Cost-Effective DIY Electrometer

Emily R. Johnson

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Cost-Effective DIY Electrometer

Ben Hahn and Emily Johnson

Advisor: Dr. Damon Miller

Sponsor: WMU Neurobiology Engineering Laboratory

ECE 4820 Electrical and Computer Engineering Design II

April 17th, 2020
Abstract

An electrometer is a critical electrophysiology instrument used to generate minuscule currents for intracellular stimulation of biological neurons. An electrometer also enables simultaneous measurement of the neuron membrane voltage response. This device is necessary to perform accurate stimulation of neurons. However, the cost of commercial electrometers, around $5000, is prohibitive to many researchers, particularly at the high-school or introductory college level. A recent Western Michigan University graduate student, Lucas Essenburg, designed a basic electrometer for $210. His thesis proved that quality electrometers can be constructed for a fraction of the price of commercial-grade equipment.

This project focused on the improvement and commercial viability of Mr. Essenburg’s work. A full kit was designed which contains three printed circuit boards, two enclosures, electrical components, and a manual that described construction and trouble-shooting. The printed circuit boards were designed using KiCad, a free printed circuit board design program. This allows future groups to update the current design. The final product cost around $375 per kit. This price is significantly less than the price for commercial grade electrometers while still offering the same basic capabilities.
DISCLAIMER

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**PROJECT SPONSOR**Did this project have a sponsor? YES X (see footnote) NO____

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Design team has requested sponsor to verify in writing to course coordinator that all promised deliverables have been received. YES____ NO____ (please check)

**TEAM MEMBERS NAMES:**

<table>
<thead>
<tr>
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<th>NAME SIGNED</th>
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<tbody>
<tr>
<td>Benjamin Hahn</td>
<td>____________</td>
<td>______</td>
</tr>
<tr>
<td>Emily Johnson</td>
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</tbody>
</table>

* Those teams with a sponsor must have sponsor provide the course coordinator with written evidence that they have provided the sponsor with a copy of the final project report as well as with other items that the team has promised to the sponsor. The evidence could be a short note via email, fax or US mail from the sponsor indicating receipt of a copy of the report and all promised deliverables.
Acknowledgments

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1. Summary

Electrometers are critical instruments in the field of electrophysiology. They stimulate neurons with nanoamp-level currents. Once stimulated, the electrometer also records the resulting voltage response from the neuron. Without this instrument, accurate stimulation and recording of neural responses would be impossible.

2. Introduction

There is a need for an electrometer kit that is affordable for teaching in collegiate laboratories. Currently, commercial-grade electrometers cost around $5000 per instrument. However, a recent Western Michigan University master’s student, Lucas Essenburg, designed and built an electrometer for around $210 [1]. This project improves on Mr. Essenburg’s design by incorporating printed circuit boards while updating the enclosures to fit within typical electrophysiology rigs.

3. Discussion

3.1. Overview

3.1.1. Background and Description

An electrometer allows researchers to stimulate neurons with nanoamp currents. The neuron will fire an action potential depending on the stimulation. These voltage changes are captured by the same electrometer. Such data is critical for understanding principles of neuron function.

One of the difficulties of entering the field of neurobiological experimentation is the cost of electrometers. High-quality electrometers cost anywhere from $4000 to $9000 per electrometer. This cost often prevents universities from teaching students about neurobiological...
stimulation. A recent graduate student at Western Michigan University, Lucas Essenburg, showed that a reasonable electrometer could be made for $220 [1]. Mr. Essenburg’s thesis served as the focal point of this project as this project took the concept and created a marketable kit.

Dr. Miller has recognized the financial barrier involved in obtaining electrometers for neurobiological research and education. He saw Mr. Essenburg’s work as an opportunity to create an electrometer kit similar to those offered by Heathkits Co that could be purchased by hobbyists and universities. The kits would include all the necessary components of the electrometer and a detailed instruction manual.

This senior design project focused on updating Mr. Essenburg’s design [1] and the construction of the kit. This required the optimization of the circuit provided by Mr. Essenburg, noise analysis of the system, the development of printed circuit boards and enclosures. This will provide Dr. Miller the groundwork for creating the kit. This project required intimate knowledge of circuit analysis, transfer functions, printed circuit boards, neurobiology, LTSpice®, KiCad, and AutoCAD®.

