	32	64
RAM (B)	4 K	2 K	1.5 K	4 K
I/O pins	53	48	34	60
Pin leakage current (nA)	1000	50	500	1000
Number of interrupts	35	40	18	29
Peripherals	Two 8-bit timers, two 16-bit timers, 10-bit ADC, two USART, I2C, SPI	Two 8-bit timers, two 16-bit timers, 12-bit ADC, two USART, SPI, LCD driver, supply voltage monitor, 16 × 16 multiplier	Two 8-bit timers, two 16-bit timers, 10-bit ADC, two USART, MSSP, PSP, 8 × 8 multiplier	One 16-bit timer, one 8-bit PWM, 10-bit ADC, CAN, SCI, SPI

In the envisioned application, the MCU spends most of its time in idle mode with periodic bursts of activity when signals are measured, thus, power consumption in the idle mode and pin leakage are the most important features that determines if one operates within a low power budget. The MSP430 in idle mode operates with a current consumption that is an order of magnitude lower than the other microcontrollers. The MSP430 also has the lowest pin leakage current and thus wastes very little power. It supports six power modes that enable the optimization of low power consumption. Furthermore, the MSP430 features the fastest switching between power modes. It can switch from idle mode to fully synchronized high-speed active mode operation within 6 μs.

The number and type of interrupts available in an MCU also has an effect on current consumption and operational efficiency. More interrupts mean that the CPU does not have to monitor or poll events. Instead, it remains idle until an interrupt brings it into active mode. The MSP430 has at least 40 interrupts. All of its integrated peripherals have interrupts and some have multiple interrupts for different events. Sixteen of its general input–output pins also have interrupt ability to respond to external events. Fig. 1 shows a block diagram of the system design using the MSP430.

In order to keep the component count low, the microcontroller's peripherals were used extensively. This minimizes costs and enables the device to remain compact. Four push buttons and a liquid crystal display (LCD) form a simple menu driven user interface. The four push buttons labeled stop, enter, up and down are connected to the MCU on port 1. An interrupt is generated every time one of them is pressed. Their functions and effect on the miniEC are defined by software (see Section 3). The LCD is the low power 4-mux SBLCDA2 (SoftBaugh, Alpharetta, GA) designed specifically to work with MSP430 microcontrollers. It is used to visually confirm device operation, display time of day when the miniEC is in idle mode and display results of running tests. The MSP430 has an on-board LCD driver that powers and drives this LCD directly through pins S0 to S39. On-board flash memory is also used for data storage. For this project the MSP430F449's 60 kB memory was partitioned into 40 kB data memory and 20 kB program memory.

An RS-232 serial interface is implemented with the TX and RX pins of the USART module. By default it is programmed to run at 9600 bps using a byte size of 8 bits and 1 stop bit with no parity checking. The serial block is set up using a MAX3221 (Maxim Integrated Products, Sunnyvale, CA) to achieve the necessary level shifting for connection to a PC [21].

2.3. Potentiostat

The amplifier and filter blocks (Fig. 1) together form a two-electrode potentiostat. Fig. 2 shows the schematic of the potentiostat. The circuit was built with low power, low noise MAX407 op-amps (Maxim Integrated Products). Each op-amp (U1A, U1B, U2) draws just 1 μA when idle and about 2 μA otherwise. The MAX407 op-amp has two other characteristics, a very high input impedance and a typical low input bias current of <0.01 nA that makes it ideal for potentiostat operations. The IDUA is connected to the output of U1B and the inverting input of U1C. The operation of an op-amp requires that its inputs (labeled + and −) must be at an equal potential. The positive terminal of U2 is connected to ground. This implies that U2's negative input and therefore one set of IDUA electrodes are also at ground potential. The other set of electrodes is maintained at V_{bias}. No current flows into the op-amp itself, therefore the measured current that flows through the feedback resistor R is the current produced as a result of redox activity.

The excitation potential, V_{bias}, to the IDUA sensor is created by filtering a PWM signal (generated by timer B of the MCU) through a single pole RC filter. The resulting potential is then buffered and inverted by op-amps before it is connected to the IDUA. The potential produced depends on the value of the PWM duty cycle. A 100% duty cycle represents a potential of 2500 mV. The potential can be changed by the user to the preferred redox potential for the electrochemical species used in the test solution.

