Development and Implementation of a Low-Cost Electrochemistry Lab Kit for Educational Outreach

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Abstract

This report presents a comprehensive review and comparative study of four different potentiostat designs: The Meloni Design, CheapStat, PaqariStat, and SimpleStat. Each design was evaluated based on the criteria of design complexity, functional efficacy, and educational accessibility. After careful consideration, the Meloni Design was selected as the foundational blueprint for our project due to its simplicity, functionality, and educational value. Modifications were made to the Meloni Design in an attempt to enhance the precision of the control signal and simplify the implementation of the hardware design. Despite these improvements, persistent issues were encountered with accurately measuring the output current at the working electrode due to signal noise. While the expected current range was -2 mA to 2 mA, our design produced readings that fluctuated between 0.1 mA and 0.4 mA. These findings underscore the challenges and complexities involved in DIY potentiostat design. Future research will focus on addressing these limitations to improve the performance and reliability of our educational potentiostat.

Introduction

Electrochemical research holds immense potential to address challenges in energy sustainability and environmental conservation. This field encompasses work on renewable energy generation, energy storage, and environmental remediation, among others. A cornerstone for propelling advancements in these areas is educating the next generation of engineers and scientists. However, the significant costs associated with essential instrumentation, coupled with a lack of educational resources, present considerable hurdles.

At the heart of electrochemical research lies the potentiostat, an instrument fundamental to a variety of experimental methods. Commercial potentiostats often retail for over a thousand dollars, a price point that restricts educational opportunities and limits the pursuit of electrochemical innovation.

An increasing number of researchers have leveraged the rising accessibility of affordable microcontrollers, like the Arduino Uno, to develop low-cost potentiostats [Cook 2020]. While these economical devices may not yet match the capabilities of their commercial counterparts, they serve as invaluable educational tools. Still a gap exists between the research and the standardization of design for academic use. Literature explored in this report has shown designs all meeting benchmark testing, however, these projects remain difficult to implement in a high school or undergraduate setting. By introducing electrochemical techniques to students and resource-constrained communities, these low-cost potentiostats facilitate learning and stimulate innovation, despite financial limitations.

Literature Review

Four potentiostat designs were reviewed: The Meloni Design [Meloni 2016], CheapStat [Rowe 2011], PaqariStat [Cordova-Huaman 2021], and SimpleStat [Butterworth 2019]. These designs will be evaluated against specific criteria that align with our ambition to enhance education and outreach in Electrochemical Engineering. These criteria include: design complexity, functional efficacy, and educational accessibility.

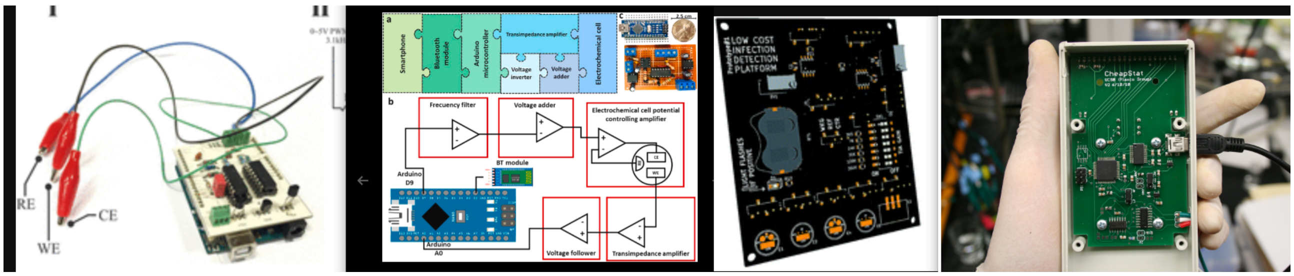


Figure 1: Left to Right: Meloni Design, PaqariStat, SimpleStat, CheapStat

Design Complexity

Potentiostat design complexity is a critical factor that influences both the user experience and the device's functional range. Among the four studied designs, two design approaches are discernible: the Arduino-based designs (the Meloni design and Paqari Stat) and the Integrated Chip (IC) based designs (Cheapstat and Simplestat). Each design's complexity is influenced by the hardware architecture and software implementation.

Hardware Architecture

The Meloni design and the Paqari Stat employ an Arduino Uno microcontroller as the backbone of their design. Their hardware architectures are modular, composed of three primary units: a Digital to Analog Converter (DAC)/signal converter, a control amplifier, and a transimpedance amplifier. This modular design approach can facilitate problem isolation, making it easier to diagnose and resolve hardware issues. However, there are slight differences between these two designs; while the Meloni design utilizes a counter electrode to measure output current, the Paqari Stat uses the working electrode for this purpose. This difference might impact the overall measurement accuracy, stability, and noise performance of the system.