This project was sponsored by Western Michigan University Neurobiology Engineering Laboratory. Dr. Miller served as a mentor for this project. Mr. Essenburg also assisted this project by providing the group his previous work. This project was primarily funded by the Neurobiological Engineering Laboratory and by Western Michigan University College of Engineering and Applied Sciences and was supported be the Lee Honors College. The final cost of this project was $376.60.

3.1.2. Needs Statement

The high price of electrometers is prohibitive to teaching neurobiology at higher learning facilities. Dr. Damon Miller requires an affordable electrometer kit that is marketable to
universities and other higher learning centers. The kits must include all parts for the construction of the electrometers (including a printed circuit board) and detailed documentation outlining assembly, use, and troubleshooting techniques.

3.1.3. **High Level System Diagram**

Figure 1 is an adaptation from [1]. It shows a circuit block diagram that includes where each sub-circuit will be housed.
Design adapted from [1]. Please see that thesis for the complete design and references to sources used to develop that design.
3.1.4. **Project Specifications**

Specifications were adapted from the World Precision Instruments Duo 773 Electrometer [3] and (some verbatim, as indicated by quotation marks) Mr. Essenburg’s design [1].

**Physical Characteristics**

1.1. All resistors and capacitors must be standard values.
1.2. All components must be through-hole or have a through-hole adapter.
1.3. The head stage must be reduced in size without sacrificing functionality.
1.4. The device's noise must not interrupt the function of the device
1.5. Gerber files must be created in order to purchase more copies of the PCBs if necessary
1.6. All high voltage traces on the printed circuit boards must be at least 30 mils (0.762 mm) thick.

**Functional**

1.1. The device must provide currents on the scale of 1 nA.
1.2. The bridge balance for the electrometer must be able to compensate for up to 1000 megaohms of electrode resistance.
1.3. The bridge balance will also have a switch that will change the maximum value of nullable resistance between 100 and 1000 megaohms.
1.4. A DC offset will allow the user to adjust the input voltage by ±300 millivolt.
1.5. Electrometer must compensate for the capacitance of the electrode within the range of -50 to 10pF.
1.6. “Current monitoring circuitry must provide a signal of 100mV per nA injected into target cell.”

1.7. The size of the head-stage must be conducive to mounting and maneuvering the head stage with the micromanipulator.

1.8. The electrometer would provide similar functionality as a commercial electrometer.

3.1.5. **Constraints**

**Economic**

This device must be constructible for approximately $250 based on Mr. Essenburg’s work [1].

**Environmental and Sustainability**

The electrometer kit should not degrade for 10 years.

**Manufacturability**

All of the printed circuit boards must be designed using KiCad for future revisions. Furthermore, a manual must be written that details the kit construction and troubleshooting.

**Other**

The device must be optimized to remove excess op-amps. A noise analysis must also be completed to evaluate electronic noise contributions from the various components. The product will be tested in laboratory applications to ensure the quality of design.

3.1.6. **Deliverables**

Below is a comprehensive list of the intended final product:

1. A working, optimized prototype of the electrometer capable of providing an adjustable nanoamp current source. This device will have capabilities to connect to a standard
oscilloscope for cell voltage observation. All the standard adjustments for a professional-grade electrometer will be present including but not limited to a bridge balance, capacitance neutralization, and a DC offset.

2. The following files and documentation required to produce a kit:
   a. A KiCad file to produce printed circuit boards
   b. Diagrams of circuitry (one for the power supply and the other for the nanoamp current source)
   c. Parts list
   d. Material bill
   e. Information manuals for customer assistance to build the kits

3. User manual for kit production that details steps in the manufacturing process, such as, how to print the circuit boards, what exact parts are necessary, and how to package the device.

4. Proof of successful implementation of system specifications including block diagrams, transfer function analysis, system descriptions, noise analysis, and any other analysis completed during the design process.

5. Schematic diagrams and circuit descriptions.

Below is a comprehensive list for items that were delivered at the conclusion of this project:

1. Three prototype printed circuit boards and electrical components that are ready to be soldered together to form a working electrometer with the capabilities of a professional grade device.

