

Wide Dynamic Range Multi-Channel Electrochemical Instrument for In-Field Measurements

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Abstract— This paper presents a multi-channel, multi-technique electrochemical instrument with the size, power and performance for portable applications such as point-of-care diagnosis, wearable sensing, and toxic chemical detection. Composed of a custom analog interface and a commercial low-power microcontroller, the portable instrument is capable of dynamically adapting to a wide input current range exhibited by many electrode/sensor types and observed in the transient response of many electrochemical techniques. The instrument can generate several standard electrochemical stimulus waveforms or an arbitrary waveform, independently and in parallel on multiple channels, while streaming measurement results to a USB host. The portable instrument was tested across multiple conditions against a commercial benchtop electrochemical instrument in a potassium ferricyanide solution. The maximum normalized root mean square difference between test results and the commercial instrument is less than 2%, cementing system robustness.

Keywords—*electrochemical sensor; point-of-care sensing.*

I. INTRODUCTION

With the recent leap in exploration of the internet of things and seamless sensing, electrochemical measurement is emerging as a prominent candidate for environmental and biomedical sensing and analysis [1]. Many fields such as protein detection, DNA analysis, toxic gas monitoring and heavy metals sensing utilize electrochemical sensors because they are relatively reliable, simple, inexpensive and potentially portable. Hence, significant academic and entrepreneurial attention has been focused on electrochemical sensing in recent years.

The versatile nature of electrochemical measurement means that testing and characterizing sensors can be conducted under various electrode conditions, in challenging locations such as outdoors, within confines of complicated machinery or in areas with limited resources and access [2]. Many efforts have been made recently to advance electrochemical sensing. For instance, a lab platform is being implemented into Google ATAP's project Ara with a custom electrochemical sensing block [3]; a portable platform with a disposable sensor chip is being developed to detect Malaria in remote locations [2]; and a platform for sensing in locations with limited web connectivity is being developed [4]. In addition, a Bluetooth-based electrochemical sensor module has been introduced [5][6]. However, like most existing electrochemical sensing systems, these devices were built to interface with a specific type of

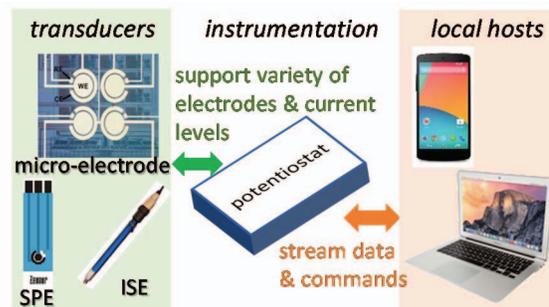


Fig. 1. Versatile electrochemical instrument for interfacing various electrodes and streaming measurements to a USB host.

electrode or are tied to a specific host platform. For example, [3] would only operate with an Ara smartphone while [2] is optimized to a specific kind of electrode. Furthermore, in real-world applications sensing is not usually possible with just one channel/sensor due to the presence of too many variables in the environment. Environmental gas sensing, for instance, is very challenging because a multitude of gases exists that may interfere with testing [7], and detecting antigens in a blood sample is complicated by random concentrations of other interfering substances [2]. Consequently, there is a need for a versatile electrochemical instrument that could interface with and dynamically adapt to many types of electrodes and electrolytes in many environments, as shown in Fig. 1. Such an instrument should have the capacity to record from multiple input channels in parallel to enable statistical sensing DSP analysis. Ideally, the instrument would also be inexpensive, able to communicate to a variety of host platforms, and exhibit the power and area metrics suitable for portable applications.

To this end, this paper describes a fully autonomous, miniaturized electrochemical instrumentation module called aMEASURE with the versatility to support many target electrodes and analytes. aMEASURE is the first fully portable multi-channel electrochemical instrument module capable of automatically tracking a wide range of currents produced from a variety of electrode types and dynamically adapting measurement gain to maximize resolution for each input current level. Furthermore, aMEASURE can generate stimulus waveforms for a variety of electrochemical techniques, and it can simultaneously perform measurements on multiple channels in parallel. The design and characterization of this portable

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instrument will be presented to demonstrate its suitability to many electrochemical sensing applications.

II. AMEASURE DESIGN SPECIFICATIONS

As illustrated in Fig. 2, the aMEASURE portable electrochemical instrumentation module consists of a custom analog sensing platform (CASP) partnered with a microcontroller (μC). A commercial low-power μC board (Texas Instruments, MSP430) was chosen to provide local control of aMEASURE functions, perform preliminary DSP, and stream data and commands to/from a host over USB or USB on-the-go (OTG) for compatibility with a variety of host platforms including PCs and smartphones. As shown in Fig. 2, the CASP module contains a multi-channel potentiostat, composed of voltage biasing and current readout functions, for signal conditioning and electrode interfacing. The potentiostat and readout circuit implemented for each channel of CASP is illustrated in Fig. 3 and further described below. The CASP module also contains a multichannel ADC/DAC block (TI-AMC7823) to digitize output data and convert digital biasing commands to analog electrochemical stimuli.