On the other hand, Cheapstat and Simplestat are centered around a surface mount IC microcontroller, a more compact and integrated approach. This kind of architecture results in reduced size and possibly lower power consumption, making these designs more suitable for field applications. However, this integrated design approach could pose challenges in terms of self-assembly and troubleshooting.

Software Implementation

The software for the Arduino-based designs (Meloni and Paqari Stat) is programmed within the Arduino itself. Software development using the Arduino is based on C++, a widely used language that provides good accessibility for non-specialists or beginners. While the Meloni design relies solely on using the Arduino for it's software, the Paqari Stat goes a step further by incorporating a smartphone-based app. While using an existing application may improve user interaction it may reduce the educational benefits of the project.

In contrast, Cheapstat and Simplestat require assembly language coding to program their hardware. Assembly language, a low-level language, allows direct hardware control and optimization but comes at the cost of complexity. Understanding and programming in assembly language can be a challenging task, especially for beginners or non-specialists. This could limit the accessibility and adaptability of these designs to specific experimental setups or novel applications.

For the Meloni design, the hardware and software engineering decisions for the design were clearly explained, making it the design best suited for implementation in an educational context. While, for PaqariStat, Cheapstat, and Simplestat, the hardware design is not well-documented. This lack of clarity could pose significant challenges during self-assembly, especially for users with limited hardware experience.

Design complexity varies significantly among the four potentiostat designs studied. The Arduino-based designs are characterized by a more modular hardware architecture, user-friendly software. On the contrary, the IC-based designs have more integrated architectures, more complex software, and require more detailed assembly documentation. The choice between these design routes will largely depend on the user's technical skills, application requirements, and available resources.

Functional Efficacy

The functional efficacy of a potentiostat design is defined by its ability to deliver accurate and reliable measurements under various experimental conditions. Each of the four potentiostat designs - the Meloni design (2016), Cheapstat (2011), Paqari Stat (2021), and Simplestat (2019) - was evaluated for their efficacy based on their performance in Cyclic Voltammetry (CV) tests using a standard potassium ferricyanide experiment.

The Meloni design has demonstrated high functional efficacy as its performance closely matched the expected results from the literature. The design follows a three-stage architecture, utilizing an 8-bit Pulse Width Modulation (PWM) signal for control, which may influence the accuracy of the results. However, it should be noted that this design is limited to performing only CV, limiting its applicability to a narrower range of electrochemical experiments. The effect of these design choices on the device's performance in a wider range of experimental conditions is an area that warrants further exploration. The voltage range of the CV scan is fixed at -1v to +1v.

The Paqari Stat demonstrated positive results, with the device's performance falling within acceptable margins when tested against lab-grade equipment. This is an encouraging indication of its functional efficacy. Like the Meloni design, it is based on an Arduino microcontroller and follows a similar three-stage hardware architecture. The Paqari Stat, however, uses the working electrode to measure output current, unlike the Meloni design, which uses a counter electrode. This difference in design choice might have an impact on the comparative functional efficacy of the two designs, though further investigation is required to confirm this.

The CheapStat performed it's benchmark testing using a potassium ferricyanide based experiment as well. The article states that the ferricyanide redox response forms the characteristic "duck" shape expect from the experiment. This was conducted using a commercial made reference electrode and a homemade reference, demonstrating close agreemnt when observing the reaction. The device was then used to perform analysis of acetaminophen content in over the counter medication and measurements of arsenic in water. These results show great promise in the efficacy of DIY potentiostat designs.

The Simplestat's performance was also tested against a potassium ferricyanide solution, yielding positive results. Like the Cheapstat, the Simplestat utilizes a surface mount IC microcontroller and is designed around a printed PCB. The Simplestat's design incorporates an 8-bit DAC and a 10-bit Analog to Digital Converter (ADC), allowing for a CV range of -0.6v to 0.6v. These design choices might contribute to the observed efficacy but, as with the Cheapstat, a more detailed elaboration of the testing parameters and comparative performance would enhance understanding of the design's efficacy.

The functional efficacy of each potentiostat design appears promising based on the described CV testing. The efficacy of these designs across a broader range of electrochemical experiments beyond CV would benefit this area of research.

