# Programmable Two-Channel Lab Power Supply

# Final Report


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ECE 493-001

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## Executive Summary

In designing and assembling a 2-channel bench power supply, we focused on making the price of the device affordable for hobbyists and students while including combining the best market features. By improving the design of numerous workbench power supplies, we can make this device more accessible to more consumers while having useful and compelling features.

Many available power supplies that satisfy the features we aim to include are generally cost-prohibitive to students and even hobbyists. After researching the market view of numerous power supplies, features on higher-end models were priced between $222 and $973. Most power supplies on the market also output a larger voltage and current range compared to what students need to perform tasks for lab projects. Our power supply would satisfy all laboratory DC requirements for George Mason University Introduction to Electrical and Computer Engineering, Electrical Circuit Analysis I & II, and Linear electronics courses offered by the Electrical & Computer Engineering department.

Our team devoted a lot of time to researching the best layout and schematic for the power device. This reduced time during the testing and debugging process.

The features of this device include a high-quality linear transformer, 2-channel output, current and voltage readings/limits, a keypad and rotary encoder to directly enter the specified output values, and control through a USB serial connection. This was the focus of the project during research and development. By implementing techniques not found in market available lab power supplies and looking at inexpensive electrical components, the project goal was achieved.

Our total cost of the prototype was calculated by using only the parts that went into the final prototype. Parts that broke, or those not implemented into the end product were not part of the cost calculation. In mass-producing each power supply, we would not debug each implementation as thoroughly (reducing cost). Additionally, mass-producing components would lower the price of the components, since they would be bought in bulk. The final BOM cost for a single unit is $105.41, which is a significant price reduction compared to these bulky expensive devices on the market. This number is reduced down to $73.66 and $60.48 when producing more than 100 and 1000 units, respectively.

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# Approach

The current market available 2-channel DC power supplies fall into three categories: 1) accuracy in terms of output noise, 2) cost-effectiveness, and 3) available higher-end features. Many available power supplies that satisfy features included in our power supply are cost-prohibitive to students and even hobbyists. Most power supplies on the market also output a larger voltage and current range compared to what George Mason University (GMU) or other college students need to perform tasks for lab projects. Our power supply satisfies all laboratory DC requirements for ECE 101, 285, 286, and 334 except for one lab. There are not any power supplies on the market which include the specific features of our product, especially within an affordable price margin.

Due to COVID-19, engineering students are enrolled in online labs and require additional power supplies and equipment to complete their lab assignments virtually. For the electrical & computer engineering (ECE) labs at GMU, all but one requires voltages lower than 10V or can be easily modified with this limit in mind. Additionally, with a maximum current limit of 500mA, the power supply is much safer to use at home for beginners than power supplies with higher current/voltage outputs. Our product delivers the needed power requirements for typical lab usage while providing safe power output at an affordable price.

Another group we are targeting is electronics hobbyists. Hobbyists often have similar needs to the students that we’ve outlined above. There is a high demand for low-cost, feature-rich variable power supplies in the hobbyist market. This is evidenced by the abundance of DIY power supply plans available on the internet. Many of these plans use an ATX power supply to achieve cheap and easy regulation, at the cost of higher minimum voltages and higher noise on the output due to the use of switching regulators.

Our design creates an alternative to these DIY projects, as well as the commonly used cheaper Chinese power supplies that have low-quality components and build quality. It would also cover their needs as most hobbyist projects depend on maximum voltages around 12 volts, which could be achieved by using both outputs of our power supply, but most projects depend on low voltages for digital applications, such as 5 or 3.3 volts. Our design allows for tinkering via the USB serial port, which is a feature that we found to be completely unavailable in our targeted price range.

This power supply will be composed of two systems. The primary system is the main PCB which controls user-specified input and output, while the secondary system operates voltage regulation. Specifically, the main PCB contains a microcontroller unit that interfaces with user inputs, USB serial input, output display, and I/O bus to interface to the secondary board. The secondary system will contain a smaller microcontroller processing unit. This will use a transformer to perform power regulation and to control the output of the two DC channels.

Supplying both a keypad and rotary encoder will allow for precise and simple input to the power supply. Allowing the power supply to be programmable would allow various lab experiments and results to be easily saved to resume at a later time.

The 2-channel bench power supply combines the best market features for about $100. Bench power supplies are tools that enable programmable voltage and current output using an AC-DC converter. By providing a precise power output at a low cost, bench power supplies become more accessible to an average electronics user.