High transitional currents are very likely to occur in electrochemical techniques such as chronoamperometry (CA) and multi-potential step (MPS). To amplify sensor response currents, a typical trans-impedance amplifier (TIA) should provide low enough gain to handle such great currents. However, we often desire to take measurements after the system has settled to a current level much lower than its peak transitional current, limiting the resolution of a fixed-gain TIA. This is corroborated by the fact that the electrochemist must have an estimate of the system faraday current and counter it beforehand with a calibration process. Furthermore, useful information may exist in the transitional stage of the signal where the output is best observed with low gain. Hence, a classic TIA system would not be able to support this wide range of expected gain requirements, and it would be preferable for a

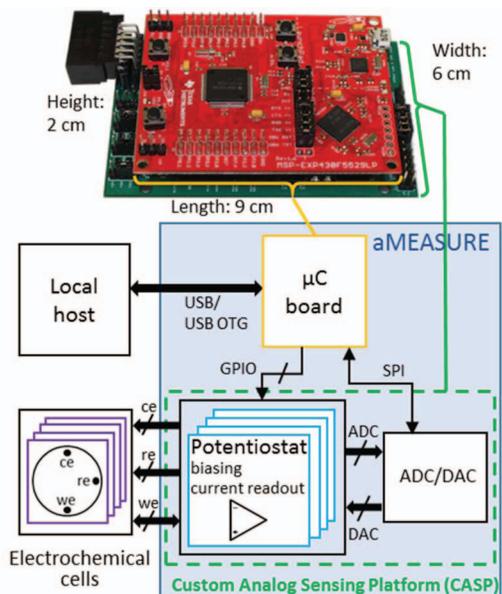


Fig. 2. aMEASURE block-diagram and prototype implementation with size dimensions.

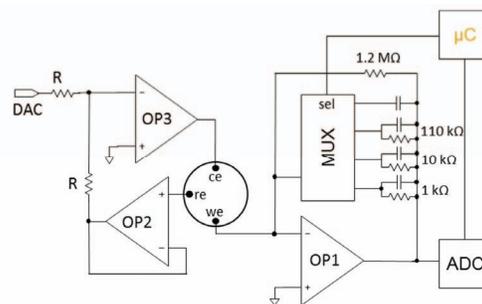


Fig. 3. Schematic diagram of aMEASURE current readout circuit.

portable instrument to be able to adapt automatically to measurement environments and conditions.

The readout configuration shown in Fig. 3 was developed to accommodate the wide current range possible in electrochemical measurements. The variable gain amplifier has four gain modes determined by the resistances 1.2 M Ω , 100 k Ω , 10 k Ω and 1 k Ω . The μC sets each channel's gain individually through the multiplexer (MUX). If the recorded current is too close to the supply rails (VDD/GND) or analog ground, the gain will decrease or increase, respectively. Hence, the TIA will always be operating at an optimal gain. The 1.2 M Ω resistance is placed outside the MUX channels to avoid any issues arising from input Faraday current flow disruption due to switching.

The need for versatility means that aMEASURE should be able to perform common electrochemical tests such as cyclic voltammetry (CV), CA, etc, as well as generate an arbitrary periodic electrochemical bias potential with a maximum bandwidth of ~ 50 Hz. This arbitrary waveform allows aMEASURE to perform a variety of standard tests, such as double-potential step, as well as experimental techniques. These waveforms can be streamed directly into the μC from the USB host. Fig. 4 depicts some of the waveforms that have been implemented with aMEASURE using this arbitrary waveform generation functionality.

III. TESTING AND VERIFICATION

To verify system operation, multiple tests have been conducted using aMEASURE in conjunction with a CHI instrument (CHI-760c) using commercial electrodes. The tests have been conducted with both a laptop PC and Nexus 5 smartphone acting as the host over USB OTG. System performance at its peak gain (1.2 M Ω) is shown on Table 1.

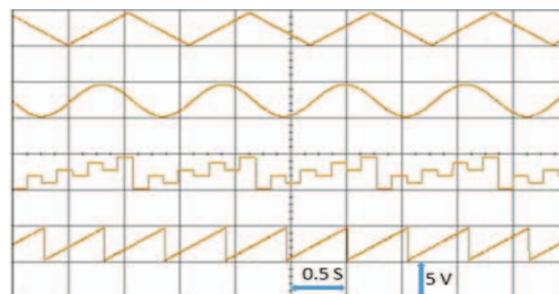


Fig. 4. Arbitrary waveforms generated using aMEASURE.

TABLE I. TABLE I: AMEASURE PERFORMANCE METRICS.