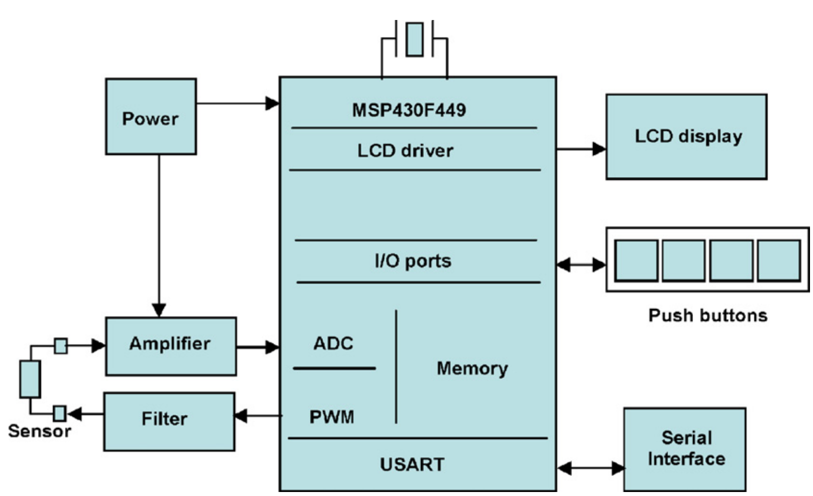

Fig. 1. Block diagram of the MSP430 based miniEC system. A PWM output from the microcontroller together with the analog filter generates the potential to bias the sensor. The sensor output is converted to a voltage and amplified to a range that can be read by the microcontroller's analog-to-digital converter. The results are displayed on the LCD and a copy stored in the microcontroller's memory for later retrieval via the serial interface.

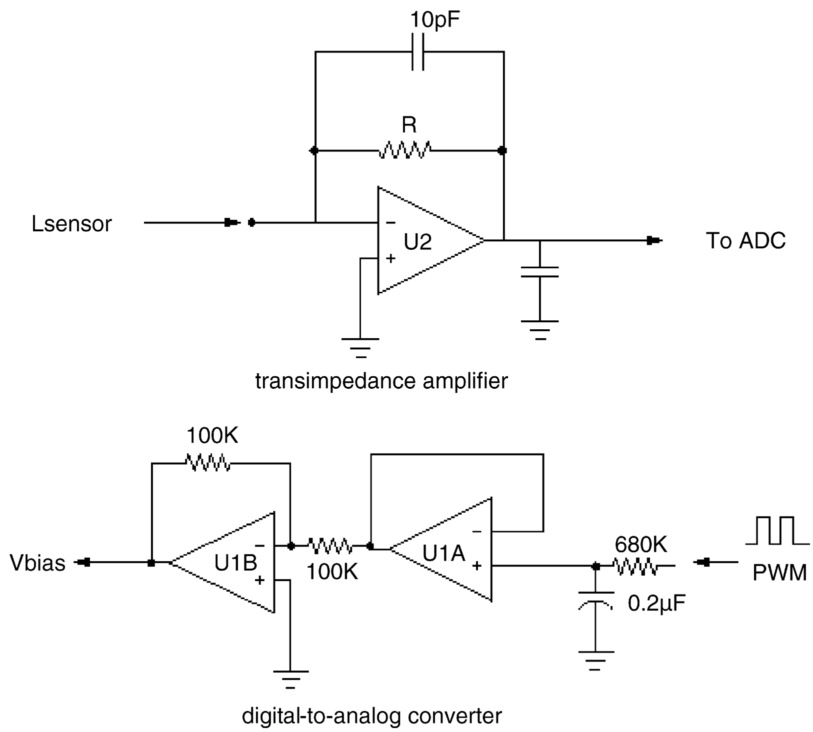

Fig. 2. Schematic of the analog block showing the miniEC's two-electrode potentiostat setup. The sensor potential is generated with a filtered PWM signal from the MCU. The sensor current is measured with a transimpedance amplifier and sent to the MCU's ADC peripheral to be recorded.