Educational Accessibility

Educational accessibility is a key consideration when assessing these potentiostat designs, particularly in terms of their suitability for teaching environments like undergraduate laboratories. This dimension encompasses the ease of understanding the device's operation, the clarity of its assembly instructions, and the feasibility of using it as a teaching tool to elucidate fundamental electrochemical principles.

The Meloni design, with its Arduino-based approach, offers a relatively straightforward design and software implementation. It relies on a commonly used Arduino Uno microcontroller, an 8-bit signal for control, and a three-stage hardware design, all of which are concepts that are relatively easy to grasp for undergraduate students. The depth of explaination of the hardware's design by Meloni makes it the clearest to implement.

Like the Meloni design, Paqari Stat utilizes an Arduino-based approach, making it comparatively more accessible for educational use. The addition of a smartphone app for controlling the potentiostat makes troubleshooting errors between the hardware and software more difficult to fix. This app could also act as a 'black box', obscuring the underlying processes and impeding students from fully understanding the potentiostat's operation. While this design seems as promising as the Meloni design in terms of educational potential, the role of the smartphone app in an educational setting requires further exploration.

The Cheapstat, with its surface mount IC microcontroller and assembly language coding, presents a more challenging approach for undergraduate students. Assembly language, being a low-level language, provides deeper control over hardware but at the cost of complexity and a steep learning curve. Furthermore, the hardware design is not well-documented, which can cause further obstacles to understanding and replicating the design. While Cheapstat might be more appropriate for graduate students or practicing electrochemists who seek a cost-effective field potentiostat, its educational accessibility for undergraduate students seems limited.

Similar to Cheapstat, SimpleStat employs a surface mounted IC microcontroller and assembly language coding. This results in a higher level of opacity in both hardware and software design, which may present significant challenges for undergraduate students with limited programming and hardware experience. Consequently, it appears more suitable for advanced users such as graduate students or professional electrochemists.

In terms of educational accessibility, the Arduino-based potentiostats (Meloni and Paqari Stat) seem more approachable for undergraduate students due to their relative simplicity and familiar software implementation. The additional smartphone interface of the Paqari Stat could be a double-edged sword, simultaneously promoting engagement while potentially limiting understanding of underlying processes. In contrast, the IC-based designs (Cheapstat and Simplestat) present higher complexity, which might pose substantial challenges for students but offer potentially richer learning experiences for more advanced users.

Balancing these criteria, we found the Meloni Design most effectively met our standards of design simplicity, functional efficacy, and educational accessibility. This led us to select it as the foundational framework for our potentiostat design.

Methods

In this section, we outline the methods employed in the development and benchmarking of our potentiostat design. The aim is to provide a comprehensive understanding of our approach, which involved two key processes. First, we modified the existing Meloni Design and developed an Arduino and Python based software for control and data collection. Second, we implemented a benchmarking protocol using a Ferri/ferrocyanide redox reaction to evaluate the performance of our design.

Potentiostat Design: Hardware and Software Modifications Based on the Meloni Design

The Meloni Design showed excellent benchmark metrics compared to professional potentiostats while also using an easy to follow beginner friendly design. The Meloni Design is comprised of 7 stages (fig. 2).

1. Software-generated Pulse Width Modulated (PWM) control signal
2. Hardware filtering of control signal
3. Control signal biasing
4. Potentiostat control amplifier
5. Current to voltage conversion
6. Output signal buffer
7. Output signal software processing

