JOURNAL OF CHEMICAL EDUCATION

Technology Report

Cite This: J. Chem. Educ. 2018, 95, 1658−1661

pubs.acs.org/jchemeduc

An Easily Fabricated Low-Cost Potentiostat Coupled with User-Friendly Software for Introducing Students to Electrochemical Reactions and Electroanalytical Techniques

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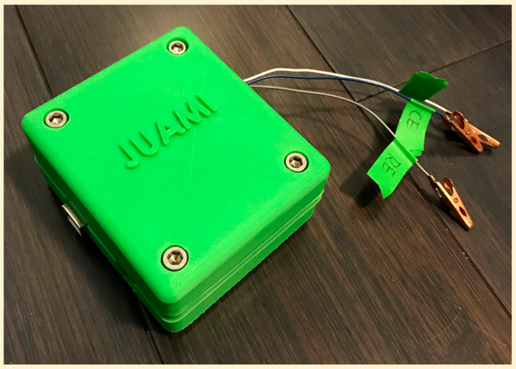
Supporting Information

ABSTRACT: This paper presents a teaching kit that combines the fabrication of a low-cost microcontroller-based potentiostat and a LabVIEW-generated graphical user interface. The potentiostat enables undergraduate-level students to learn electroanalytical techniques and characterize energy conversion devices such as solar cells. The purpose of this teaching module is to make the introduction of electrochemistry accessible to undergraduate laboratories, especially those with limited financial resources and without expertise in electronics or programming. The electronic circuit components for the potentiostat are readily available and easy to assemble. The graphical user interface replaces any programming-based interface, displays data in real time, and interacts with user commands. The software package is a stand-alone executable file that is compatible with any PC and is provided in the Supporting Information. Cyclic voltammetry, linear sweep voltammetry, and chronoamperometry functions are demonstrated with representative electrochemical experiments, and the data obtained are comparable to those obtained with a research-grade potentiostat. This teaching module is user-friendly so that it can be easily adapted into the undergraduate classroom. We make available in the Supporting Information all of the necessary instructions and information, including schematics for the potentiostat, circuit layout, electronic components, case fabrication, step-by-step instructions for assembly, software user interface, and detailed operating instructions.



KEYWORDS: *Upper-Division Undergraduate, Analytical Chemistry, Hands-On Learning/Manipulatives, Electrochemistry, Oxidation/Reduction, Laboratory Equipment/Apparatus*

INTRODUCTION

Low-cost and homemade electronics have enabled many new applications and opportunities in chemical education. Several previous reports have demonstrated the feasibility of inexpensive and do-it-yourself style potentiostats that are suitable for performing experiments such as cyclic voltammetry, linear sweep voltammetry, and square wave voltammetry.[1−5] These devices offer a valuable opportunity to teach modern electrochemistry in an undergraduate laboratory setting. Unfortunately, the low-cost potentiostats that have been reported to date have some issues that limit their implementation. Instruments that incorporate custom-made printed circuit boards have limited flexibility for expanding their functionality.[1−3] Published designs for low-cost potentio-

Received: May 11, 2018
Revised: July 1, 2018
Published: July 17, 2018

stats typically describe the hardware only.[4] In these cases, the communication between the hardware and a computer requires programming skill that may not be available to undergraduate students or their instructors. Finally, the information needed to construct the low-cost potentiostat is not always detailed enough for non-expert potential users.

Here we provide access to a kit that combines a low-cost microcontroller-based potentiostat with a LabVIEW-generated graphical interface. We have named it the JUAMI potentiostat, after a two-week program, the **J**oint **U**ndertaking for an **A**frican **M**aterials **I**nstitute, at which the authors met and initiated the project. The goal was to design a research-grade potentiostat that could be assembled easily and inexpensively from available electronic parts and to provide plug-and-play software and electrochemical experiments for use in Africa and other resource-constrained environments. The potentiostat and associated laboratory experiments provide an analytical tool for students to study a variety of electrochemical reactions and systems. With its modular construction and graphical interface, students and instructors also have the flexibility to modify the JUAMI potentiostat, e.g., by adding to the circuit board to expand its functionality for projects beyond the original design.

