

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 its 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. Assem-

bly 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 its benchmark testing using a potassium ferricyanide based experiment as well. The article states that the ferricyanide redox response forms the characteristic "duck" shape expected from the experiment. This was conducted using a commercial made reference electrode and a homemade reference, demonstrating close agreement 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 explanation 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.

Methodology

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 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

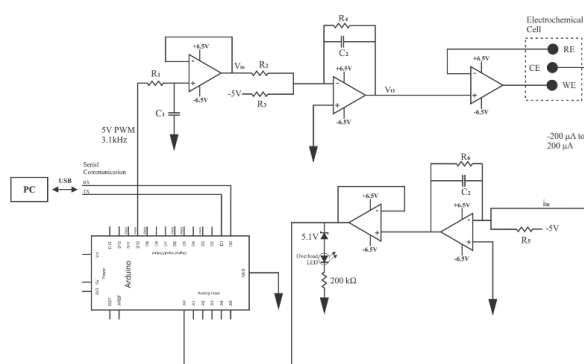


Figure 2: Meloni Design

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.

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. Second, 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 must alter the values of the current to voltage converter. We will use the benchmark testing current maximum and minimum values to calculate the appropriate resistor and capacitor values for this circuit.

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.

We are adopting a twofold data collection process. First, we will collect circuit output measurements to validate each stage of the design. This ensures that the hardware is outputting the expected values in each stage of the hardware before conducting any electrochemical experiments. Next, we will perform the ferri/ferrocyanide experiment. The current from the working electrode will be converted to a voltage between 0-5V. The data collected will be transferred to a PC and then processed using python.

Our research, while thorough, encounters certain limitations. The resolution of the cyclic voltammetry control signal and the analog input detector is 4.88 millivolts, which may not be sufficient for some highly sensitive applications. In addition, aligning the output current to a 0-5V scale presents a challenge as it's not entirely accurate. The signal conversion hardware assumes a maximum and minimum current, which could be variable. If the current is outside this range, the sensor either outputs 0 or 1023, meaning the measurements could be clipped or skewed.

This research presents a comprehensive methodology to assess, improve, and compare Arduino-based potentiostat designs. While there are some limitations, the study leverages the strengths of existing designs, particularly the Meloni Design, and contributes valuable enhancements to this field. Further studies can build on these findings, optimizing and addressing the identified limitations.

Benchmarking: Ferri/Ferrocyanide Redox Reaction Electrochemical Cell Setup

Results

Discussion

Conclusion

References

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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).

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()
```