The signal from the sensor is a very small current in the nA range. It is, therefore, necessary to amplify and convert it to a voltage range (0–2500 mV) that the MCU's analog-to-digital converter can measure. This is achieved with the transimpedance amplifier circuit (Fig. 3). Based on Ohm's law the amplifier gain is determined by the value of the resistance R in the feedback loop of the op-amp U1C. With an R of 2.0 MΩ a current of 1 nA is converted to a voltage of 2 mV, so the miniEC is able to measure a wide current range from 0 to 1250 nA. In addition, the amplifier can be made programmable by replacing R with a range of resistors and a digitally controlled switch, such as the MAX4652, for variable gain selection.

2.4. Power supply

The miniEC can be run directly off of a battery pack since the miniEC's low power components operate within a range (1.8–3.6 V) that coincides with the useful life of a 2 AA, 2 AAA battery pack or a single 3 V cell. Managing the battery voltage with a voltage regulator compensates for linear battery discharge profiles and provides a constant voltage to the miniEC

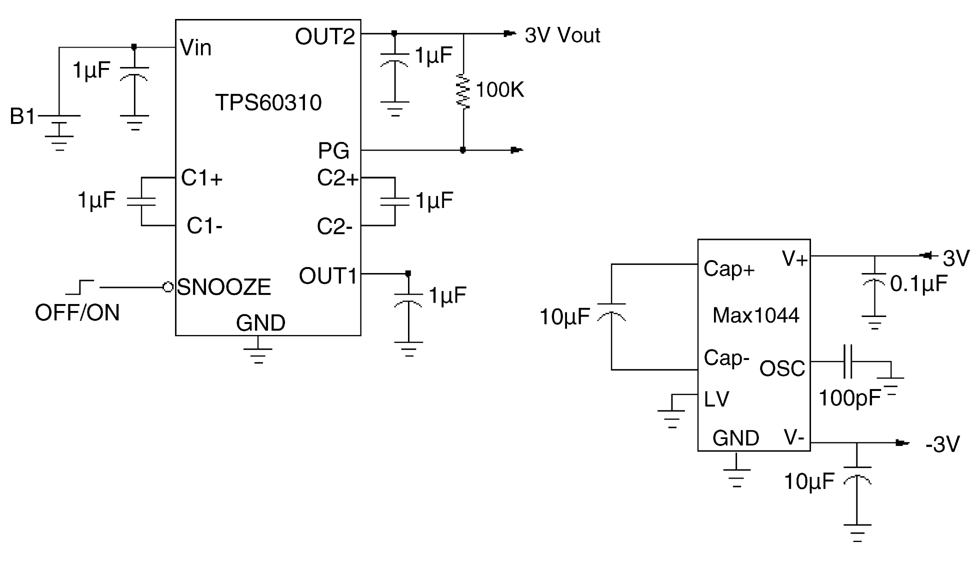

Fig. 3. MiniEC power block. The TPS60310 converts the input from a single AA or AAA cell (B1) to a regulated 3 V system supply. The 3 V powers a MAX1044 that produces a symmetrical negative supply.

circuitry regardless of varying current demands. Texas Instrument's TPS60310 high efficiency charge pump was selected for this purpose.

The TPS60310 produces a regulated 3 V output voltage from a 0.9 to 1.8 V input thus reducing the battery requirement to a single AA or AAA battery cell (Fig. 3). In 'snooze mode' it has a quiescent current of just 2 μA but can supply 2 mA to the rest of the circuit. Two milliamperes is enough for most of the miniEC's operation. The MCU may require more than 2 mA momentarily for certain events such as writing data to flash memory. Demand for more than the 2 mA threshold causes the TPS60310 to automatically exit snooze mode to supply up to 20 mA. The MCU returns the TPS60310 to snooze mode after the high demand event with a logic low signal to the TPS60310 snooze input. A MAX1044 (Maxim Integrated Products) inverter is used to produce a negative supply $-V_{cc}$ for the digital-to-analog filter circuitry since both a positive and negative power supply is needed for the op-amps in the circuit that convert the PWM signal to the IDUA potential (Fig. 2).

3. Software

Given the pace of innovation in microelectronics, it was expected that newer, faster and better MCUs would be produced within each family after the initial selection process. Therefore, to ensure portability of firmware to new MSP430 MCUs or a different MCU family, the embedded software was written in C using the free mspgcc tool chain.