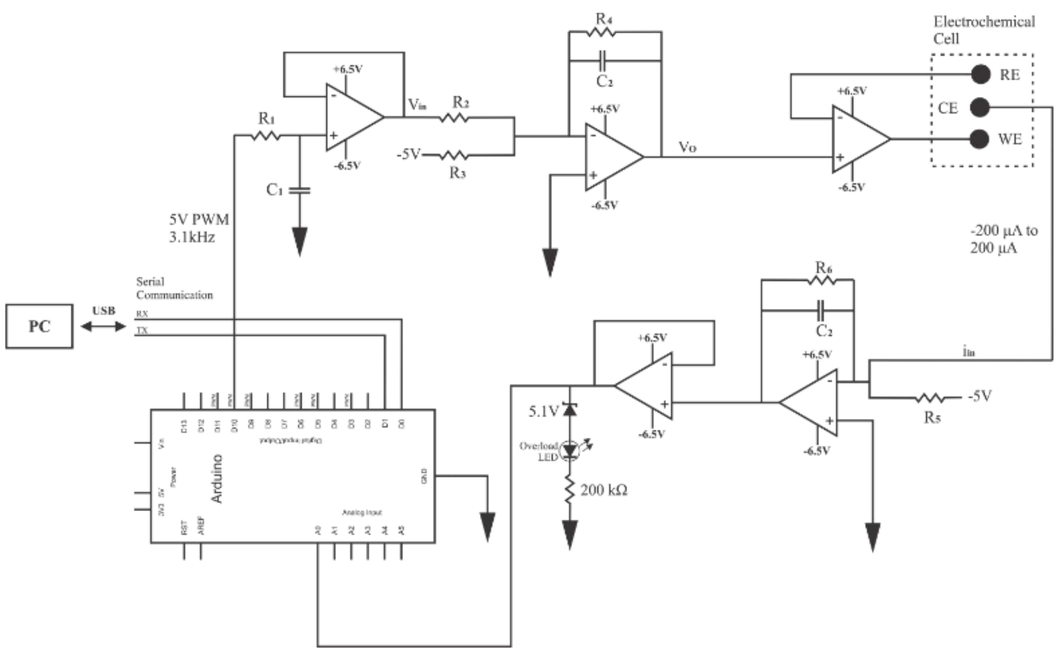


Figure 2: Meloni Design

There are three design components that are being adjusted from the Meloni Design. First, we changed how the control signal is generated. The Meloni Design uses a single PWM pin from the Arduino in combination with an RC filter and an op-amp in an integrator configuration to produce the control signal for the CV. For our design, we chose to use a 10-bit Digital-Analog Converter (DAC) using an R2R ladder. This offers two benefits: first, it offers greater resolution for the control signal - 10-bit precision instead of 8-bit with the PWM design. The R2R ladder is a fundamental circuit design used in entry-level electrical engineering coursework, whereas the PWM design may be considered more advanced. Second, we chose to swap the connections between the working electrode (WE) and the counter electrode (CE). This design decision was made with consultation from a BioLogic representative who claimed that since we are concerned about the current through the working electrode, it is assumed that measuring the current directly through it is the optimal design solution. Third, we will change the method used for current to voltage conversion. We will use the benchmark testing current maximum and minimum values to calculate an appropriate current measuring resistor and this voltage will buffered, amplified, and then buffered again before being sent to the Arduino for further processing.

The modifications to the original Meloni Design were made in line with theoretical circuit analysis techniques. The use of an R2R ladder and the need for future students to perform circuit analysis to attenuate component values offer a greater learning opportunity for students. With this in mind the construction of the potentiostat used in this report can be understood as follows:

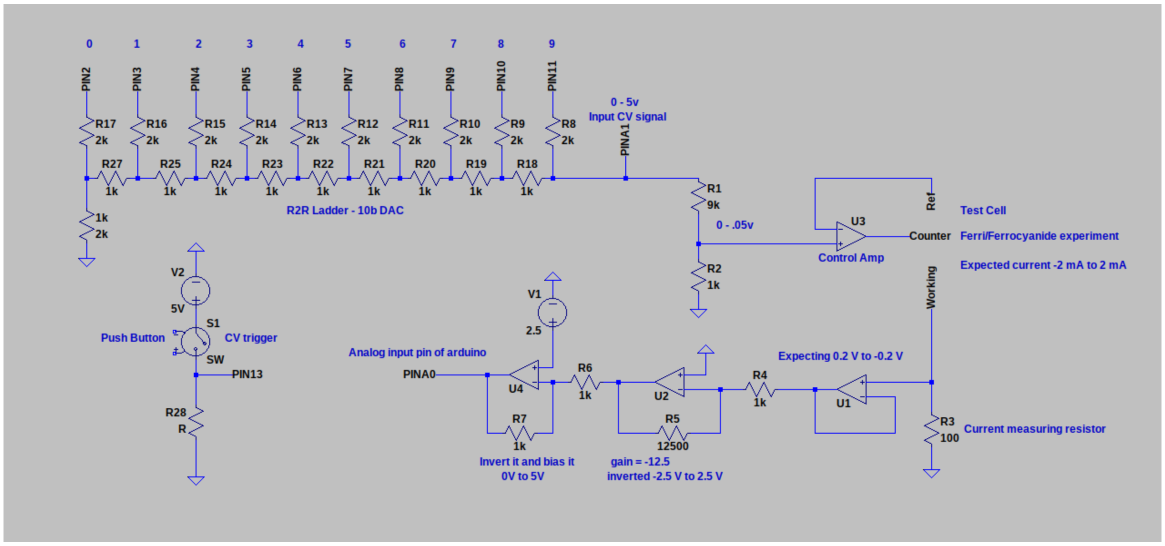


Figure 3: Our Design

Hardware Design

For our potentiostat design we are using an Arduino Uno as the main controller of the potentiostat(resource ref). The Arduino Uno will be responsible for outputing the CV control signal and it will be responsible for sensing the potential applied at the test cell and the output voltage to be used to calculate the output current that passes through the working electrode of the test cell. Further data processing will be conducted using serial communication between the Arduino and a computer (see Software Design for greater detail).