Dimensions	6 cm × 9 cm × 2 cm
Dynamic range @ 1Hz	186 dB (~1 nA – 2 mA)
SNR (0.1 - 100 Hz) 1.2 MΩ	62.7 dB
ENOB (0.1 - 100 Hz) and 1.2 MΩ	10.12 bits
Sampling Frequency	1 kHz
Power Consumption	~90 mA

CV tests were conducted in 40 mM, 30 mM and 20 mM potassium ferricyanide solution, $K_4[Fe(CN)_6]$ (0.1M KCl), with the CV potential swept from 0 V to 600 mV. Each of the three concentrations were tested at scan-rates of 50 mV/s, 100 mV/s and 200 mV/s conducted for 10 cycles. Fig. 5 plots the results from the 9th CV cycle for both the portable instrument and a commercial benchtop electrochemical instrument (CHI-760c). Fig. 5 also lists the root mean square (RMS) difference between the two instruments for all test conditions. The maximum normalized RMS is less than 2%, demonstrating strong match and robustness. Fig. 6 shows the calibration curves of peak

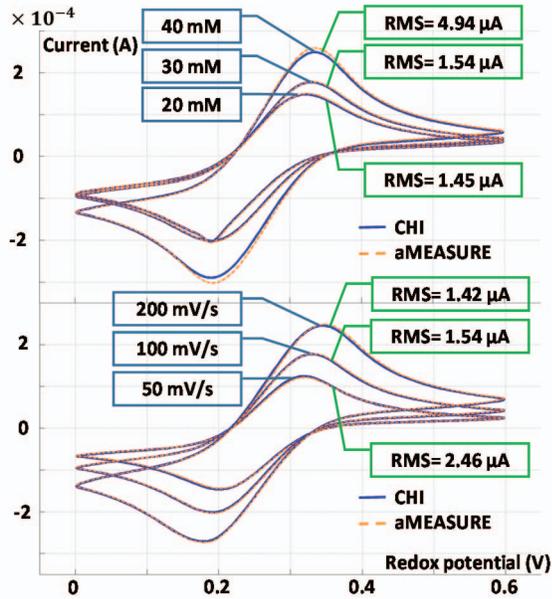


Fig. 5. CV measurements for both CHI-760c and aMEASURE in a) 40 mM, 30 mM and 20 mM $K_4[Fe(CN)_6]$ at 100 mV/s and b) 30 mM $K_4[Fe(CN)_6]$ with scan-rates of 50 mV/s, 100 mV/s and 200mV/s. RMS difference is listed for all measurements.

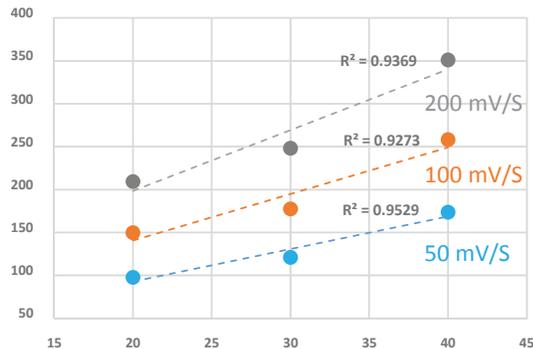


Fig. 6. Peak current vs. concentration at different scan-rates.

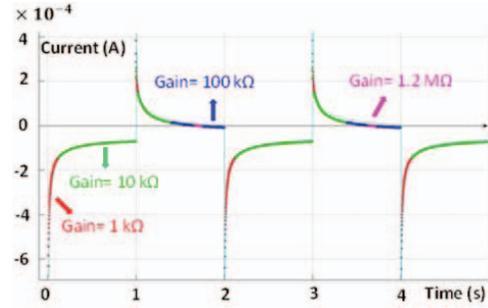


Fig. 7. System response to a MPS test showcasing aMEASURE dynamic gain changing features.

currents recorded by the aMEASURE system for each CV scan rate, illustrating good linearity.

An MPS test was implemented in the 30 mM potassium ferricyanide solution to showcase the dynamic gain adjustment feature of aMEASURE. The results shown in Fig. 7 were validated against the CHI instrument running a similar test. Each shaded region in the plot indicates the dynamic gain that the system is employing at each given time. The gain adjusts itself to accommodate higher input currents and avoid saturating the TIA, consequently maintaining proper electrochemical cell biasing conditions. The reaction time for gain switching was observed to be less than 1 ms, which indicates that aMEASURE is able to dynamically and quickly respond to large variations in electrochemical reactions.

CONCLUSION

This paper has presented the design and characterization of a USB-based portable adaptive multichannel electrochemical instrument. Tests results demonstrate that the portable instrument match a commercially available electrochemical instrument. Furthermore, dynamically variable gain for electrochemical measurement was demonstrated and verified.

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