The firmware logic is event driven. The MCU is programmed to run in low power mode 3 (LPM3 or idle mode) until an event puts it into active mode by waking up the CPU (Fig. 4). The MCU returns to the idle mode as soon as it completes the action associated with the event.

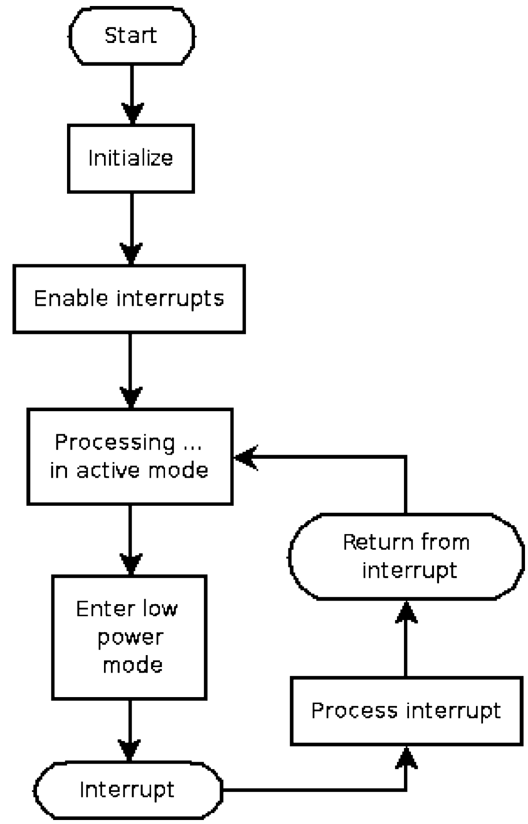

Fig. 4. Microcontroller program flow. Operation is interrupt driven. The MCU stays idle until an interrupt occurs. It then enters active mode and performs the action requested by the interrupt.

On startup, the MCU is programmed to initialize program variables such as the location of data memory, the time and the default values. The basic timer serves as the pulse for a real-time clock so it is set up to cause an interrupt every second. Port 1 is set up as interruptible input for the button interface. Port 2 and timer B are set up for PWM output. LCD control, ADC and the USART are enabled as well. After setup, all interrupts are enabled. The MCU then proceeds into the main routine loop that logically implements a finite state machine. Fig. 5 shows the relationship between the states and the events that cause the miniEC to transition from one state to another. The user operates the device by pressing one of the four buttons or by sending commands mimicking button events via the serial connection.

The main loop starts out in the IDLE state. In this state, all peripherals except the basic timer are powered down. Time is updated and displayed on the LCD. Pressing the 'enter' button sends the system into the READY state. The MCU enables all the necessary peripherals (PWM, ADC) and checks that they are operating properly. It also determines if enough memory to store the data is available. If everything passes these controls, the message "Ready" is displayed on the screen. Recording starts when the user presses the 'enter' button again. At the start of the recording session, the time is noted and a file is opened to store the results for the duration. At each interval, the recorded data are displayed on the LCD and a copy stored (or transferred to a PC). At the end of the measurement duration or if a user presses the 'stop' button, the miniEC closes the data file and enters the PAUSE state. From this state, the user can initiate another measurement or return to the IDLE state. In both the READY and PAUSE states, the system will revert to the IDLE state after 5 min of inactivity.

In the OPTIONS state the user can cycle through variables to update time, and change the settings for electrochemical measurements. By default, the MCU is programmed to perform direct current amperometry (DCPA) measurements. The potential range available for DCPA is from 0 to 2500 mV in steps of 10 mV. The interval range available is from 1 to 60 s in steps of 1 s. The duration can be set from 1 min to 24 h. The amount of data that can be stored is limited by the interval selected. At 1-min intervals 10 days worth of data can be stored, while at 1-s intervals only about 4.5 h of data can be stored. Once the data memory of the miniEC is full, measurements can still be made and viewed or transmitted. The miniEC will not automatically delete any files. Instead the user is notified of the memory full condition on the LCD and prompted to delete files when convenient. Each recorded file is assigned a numerical ID. In the LOGS state, the user can delete files or use the up/down buttons to cycle through the files to view the value of the peak signal recorded for each one.