The output control signal that will generate the CV begins with the Arduino's digital pins 2-11. These pins are connected to a corresponding 10 bit R2R ladder which acts as the potentiostats DAC. Since the digital output of each pin is 5 volts the possible output of this R2R ladder will range from 0 to 5 volts. In order to get an accurate reading of the potential being applied to the control amplifier, the Arduino will be sensing the voltage at the output of this R2R ladder, which is connected to the Arduino's analog input pin A1.

The next stage we will process the signal to fit within the desired potential range. For our experiment we are using a CV potential range from 0v to 0.5v. This can be achieved using a voltage divider to scale the control signal by one tenth. It should be noted that this value can be adjusted to fit other potential ranges depending on the needs of future researchers. This scaled signal is then fed to the non inverting input terminal of the control amplifier.

The output of the control amplifier is connected to the CE of the test cell, while the reference electrode (RE) is connected to the inverting input of the control amplifier. The control amplifier is the heart of the potentiostat. This element is what ensures that the voltage at the RE follows the control signal. The WE is then connected to a measurement resistor which is then connected to ground.

This voltage is then scaled to fit within the Arduino's 0 to 5 volt sensing range. It is important to note that the scaling function and component values may need to be adjusted depending on the voltage that is detected across the measurement resistor. It is crucial that the signal can fit well within this range, if not the signal will become clipped and experimental data will be lost.

For our experiment we expect a current within the bounds of -2mA to 2mA. This will then be amplified using an op amp in an inverting amplifier configuration and then the signal will be inverted again and biased to fit within the 0 to 5 volt range of the Arduino sensing range. We will see in the results that this configuration will be adjusted due to errors in the experimental set up.

In addition to the potentiostat circuit, there is also a push button that is used to initialize the CV experiment. This takes a 5v signal from the Arduino, passes it to a button, which then completes a circuit through a resistor to ground, when the 5v is sensed it will begin the CV sweep.

Software Design

The software design has two core components: the CV function and data processing. The CV function has two components, the C++ Arduino code and a python script to capture serial transmission data from the Arduino. The data processing step will take the recorded data, process it and output the CV graph and data.

The Arduino code presents a functional potentiostat software tailored for conducting CV measurements. The sketch operates in a loop, waiting for a trigger signal to activate the CV mode. Within the CV mode, the `cvMode` function controls the voltage output to the potentiostat based on elapsed time and a specified scan rate, generating the desired waveform. The function employs a while loop to execute a series of CV cycles until the desired cycle count is reached. During each cycle, the sketch reads voltage output from the potentiostat and the electrochemical cell's response using analog-to-digital converters. Real-time data is printed to the Serial Monitor, allowing researchers to monitor the CV operation. The sketch can be extended for other electrochemical studies, offering a versatile tool for exploring redox behavior in materials.

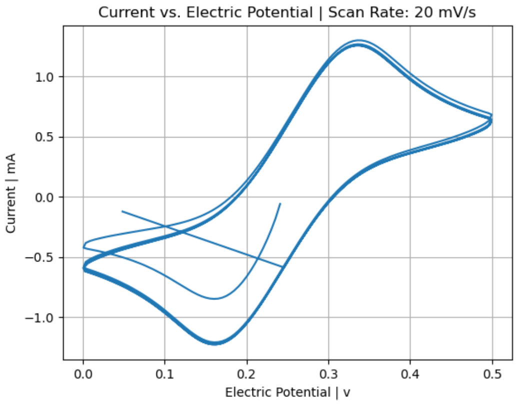
The Python script facilitates real-time data acquisition via the Arduino's USB serial connection. Upon establishing the serial port configuration, the script enters a continuous loop to read data from the potentiostat. The acquired data is written to a text file enabling the accumulation of results. The script is designed to run indefinitely until interrupted by a keyboard interrupt. This script provides a convenient means of acquiring and saving data.