2. The following files and documentation required to produce a kit:
   a. A KiCad file to produce printed circuit boards
b. Diagrams of circuitry (one for the power supply and the other for the nanoamp current source)

c. Parts list

d. Material bill

3. Proof of successful implementation of system specifications including block diagrams, transfer function analysis, system descriptions, noise analysis, and any other analysis completed during the design process.

4. Schematic diagrams and circuit descriptions.

3.2. Design and Implementation

3.2.1. Printed Circuit Board Layout

All hardware will be contained on one of three printed circuit boards (PCB) by the kit user. In total, there will be three PCBs designed within this project: Power Supply, Main Stage, and Head Stage. The PCBs were designed via the open-source Electronic Design Automation suite, KiCad, due to its expansive community and resources, its partnership with DigiKey and LTspice®, and usability. The tool generates ready to use Gerber files from simple printed circuit board layout application. Once generated, the Gerber files are created within a zipped folder ready to send to PCB manufactures.

While Designing PCBs, consideration of component spacing, trace widths, and usability was considered. Each PCB layout manifested its complications discussed further below.

*Power Supply PCB*

The electrometer is powered by a 120 V AC power supply. A 30 VA transformer was paired with 7805 +5 V and 7905 –5 V regulators to transform the 120 V AC power supply into
both a +5 V and –5 V DC power supply. Large transformers are placed between the regulators and ground to produce a low-noise output. There is also fuse protection that limits the current to 500 mA on the ±5 V side and 250 mA on the 120 V side. The design for the power supply is adapted from [1].

**Power Supply PCB Layout**

Due to the simplicity of design and lack of need for a ground plane, the power supply board was designed as a two-layer board, shown in Figure 2. Because the traces are all relatively high power, traces were placed on both sides to increase the distance between them.

After ordering this stage, several small errors were found that were later updated within KiCad. The first error revolved around the holes for the transformer. This component was the only component that had to have a custom footprint created. While creating the footprint, the distance between the two lines was accidentally set too large. Although this functioned for the prototype, it was updated for later printing. Beyond that, multiple thin, short traces were found throughout the board from a prior design. These errors were resolved and likely did not affect board function. Additionally, a few traces were placed too tight to other traces or holes. These created an extra strain on the solderers to be precise and were therefore adjusted to improve ease. Some hole sizes were then adjusted to match the components and most solder pads were increased to improve ease of soldering.
Figure 2: Power Board Layout within KiCad

Figure 3: Power Supply PCB
The design supplies ±5 V to the electrometer while utilizing large capacitors to lower the noise of the output. Fuses are added to protect the electrical components [1].

**Main Stage PCB**

Intracellular stimulation experimentation requires the ability to adjust the signal input to the individual cell. The majority of this calibration circuitry is found within the main stage. This includes DC offset, bridge balance, tickle circuitry, and current monitor. The design of each circuit is adapted from [1]. Below is a brief overview of the circuitry functions and information about any design changes implemented and then discuss the design elements to the PCB layout.

**DC Offset**

The measured response of the stimulated cell is often required to be offset by several hundred millivolts to allow for observation of the waveform characteristics and shape. The current configuration allows for adjustment of ±450 mV with a 1-turn potentiometer during cellular stimulation [1]. The DC offset was not altered from the original design.

**Bridge Balance**

Various types of glass electrodes are used for intracellular experimentations. Slight variations within the electrode shape and size can cause dramatic differences in the electrode resistance. The original design could nullify a voltage drop across the stimulation electrode between 0 and 100 MΩ. However, some experimentation requires an electrode balance capable of nulling the voltage drop across an electrode with resistance as high as 1000 MΩ. The kit includes a switch to select between the ranges of 0 – 100 MΩ and 0 – 1000 MΩ to increase the type of intracellular experimentation capable of being performed with the instrument. A
calculation guide will be included in the assembly directions to give the consumer the ability to customize the range of resistances.

An analysis of the original design showed redundancies within the current monitor and bridge balance circuitry. Removing the redundancy subsequently removed an LTC 6081 op-amp from the design. The updated circuit design is found in Figure 4.