A variety of strategies are used in the firmware to achieve low power operation and to optimize performance. An example

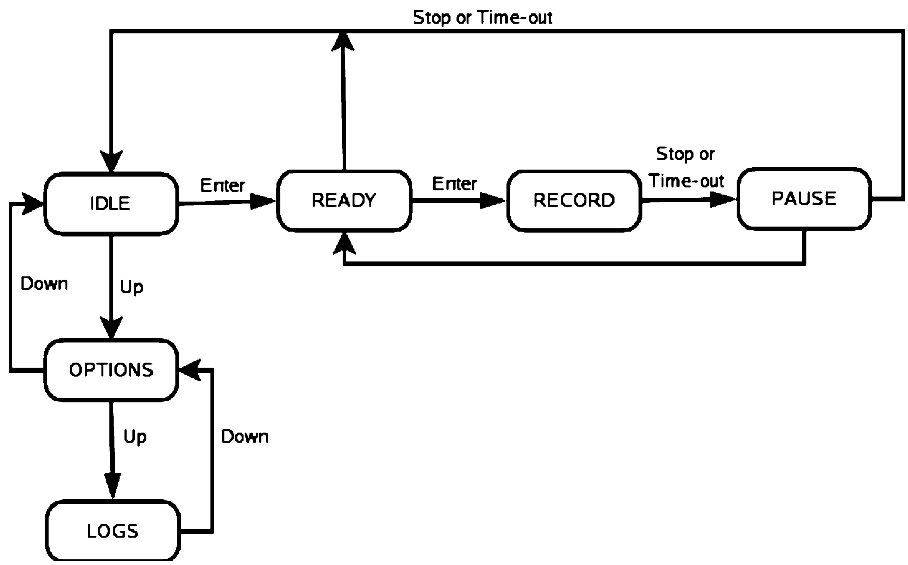

Fig. 5. MiniEC main loop state chart. The device starts out in the idle state. When the 'enter' button is pressed, the miniEC transitions to the ready state. In the ready state another 'enter' button event transitions the miniEC into record state. During recording, the test can be paused by pressing the 'stop' button. In pause mode, pressing the 'enter' button will restart recording. The pause and ready modes have timeout periods. If no events occur within the timeout periods, the miniEC will return to the idle mode. The user reverts to the idle state from other states by pressing the 'stop' button.

is implementation of a software filter by oversampling and then averaging the sensor signal. For each interval, the ADC takes 256 (4^4) successive readings and records the average value. Each factor of 4 adds 1 bit of resolution to the measurement and improves the signal-to-noise ratio by a factor of 6 db [22]. As a result, this simple technique greatly improves the signal-to-noise ratio and effectively increases the ADC resolution from 12 to 16 bits without adding extra components and expense. Furthermore, the CPU is disabled during sampling and conversion of signals by the ADC. Fast processing speed is maintained by keeping the system in LPM0, an intermediate low power mode between idle mode and active mode that uses less than a fifth of the active mode power. The MCU is fully active and thus consuming the most power mainly for the few milliseconds it takes each interval to average, scale and store the sensor data.

The MSP430 is programmed to transmit serial data in human readable ASCII format. This makes the output easy to view and capture with any terminal program such as HyperTerminal (on Microsoft Windows), ZTerm (on MacOs) or Minicom (on Linux/Unix). The provision of a graphical user interface (Fig. 6) however simplifies communication with the miniEC and provides opportunity for real-time visual monitoring and graphing of data trends. In addition a user can perform system setup with a familiar user-friendly interface. The miniEC system thus