Benchmarking: Ferri/Ferrocyanide Redox Reaction Electrochemical Cell Setup

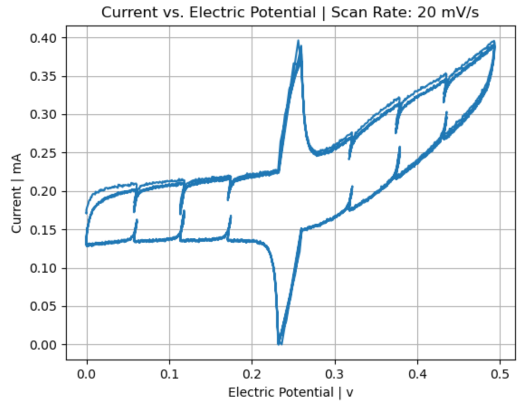
The electrochemical reaction to be studied is a ferricyanide/ferrocyanide redox reaction. This reaction will first be conducted using a BioLogic VSP-300 potentiostat using the EC-Lab software. A CV will be produced using a potential window from 0 to 0.5 volts, with scan rates of 20, 50, and 100 mV/s. This benchmark testing will provide an expected current range of the redox reaction.

For the complete parts list, experimental procedure and lab companion see the Supplemental Material section.

Results

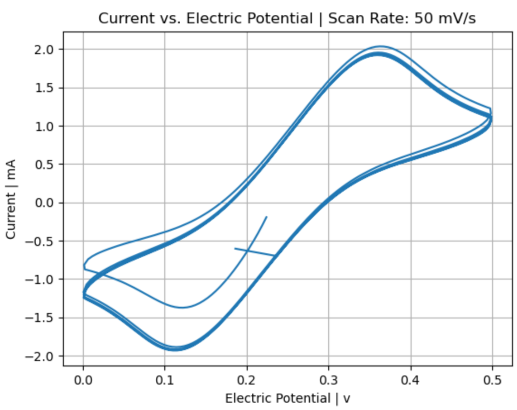


(a) BioLogic VSP-300 FeCN 20 mV/s 5 cycles

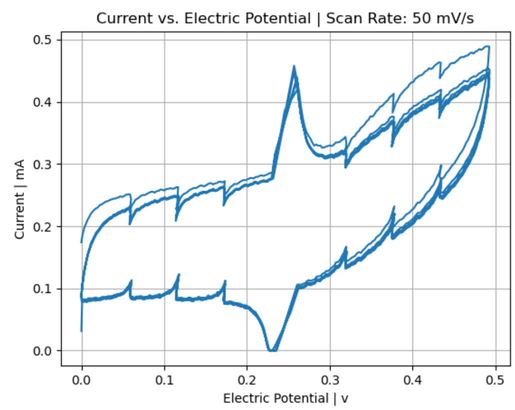


(b) DIY Potentiostat FeCN 20 mV/s 5 cycles

Figure 4: Side-by-side images

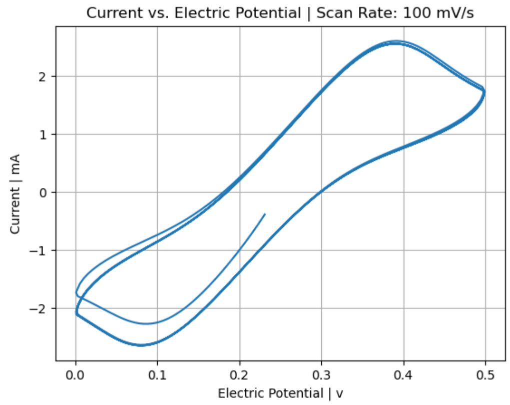


(a) BioLogic VSP-300 FeCN 50 mV/s 5 cycles

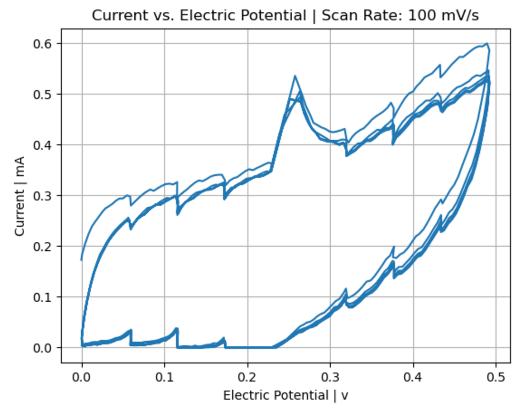


(b) DIY Potentiostat FeCN 50 mV/s 5 cycles

Figure 5: Side-by-side images



(a) BioLogic VSP-300 FeCN 100 mV/s 5 cycles



(b) DIY Potentiostat FeCN 100 mV/s 5 cycles

(c) Caption for Image 2

Figure 6: Side-by-side images

Discussion

Conclusion

Acknowledgements

References

Butterworth A, Corrigan DK, et al. (2019) Electrochemical detection of oxacillin resistance with SimpleStat: a low cost integrated potentiostat and sensor platform. *Analytical Methods.* Issue 14.

