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

Student: Christopher Hunt
Mentor: Dr. Kelsey Stoerzinger

Electrochemical research holds immense potential to address challenges in energy sustainability and environmental conservation. This field encompasses work on renewable energy generation, energy storage, carbon capture, 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 [Rowe AA 2011].

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 review 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.

This review encompasses four potentiostat designs. A design by Gabriel N. Meloni from the University of Sao Paulo, refered here as The Meloni design. Another by Aaron A. Rowe, et al. from the University of Santa Barbara called the CheapStat. Another by Allison V. Cordova-Huaman, et al. called the PaqariStat. And another designed by Adrian Butterworth, et al. named the SimpleStat. 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, educational accessibility.

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 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. [Meloni 2016] 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 code, a high-level, user-friendly 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 [Cordova 2021]. 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.

Another factor influencing design complexity is the transparency of the information provided in the design documents. This includes the clarity of component values, assembly instructions, and system schematics. For the Meloni design, the component values and the engineering decisions for the design were clearly explained, making it the design best suited for implementation in an educational context [Meloni 2016].

For 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. The Paqari Stat design documentation appears to be more comprehensive, providing clearer guidance on component selection and assembly.

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 Cyclic Voltammetry, 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. [Meloni 2016]

The Paqari Stat demonstrated positive results, with the device's performance falling within acceptable margins when tested against lab-grade equipment [Cordova 2021]. 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 [Rowe 2011]. 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 ADC, allowing for a CV range of -0.6v to 0.6v [Butterworth 2019]. 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 Cyclic Voltammetry 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 and errors between the hardware and software much more difficult to fix. This app could also potentially 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 mount 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. Further research, with a focus on user experience in a real educational setting, could provide valuable insights into the educational accessibility of these designs.

Conclusion

In this literature review, we explored four distinctive low-cost potentiostat designs for educational outreach: The Meloni design, CheapStat, PaqariStat, and SimpleStat. We evaluated them based on their design complexity, functional efficacy, and educational accessibility.

From the perspective of design complexity, the Arduino-based designs (Meloni and Paqari Stat) emerged as user-friendly options due to their modular hardware architectures and high-level software. However, this came with the need for clear component specifications for replication. IC-based designs (Cheapstat and Simplestat), although more integrated and possibly energy efficient, presented challenges in self-assembly and required more detailed assembly documentation.

As for functional efficacy, all four designs showcased promising results based on the Cyclic Voltammetry tests. However, given the variation in the level of detail provided and the range of electrochemical experiments, more comprehensive testing and documentation are necessary for a thorough comparison and understanding of their functional capabilities.

In terms of educational accessibility, the Arduino-based designs (Meloni and Paqari Stat) appeared more suited for undergraduate students, whereas IC-based designs (Cheapstat and Simplestat), despite their higher complexity, might offer a richer learning experience for more advanced users.

While this review provides a comprehensive exploration of these four low-cost potentiostat designs, the final selection would inevitably depend on the users' specific needs and the educational environment they will be deployed in. Further hands-on exploration and user experience studies could augment the understanding of these designs' real-world applicability and potential. It is our hope that this review aids in identifying suitable low-cost potentiostat designs for educators and researchers striving to democratize and innovate electrochemical education. We are enthusiastic about the promise that these low-cost designs hold for bridging the gap between electrochemical research and educational outreach.

However, it is clear that more work is needed to standardize these designs for academic use. The community should continue pushing towards producing low-cost, reliable, and accessible potentiostat designs, thereby accelerating learning and innovation in the field of electrochemistry.

References

Gabriel N. Meloni, 2016. Building a Microcontroller Based Potentiostat: A Inexpensive and Versatile Platform for Teaching Electrochemistry and Instrumentation. *Journal of Chemical Education* 93(7), 1320-1322. https://pubs.acs.org/doi/10.1021/acs.jchemed.5b00961

Rowe AA, Bonham AJ, et al. 2011 CheapStat: An Open-Source, "Do-It-Yourself" Potentiostat for Analytical and Educational Applications. *PLoS ONE* 6(9). https://pubmed.ncbi.nlm.nih.gov/21931613/

Allison V. Cordova-Huaman, Victor R. Jauja-Ccana, Adolfo La Rosa-Toro, 2021 Low-cost smartphone-controlled potentiostat based on Arduino for teaching electrochemistry fundamentals and applications.*Heliyon*, Volume 7, Issue 2. https://doi.org/10.1016/j.heliyon.2021.e06259.

Adrian Butterworth, Damion K. Corrigan, Andrew C. Ward. 2019 Electrochemical detection of oxacillin resistance with SimpleStat: a low cost integrated potentiostat and sensor platform. *Analytical Methods.* Issue 14. https://pubs.rsc.org/en/content/articlelanding/2019/ay/c9ay00383e

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