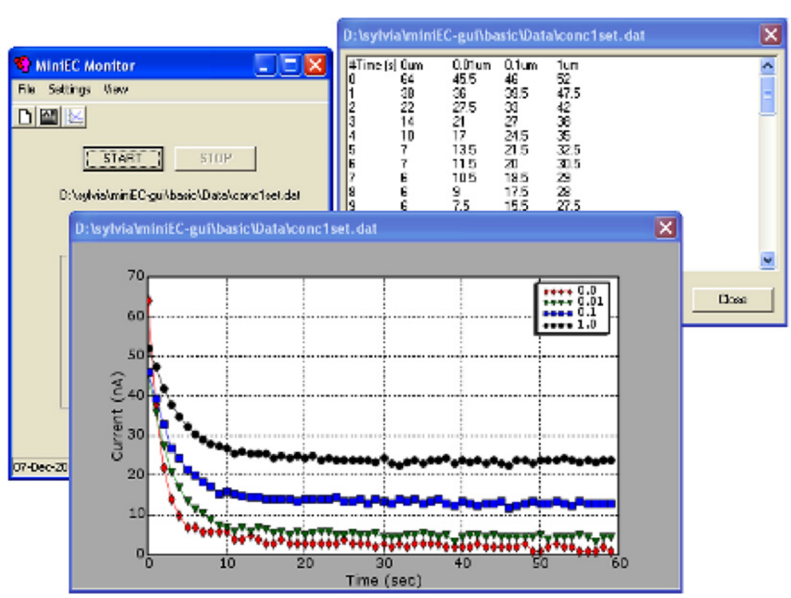

Fig. 6. A screenshot of the miniEC graphical user interface displaying sensor current over time for potassium ferri/ferrohexacyanide concentrations of 0, 0.01, 0.1 and 1 μM in static 10 μL droplets.

includes a small cross platform interface implemented with the royalty-free WxPython toolkit.

4. Discussion

The miniEC (Fig. 7) is intended for electrochemical measurements by technical and non-technical users. As such its use does not require any special skills. Its four-button keypad and LCD provides an easy to use interface (Fig. 4). By default, it is set to perform direct current potential amperometric (DCPA) experiments but can easily be programmed to perform other electrochemical tests. With DCPA settings of 400 mV potential, test duration of 1 min and sampling interval of 1 s, the estimated average current consumption is 2.5 mA. At this rate, the miniEC can run continuously for 2 weeks taking data at 1-s intervals with a single AAA battery rated at 1000 mAh. In a typical scenario where the miniEC is used intermittently, for example for a total time of 2 h a day in the default configuration, it can run at least 6 months on a single AAA battery. Most of the electronic parts selected for the miniEC are rated to perform in the industrial temperature range of −40 to 85 °C. Thus they work with minimal deviation within the range of 0–70 °C typical for mass market commercial devices without extra temperature compensation circuitry.

Subsequent to the current design and implementation, Texas Instruments released the MSP430FG439 designed specifically for portable medical applications. The MSP430FG439 has three integrated programmable gain op-amps to take analog readings and a 12-bit DAC to generate potentials from 0 to 2500 mV. It also supports direct memory access so data can be manipulated without the intervention of the CPU. Apart from these enhancements, it is identical to the MSP430F449. The microcontroller firmware described above was successfully ported to the new chip to take advantage of the new peripherals thus validating our approach to miniEC instrumentation development, because this approach will enable the production of a range of devices evolving from the basic miniEC functionality described here. Devices can be made smaller or functionality can be added to create deluxe versions with more features. Even with the MSP430F449, there is still plenty of room for incremental enhancements which is currently under investigation. The ADC port, for instance, has eight inputs, thus, with the addition of sensor hardware and minor modifications to the embedded software, the miniEC can monitor up to eight samples at a time. Storage capacity can also be expanded with serial memory chips via the microcontroller's serial peripheral interface.

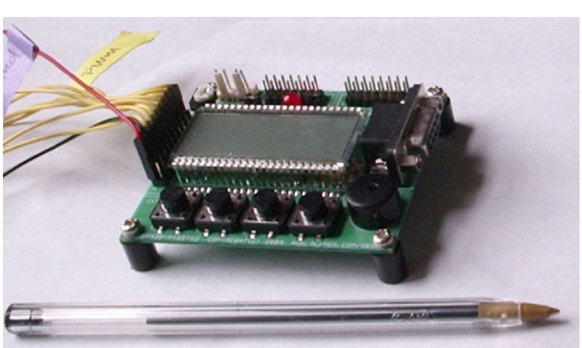

Fig. 7. Photograph of prototype miniEC instrumentation (assembled by Olimex Ltd., Plovdiv, Bulgaria). The overall dimensions are about 80 mm × 65 mm. The pen is shown for size comparison.