Cook J (2020). SIMstat: Hardware Design Considerations for Implementing a Low-Cost, Portable Potentiostat. *Unpublished Bachelor's Thesis.* Oregon State University

Cordova-Huaman AV, Jauja-Ccana VR, et al. (2021) Low-cost smartphone-controlled potentiostat based on Arduino for teaching electrochemistry fundamentals and applications.*Heliyon*, Volume 7, Issue 2.

Meloni, GN (2016). Building a Microcontroller Based Potentiostat: A Inexpensive and Versatile Platform for Teaching Electrochemistry and Instrumentation. *Journal of Chemical Education* 93(7), 1320-1322.

Rowe AA, Bonham AJ, et al. (2011) CheapStat: An Open-Source, "Do-It-Yourself" Potentiostat for Analytical and Educational Applications. *PLoS ONE* 6(9).

Supplemental Material

Appendix

1

```
// Christopher Hunt
// potentiostat.ino

// User Set Init Params
const int CELL_OUTPUT = A0; // Analog Read pin to read electrochemical cell
    output. Reads voltage data from TIA in circuit.
const int CV_VOLTAGE = A1; // Reads current voltage being supplied to the
    potentiostat.
const uint8_t TRIGGER_PIN = 13; // Trigger pin. Detecting push button to trigger
    the CV.
const int MODE = 0; // Mode 0 is CV. Designed to potentially expand to perform
    EIS

// Cyclic Voltammetry : mode = 0
const float SCAN_RATE = .02; // The rate of the CV scan in V/s
const int CYCLES = 100; // How many times the CV is performed

/**
 * Function: cvMode
 * ----------------
 * Implements the CV (Cyclic Voltammetry) mode of operation. The function
     performs a series
 * of CV cycles until the specified number of cycles (CV_CYCLES) is reached. It
     controls the
 * voltage output based on the elapsed time and scan rate, updating the DAC ports
      to generate
 * the desired waveform.
 *
 *   The function utilizes a while loop to execute the CV cycles until the cycle
     count reaches
 *   the desired number of cycles. It maintains the elapsed time since the start
     of the CV mode
 *   using the `micros()` function. By comparing this elapsed time with the scan
     rate and direction,
 *   it calculates the corresponding voltage value (`value`) for the DAC ports.
 *
 *   The function employs an if-else statement to determine whether the voltage
     should increment
 *   or decrement based on the current direction (`forward`). The `adj_scan_rate`
      is used to adjust
 *   the rate of change per unit time. If the calculated value exceeds the range
     of 0 to 1023,
 *   it is clamped to the corresponding limit, and the direction is switched
     accordingly.
 *
 *   The function then calls the `portSelectDAC` function to configure the DAC
     ports with the
 *   calculated voltage value. The DAC value is split into two bytes (`
     portdb_bytes[0]` and `portdb_bytes[1]`),
 *   which are then assigned to the appropriate DAC ports. This enables the
     generation of the desired waveform.
 *
 *   Additionally, the current `value` is printed to the Serial Monitor using `
     Serial.println()`,
 *   providing real-time feedback and monitoring of the CV operation.
```

```
 */
void cvMode() {
  const float scan_rate = SCAN_RATE * (10230.0 / 5000000.0);
  bool forward = true;
  int cycle = 0;
  unsigned long start_time = micros();
  unsigned long time = 0;
  float value = 0;
  int rounded_value = 0;
  int sensor_value = 0;
  int control_value = 0;
  unsigned long last_read_time1 = 0;
  unsigned long last_read_time2 = 0;
  unsigned long sensor_data[10];
  unsigned long control_data[10];
  int sensor_data_index = 0;
  const unsigned long read_interval1 = 100;   //
  const unsigned long read_interval2 = 1000;  // Microseconds between reads
  const float inv_num_readings = 0.1;  // 1/10 for 10 readings

  while (cycle < CYCLES) {
    time = micros() - start_time;

    if (forward) {
      value = scan_rate * time;
      rounded_value = (int)value;  // Typecast directly to int
      if (rounded_value >= 1023) {
        rounded_value = 1023;
        forward = false;
        start_time = micros();
      }

    } else {
      value = -scan_rate * time + 1023;
      rounded_value = (int)value;  // Typecast directly to int

      if (rounded_value <= 0) {
        rounded_value = 0;
        forward = true;
        start_time = micros();
        cycle++;
      }
    }

    // Send value to 10-bit DAC
    PORTD = (rounded_value << 2) & 0xFC;
    PORTB = (rounded_value >> 6) & 0x0F;

    // Read sensor data every read_interval1 microseconds
    if (micros() - last_read_time1 >= read_interval1) {
      last_read_time1 = micros();
      sensor_data[sensor_data_index] = analogRead(CELL_OUTPUT);
      control_data[sensor_data_index] = analogRead(CV_VOLTAGE);
      sensor_data_index++;
    }

    // Calculate average and send data every read_interval2 microseconds
    if (micros() - last_read_time2 >= read_interval2) {
      last_read_time2 = micros();
      int sum_sensor = 0;
```

```
        int sum_control = 0;
        for (int i = 0; i < 10; i++) {
          sum_sensor += sensor_data[i];
          sum_control += control_data[i];
        }
        sensor_data_index = 0;
        sum_sensor *= inv_num_readings;  // Multiply by the inverse to avoid
            division
        sum_control *= inv_num_readings;
        sensor_value = sum_sensor;
        control_value = sum_control;
        Serial.print(control_value);
        Serial.print('\t');
        Serial.println(sensor_value);
      }
    }
  }



  /**
   * Function: setup
   * ----------------
   * Configures the initial setup and pin modes for an Arduino sketch.
   * It sets the data direction registers (DDRx) for digital pins D2 to D7 and B0
      to B3,
   * configures pin C0 as an input pin, and initializes the Serial communication at
       9600 baud rate.
   *
   * Pin Configuration:
   *   - Digital pins D2 to D7 are set as output pins by setting the corresponding
      bits in DDRD to HIGH (1).
   *   - Digital pins B0 to B3 are set as output pins by setting the corresponding
      bits in DDRB to HIGH (1).
   *
   * Serial Communication:
   *   - Serial communication is initiated by calling `Serial.begin(9600)`.
   *   - The baud rate is set to 9600 bits per second.
   */
  void setup() {
    DDRD |= B11111100;
    DDRB |= B00001111;
    pinMode(CELL_OUTPUT, INPUT);
    pinMode(CV_VOLTAGE, INPUT);

    // Set pins to 0v
    PORTD = 0x00;
    PORTB = 0x00;
    Serial.begin(9600);
  }


  /**
   * Function: loop
   * ----------------
   * The main execution loop for the Arduino sketch.
   * It waits for the trigger pin to go HIGH and then executes the selected mode
      based on the MODE variable.
   * After completing the mode execution, it waits for a specified delay before
      starting the sequence again.
```

```
 *
 */
void loop() {
  // Wait for trigger pin to go HIGH
  while (digitalRead(TRIGGER_PIN) == LOW) {
  }

  switch (MODE) {
    case 0:
      cvMode();
      break;

    default:
      Serial.print("Incorrect Mode.");
      break;
  }

  // Wait before starting the sequence again
  delay(1000); // Adjust the delay between repetitions as needed
}
```