![Updated Bridge Balance and DC Offset Schematic Adapted from [1]](#)

**Tickle Circuitry**

During electrophysiology experiments, a rinsing electrode voltage is often used to remove excess material from the electrode tip and to aid penetration of the cell membrane during intracellular experimentation referred to as the “tickle” mode. The previous design includes circuitry to generate a 0 – 8V, 1-8 kHz tickle voltage. This is a smaller amplitude than that provided by the Duo-773. As a result, the design from [1] will be updated to generate a 1 – 15V, 1-8 kHz tickle voltage. The circuitry was not altered from the original design.
Current Monitor

The current monitor reads out the current that is produced through the stimulation of the cell. For reference, the circuit is shown in Figure 5. The voltage going into R31 is taken from the output of U3 and the voltage going into R32 is taken from the output of the head stage. This circuit compares those values and will output a voltage that is based on the scale 100mV/1nA. The output of this circuit was modified to include the bridge balance to remove previously mentioned redundancies.

![Current Monitor Circuit Diagram](image)

Figure 5: Current Monitor Adapted from [1]

Main Stage PCB Layout

Due to a high number of LTC 6081 operational amplifiers required within this stage, the board designed as a four-layer board, shown in Figure 6, with the two outermost layers used exclusively for traces. Any traces with highly sensitive signals were placed on the top layer. The hidden layer next to the top layer was devoted to a ground plane. The ground plane also served as a shield for the sensitive traces from the ± 5 V power planes on the next layer. The final layer was contained any remaining traces.
Figure 6: Main Stage Board Layout within KiCad

Figure 7: Main Stage PCB
To accommodate novice solderers, a large emphasis was placed on the readability of the circuitry for this stage. Each circuit was isolated as much as possible. Additional silkscreen was utilized as boundaries and labels to the circuit.

Since the main stage is between the head stage and power supply stage, there is a multitude of connectors within this stage. The number of connectors was reduced to three BNC connectors, 2 twelve-pin connectors and three-pin connectors to provide a sleek and intuitive design. The connectors served as a second purpose as mechanical support of the PCB to the housing unit.

**Head Stage**

Sensitive circuitry is required to be close to the experimentation to reduce noise within the system. This circuitry includes the nA V/I Converter and Capacitance Compensation. Below is a brief overview of the circuitry functions and information about any design changes implemented and then discuss the design elements to the PCB layout.

**nA V/I Converter**

The design is based on a Linear Technology LTC6081 nA current source shown in Figure 8 [4]. The design utilizes LTC6081 op-amps to create nanoamp current rated to an accuracy of 10 pA. The circuitry was not altered from the original design.
Due to the high accuracy at low currents, the LTC6081 has been used throughout the design. A major barrier of the LTC6081 is it only comes in packaging that requires surface mounting. Through-hole adapters are utilized to prioritize the ease of the soldering.

**Capacitance Compensation**

Electrode capacitance leakage currents cause unwanted variations in the injected current and measured membrane voltage. Electrometers can compensate for these leakage currents. A negative impedance converter provides a compensation capacitance adjustable via a 10-turn potentiometer [1]. The circuitry was not altered from the original design.

**Head Stage PCB Layout**
Similar to the main stage, the design of the head stage has a high quantity of LTC 6081 operational amplifiers. Thus, the head stage was designed as a four-layer board with a similar layer structure as the main stage.

The head stage layout was designed in multiple different orientations in attempts to minimize trace lengths of highly sensitive length. Additional protective traces to shield these highly sensitive traces were considered. However, the PCB size directly impacts the size of the housing unit for the head stage. Thus, priority was given to minimizing the PCB size to fit a standard micromanipulator. The final layout can be seen in Figures 9 and 10.