The system's flexibility is not limited to the hardware architecture. The finite state machine main loop algorithm for the miniEC is a very efficient way for implementing control logic. The FSM code uses status bytes and a fast lookup table to minimize CPU overhead. The system's behavior is encapsulated by states and actions with well-defined conditions for state transitions. Given a set of inputs and a known current state, the state transition can be predicted, allowing for easy system simulation and testing. The technique also encourages modular design thus simplifies firmware upgrades in the future.

The accuracy of the miniEC was evaluated by comparing its performance to an industry standard bench top electrochemical workstation in static and dynamic DCPA direct detection experiments of the redox couple potassium ferri/ferrohexacyanide [17]. In both sets of experiments, the inexpensive miniEC performance was comparable to that of the electrochemical workstation. In fact, the miniEC achieved a detection limit of 0.01 μM combined ferri/ferrohexacyanide concentration which was 10× lower than that of the standard lab-bench system. Experiments were done in static mode (i.e. stationary droplets) and dynamic mode (i.e. flowing in a microfluidic channel). The response time of the miniEC was in all cases very similar to the exquisite response time of the bench top electrochemical workstation. In static mode, typically better percent errors were obtained with the miniEC system (except of for the signals of pure buffer which were 1.8 ± 0.5 and 2.0 ± 0.5 nA for the miniEC and bench top potentiostat, respectively) and were between 11 and 2% depending on the concentration detected (between 0.01 and 50 μM) with the miniEC, and between 19 and 7% with the bench top potentiostat. In the case of the dynamic experiments, percent errors were slightly better with the bench top system (between 0.6 and 3.8%) than with the miniEC (between 1 and 6%). It was therefore concluded that the miniEC was a useful transducer and detector system for a complete biosensor assay as described in Ref. [17] for the detection of Dengue virus RNA.

5. Conclusion

We have presented the miniEC, an electronic appliance designed as a portable electrochemical transduction system with integrated recording and data manipulation. It potentially could replace electrodes, potentiostat and computer systems in conventional electrochemical setups. Use of the inexpensive, low power, powerful and efficient MSP430 microcontroller together with other carefully selected low power components results in a design that can run for months on a single AA or AAA battery. Also, emphasis on low cost resulted in a compact design with a minimal number of off-the-shelf components that altogether cost less than US$ 50 in prototype quantities. Both the hardware and software designs are general, modular and flexible. The microcontroller can be programmed to perform different electrochemical tests providing the user with a fully integrated mini-electrochemical system. The application described here in a direct current potential amperometry experiment used only a fraction of the MCU's capability. The sophisticated MSP430 can also control many additional components (a pump actuator for instance) and could perform other functions such as digital signal processing of complex electrochemical signals in future prototypes.

Acknowledgements

The authors thank Dr. Richard Montagna, Biotechnologies International, Inc., Dr. Richard Durst, Cornell University, and Stefan Minott, Cornell University, for many helpful and useful discussions. We also acknowledge financial support for this project from the department of Biological and Environmental Engineering, Cornell University, and the Cooperative State Research, Education and Extension Services (NYC-123404).

References

[1] R.H. Liu, J. Yang, R. Lenigk, J. Bonanno, P. Grodzinski, Self-contained, fully integrated biochip for sample preparation, polymerase chain reaction amplification, and DNA microarray detection, Anal. Chem. 76 (2004) 1824–1831.

[2] Z. Trajanoski, P. Wach, R. Gfrerer, Portable device for continuous fractionated blood sampling and continuous ex vivo blood glucose monitoring, Biosens. Bioelectron. 11 (5) (1996) 479–487.

[3] G. Li, N.Z. Ma, Y. Wang, A new handheld biosensor for monitoring blood ketones, Sens. Actuators B 109 (2005) 285–290.

[4] T. Kappes, P. Schnierle, P.C. Hauser, Field-portable capillary electrophoresis instrument with potentiometric and amperometric detection, Anal. Chim. Acta 393 (1999) 77–82.

[5] R. Knake, P.C. Hauser, Portable instrument for electrochemical gas sensing, Anal. Chim. Acta 500 (2003) 145–153.

[6] C. Papadea, J. Foster, S. Grant, S.A. Ballard, J.C. Cate IV, W.M. Southgate, D.M. Purohit, Evaluation of the i-STAT portable clinical analyzer for point-of-care blood testing in the intensive care units of a university children's hospital, Ann. Clin. Lab. Sci. 32 (3) (2002) 231–243.