2

```
# Christopher Hunt
# serial_2_txt.py
import serial
import sys

# Serial port configuration
serial_port = '/dev/ttyACM0'  # Replace with the appropriate serial port
baud_rate = 9600

# File path for saving data
file_path = 'data.txt'

# Open the serial port
ser = serial.Serial(serial_port, baud_rate)

# Open the file in append mode
with open(file_path, 'a') as file:
    try:
        # Read data from the serial port and write it to the file
        while True:
            if ser.in_waiting > 0:
                data = ser.readline().decode().strip()
                file.write(data + '\n')
                file.flush()  # Flush the buffer to ensure immediate writing

    except KeyboardInterrupt:
        # Handle keyboard interrupt (Ctrl+C)
        print("Keyboard interrupt detected. Exiting...")
        ser.close()  # Close the serial port
        sys.exit(0)
```

3

```
# Christopher Hunt
# graph.py

import matplotlib.pyplot as plt

def read_data(file_path):
    x_values = []
    y_values = []

    with open(file_path, 'r') as file:
        for line in file:
            data = line.strip().split('\t')
            if len(data) == 2:
                data[0] = (.5/1023)*float(data[0])
                data[1] = ((4/1023)*float(data[1]) - 2)/12500*10**6
                x_values.append(data[0])
                y_values.append(data[1])

    return x_values, y_values

data_file = 'data.txt'  # Update with your file path
x, y = read_data(data_file)

plt.scatter(x, y)
plt.xlabel('V_in')
plt.ylabel('I_out')
plt.title('Data Plot')
plt.grid(True)
plt.show()
```