■ INSTRUMENT DEVELOPMENT AND RESULTS

Hardware

The design of the JUAMI potentiostat was adapted from earlier reports.[3,4] We adjusted the electronic design to improve the current compliance and frequency ranges in order to enable the current, voltage, and time resolution needed for the most common experiments in electroanalysis and electrochemical energy conversion. The device is based on an Arduino Uno circuit board and a user-fabricated daughter board, which are shown in Figure 1. The Arduino circuit board

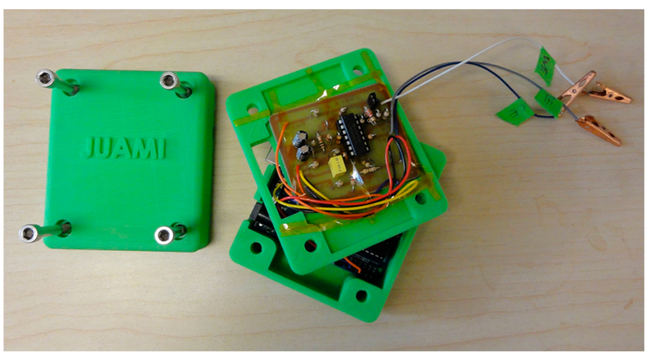


Figure 1. Hardware components of the JUAMI potentiostat, disassembled for display purposes.

generates a fixed-voltage waveform through the control of the pulse width modulation (PWM) pin. This voltage oscillates between high and low values at a fixed frequency. By control of the duty cycle of the voltage pulses, it is possible to generate voltage ramps at different scan rates and in different electrochemical windows to perform cyclic voltammetry, linear sweep voltammetry, or chronoamperometry. The current generated at the working electrode in electrochemical experiments is converted to voltage via a series shunt resistor and is recorded via the Arduino analog input pin. In addition to standard electroanalytical techniques, the JUAMI potentiostat provides the functionality needed to analyze electrochemical energy conversion devices, such as rechargeable coin cell batteries and solar cells. The microcontroller-based potentiostat design was chosen over a printed circuit board-based potentiostat because it requires fewer fabrication steps and provides extra flexibility for add-on modifications.[2] The user can reconfigure the Arduino board to perform additional tasks, such as recording a temperature input or sending output signals to control other electronics. A number of other Arduino-based analytical instruments such as pH meters, photometers, and gas chromatographs have been previously reported.[6−8] The Arduino also provides the flexibility for students to customize their own experiments. The electronic components are readily available, and the current total cost for the hardware is estimated to be $40. The technical details, circuit board design, and step-by-step assembly instructions for the JUAMI potentiostat are provided in the Supporting Information.

Software

Ease of use is a key figure of merit for low-cost, do-it-yourself instruments. Most available designs for user-fabricated potentiostats require at least some user programming experience to enable the computer interface. We provide here a LabVIEW-generated graphical user interface (GUI) that is simple to implement and use. The GUI records and displays current and voltage data from the potentiostat in real time on a Windows-based PC. This enables the student to make a direct correlation between his/her experimental observations and the data. The GUI also handles all of the programming and the communication to the Arduino board passively in the background via a USB connection. Thus, students interact only with the experimental parameters such as the scan rate or scanning window. These features improve the accessibility of the instrument for students and instructors with limited programming skills and shift the focus back to chemical education. The GUI is a stand-alone executable file generated from LabVIEW. A screen capture of the GUI is shown in Figure 2. Currently the GUI is designed to do cyclic

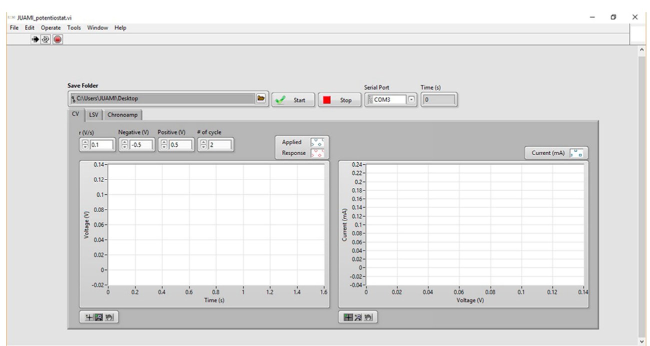


Figure 2. LabVIEW-generated graphical user interface for the JUAMI potentiostat.

voltammetry, linear scan voltammetry, and chronoamperometry. Each experiment corresponds to a tab on the GUI. Students set the parameters under the appropriate tab and hit "Start" to initiate an experiment. An experiment can be stopped midway by pressing the "Stop" button and restarted as needed. The experimental data are saved and exported as a .txt file for post analysis. The GUI software package and detailed instructions are provided in the Supporting Information.