[7] J.A. Fruetel, R.F. Renzi, V.A. Vandernoot, J. Stamps, B.A. Horn, J.A. West, S. Ferko, R. Crocker, C.G. Bailey, D. Arnold, B. Wiedenman, W.Y. Choi, D. Yee, I. Shokair, E. Hasselbrink, P. Paul, D. Rakestraw, D. Padgen, Microchip separations of protein biotoxins using an integrated hand-held device, Electrophoresis 26 (6) (2005) 1144–1154.

[8] M. Bourne, 2005 may be a momentous year for MEMS, or maybe just a momentum-building year, Small Times: News About MEMS, Nanotechnology and Microsystems, January 21, 2005, http://www.smalltimes.com/.

[9] G. Drummond, M.G. Hill, J.K. Barton, Electrochemical DNA sensors, Nat. Biotechnol. 21 (2003) 1992–1999.

[10] E. Manger, Trends in electrochemical sensors, Analyst 123 (1998) 1967–1970.

[11] H.S. Narula, J.G. Harris, VLSI potentiostat for amperometric measurements for electrolytic reactions, in: Proceedings of the 2004 International Symposium on Circuits and Systems, Vancover, Canada, May 23–26, 2004.

[12] A. Frey, M. Jenkner, M. Schienle, C. Paulus, B. Holzapfl, P. Schindler-Bauer, F. Hofmann, D. Kuhtmeier, J. Krause, J. Albers, W. Gumbrecht, D. Schmitt-Landiedel, R. Thewes, Design of an integrated potentiostat circuit for CMOS bio sensor chips, in: Proceedings of the 2003 International Symposium on Circuits and Systems, Bangkok, Thailand, May 25–28, 2003.

[13] R.G. Kakerow, H. Kappert, E. Spiegel, Y. Manoli, Low-power single-chip CMOS potentiostat, in: International Conference on Solid-State Sensors and Actuators, Stockholm, Sweden, June 25–29, 1995.

[14] K. Murari, N. Thakor, M. Stanacevic, G. Cauwenberghs, Wide-range, picoampere-sensitivity multichannel VLSI potentiostat for neurotransmitter sensing, in: Proceedings of the 26th Annual International Conference, IEEE Engineering in Medicine and Biology Society (EMBS'2004), San Francisco, September 1–4, 2004.

[15] M.D. Steinberg, C.R. Lowe, A micropower amperometric potentiostat, Sens. Actuators B: Chem. 97 (2–3) (2004) 284–289.

[16] E.M. Avdikos, M.I. Prodromidis, C.E. Efstathiou, Construction and analytical applications of a palm-sized microcontroller-based amperometric analyzer, Sens. Actuators B: Chem. 107 (2005) 372–378.

[17] S. Kwakye, A.J. Baeumner, V.N. Goral, Electrochemical microfluidic biosensor for nucleic acid detection with integrated minipotentiostat, Biosens. Bioelectron. 21 (12) (2006) 2217–2223.

[18] K.R. Fowler, Electronic Instrument Design: Architecting for the Life Cycle, Oxford University Press, New York, NY, 1996.

[19] J.H. Min, A. Baeumner, Characterization and optimization of interdigitated ultramicroelectrode arrays as electrochemical biosensor transducers, Electroanalysis 16 (9) (2004) 724–729.

[20] V.N. Goral, N.V. Zaytseva, A.J. Baeumner, Electrochemical microfluidic biosensor for the detection of nucleic acid sequences, Lab Chip 6 (2006) 414–421.

[21] Application Note 882, RS-232 Features Explained, Maxim, http://www.maxim-ic.com/appnotes.cfm/appnote_number/882.

[22] J.C. Candy, G.C. Temes, in: J.C. Candy, G.C. Temes (Eds.), Oversampling Delta-Sigma Data Converters, IEEE Press, New York, 1991, pp. 1–25.

Biographies

Sylvia Kwakye is currently a candidate for a PhD in biological and environmental engineering, Cornell University, Ithaca, New York.

Antje Baeumner is currently an associate professor in the Department of Biological and Environmental Engineering, Cornell University.