Figure 9: Head Stage Board Layout within KiCad
3.2.2. **Enclosures**

There are two enclosures for the PCBs. One for the power supply stage and the main stage and another for the head stage. Both enclosures are designed to be built with steel to act as a Faraday cage around the circuitry. Unfortunately, the designs of the enclosure were not built before the report due to the COVID-19 Stay at home order issued by Governor Whitmer. The design layouts of each enclosure are included in Appendix B.1 and B.2 respectively.
Power Supply Stage and Main Stage Enclosure

The dimensions of the power supply and main stage enclosure are 8.5 x 5.25 x 10 inches with an additional wall separate the two PCBs. The enclosure design has an easily removable top for the future to the hardware for troubleshooting and reconfiguration. The size of the enclosure is half the size of a standard electrophysiology rack. This feature was decided to allow users the ability to include two electrometers on one rack or one electrometer with space for additional add-ons alongside it.

Head Stage Enclosure

The priority feature within the head stage was designed to compatible with micromanipulators.

3.2.3. Manuals

Manuals need to be created with assembly ease and education as the priority. There will be a minimum of three manuals: Assembly Manual, Troubleshooting Manual, and User Manual. The assembly manual will be a step-by-step guide to assemble the kit. The troubleshooting manual will be a collection likely malfunction, and how to address the errors. Finally, the user manual will be a detailed explanation of the design and how each component works.

3.3. Performance Testing and Analysis

3.3.1. COVID-19 Impact

On March 23, 2020, Governor Gretchen Whitmer signed a “Stay Home, Stay Safe” executive order. Therefore, starting March 24, 2020, all in-person work on this project was
stopped. Although some simulations and other updates were able to be done for the project, the construction of the prototype electrometer ceased.

### 3.3.2. Simulations

A model of the circuit was built in LTSpice® by Mr. Essenburg and was provided to the group around the onset of this project. The model has been refined to optimize components, simplify circuitry, and expand the experimentation capabilities. The revised model was simulated using LTSpice® and produced similar results to the original design.

A noise analysis on the DC offset, bridge balance, current monitor, and nanoamp source was conducted. Figure 5 shows the results from the input voltage to the output voltage. The majority of the noise was found to be the cause by a 10 MΩ resistor, R10, which can be found in Figure 2. No further changes will be created due to the noise analysis results to meet specification requirements.

![Figure 11: Noise Analysis Results](image-url)
3.3.3. **Kit Testing**

The following steps outline the validation of the final product:

1. Upon kit finalization, a volunteer hobbyist will assemble the kit following instructions provided. The devices will then be inspected to ensure that they are correctly built.
2. The hobbyist will then perform a basic experiment of neuron stimulation using the constructed electrometer.
3. All settings will be adjusted to their extremes to ensure the expected results from the device.
4. Output data received from the constructed electrometer design will then be compared to previous results from a commercial-grade electrometer.
5. An interview with the hobbyist to collect information on the ease of the construction process and use of the machine will be conducted.
6. This test will be deemed successful if the construction process was deemed simple, the hobbyists rated the use of the electrometer high, and they reach similar (no more than 5% variance) resulting outputs via stimulation experimentation.

4 Conclusions

The results of this project include three designed printed circuit boards, two enclosures, and a list of all electrical components necessary to create an electrometer. Unfortunately, due to the stay-at-home order, the construction of the electrometer had to be stopped. However, based on the results of Mr. Essenburg’s thesis, it is believed that the designed prototype would have worked [1]. Although the project came in over budget, the construction price for this electrometer kit is still significantly less than that of a commercial grade device. This should
meet the goal of allowing collegiate laboratories to teach neurophysiology to students for a fraction of the prior cost.

5 Recommendations

Although the prototype was unable to be constructed and tested, the final product will provide the opportunity for many collegiate laboratories and hobbyists to explore and understand neurophysiology.

It is recommended to finish the construction of the prototype electrometer. From there, the device should be tested in Dr. Jellies’s laboratory to prove its function. Any updates that need to be made to the printed circuit boards and the enclosures should then be made. The electrometer should be able to be fully integrated with standard electrophysiology equipment. After the construction and testing of the device, a manual should be written that details the construction of the electrometer. Ideally, this manual will also include sections on troubleshooting any problems that might arise during construction and use as well as the science behind the electrometer.
6 Appendices

A.1. Budget/Cost

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B.1. Power Supply Stage and Main Stage Enclosure
B.2. Head Stage Enclosure
7 References


   nosensory Cells,” M.S. Thesis, ECE Dept., WMU, Kalamazoo, MI, 2017