DOI: 10.1021/acs.jchemed.8b00340
J. Chem. Educ. 2018, 95, 1658−1661

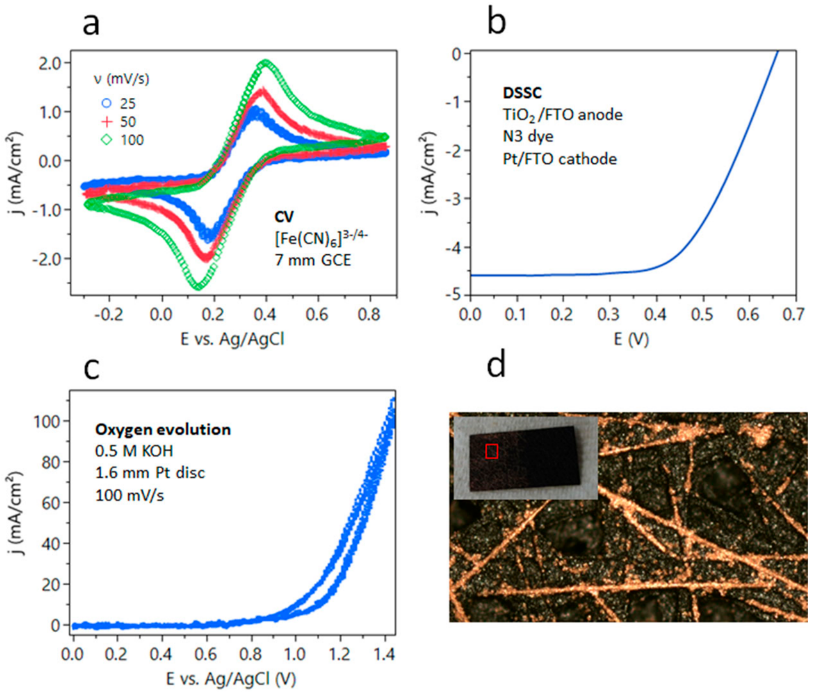


Figure 3. Electrochemical reactions recorded with the JUAMI potentiostat: (a) cyclic voltammetry of the $Fe(CN)_6^{3-/4-}$ redox couple; (b) *i*−*V* curve for an illuminated dye-sensitized solar cell; (c) *i*−*V* curve for the oxygen evolution reaction at a catalytic Pt electrode; (d) copper electrodeposition on a carbon paper electrode.

Performance Results

To demonstrate the capability of both the hardware and the software, several representative electrochemical applications were tested. Figure 3 shows (a) cyclic voltammograms of a $Fe(CN)_6^{3-/4-}$ redox couple, (b) an *i*−*V* curve for an illuminated dye-sensitized solar cell, (c) an *i*−*V* curve for the oxygen evolution reaction from water using an electrocatalytic Pt electrode, and (d) copper electrodeposition. The cyclic voltammetry experiment was carried out in a $K_3Fe(CN)_6$ solution with glassy carbon as the working electrode, Pt mesh as the counter electrode, and Ag/AgCl (saturated KCl) as the reference electrode. The scan rate was set to 25, 50, or 100 mV/s. The reversible electrochemical behavior of the redox couple and the dependence of the peak current on the square root of the scan rate, following the Randles−Sevcik equation, were successfully captured with the potentiostat. Detailed procedures for all of the experiments are available in the Supporting Information. Together these experiments demonstrate the scan rate, current/voltage windows, data resolution, and functionalities of the JUAMI potentiostat, which are on par with those of a typical research-grade potentiostat but at a much lower cost. The electrochemical behavior expected for each reaction is also captured successfully. The specifications of the JUAMI potentiostat are ±2.5 V, ∼10 mA current range, and ∼10 μA resolution. Most electrochemical reactions of interest lie within the −2.5 to 2.5 V electrochemical potential window. The maximum current limitation can be mitigated by the use of a working microelectrode, as demonstrated in Figure 3c for the oxygen evolution reaction, with good signal-to-noise ratio. Thus, the specifications of the JUAMI potentiostat are perfectly suitable for teaching electroanalytical techniques at the undergraduate laboratory level.

■ CONCLUSION

We provide a package of materials that affords easy access for students to learn about electroanalytical techniques. A low-cost potentiostat is fabricated from an Arduino Uno circuit board and readily available electronic components. A graphical user interface is generated with LabVIEW to simplify data communication between the hardware and a PC and to provide intuitive control software for the user. The device and software were tested with representative electrochemical reactions, and the results indicate that they should be broadly useful for studying electroanalytical techniques and electrochemical energy conversion. The JUAMI potentiostat has been distributed to and tested at different African universities with undergraduate students at some of the coauthors' home universities, and it has proven to be easy to use in that environment. The JUAMI potentiostat and GUI can be easily integrated into an undergraduate laboratory course and serve as an effective tool to promote the study of electrochemistry.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.8b00340.

3D drawing files for the potentiostat casing, Gerber file for the daughter board, and JUAMI software user interface (ZIP)

Materials, hardware assembly instructions, software instructions, and detailed experimental procedures (PDF, DOCX)

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DOI: 10.1021/acs.jchemed.8b00340
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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank the Materials Research Society for financial support. We also thank JUAMI (www.juami.org) for organizing the summer program where the authors met and conceived the idea for the project. JUAMI 2016, where the project was initiated, was supported by the National Science Foundation under Grant DMR-1539724.

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