Our team did not spend much time researching alternative approaches before building the power supply. The minimal consideration to alternative approaches is due to the design having strict guidelines that dictated how to go about designing the product. However, implementing small changes to provide different features is possible. It is important to note that implementing different features could increase or decrease the cost. If a user wanted a lab power supply that had different features such as a different type of USB this could be configured to the product. Also if a user wanted to have additional buttons on a keypad this could be accomplished by adding a few lines of code to the keypad file.

Other alternative designs include using a bigger container to hold the MSPs, PCB, and other components of the power supply. The case used in our design was somewhat small relative to the total volume the remaining pieces took up. Using a small case eases shipping difficulty as well as transport issues the customer may face in managing the device. However, when constructing the power supply a larger container eases restrictions of the user interface or amount of features the device can supply.

# Technical section

## Top-Down Design Approach

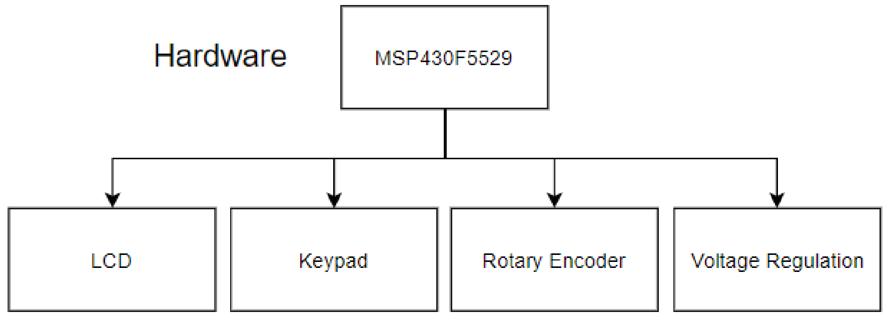


Figure 1: The hardware flow chart shows the connections between the main microprocessor (MSP430F5529) and the secondary components. The voltage regulation box is the regulator circuit which uses an opamp to regulate output. The LCD, keypad, and rotary encoder all make up parts of the user interface.

## Software Design

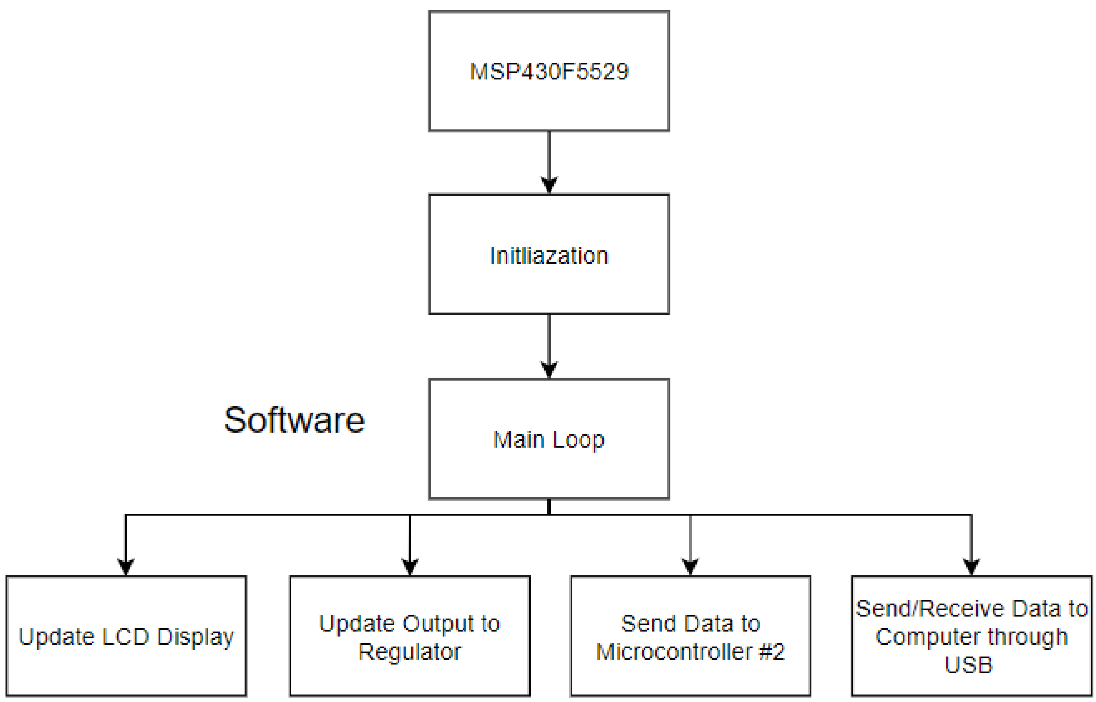


Figure 2: The MSP430F5529 was programmed to interface software between all components. The MSP uses the main loop after the everything it initialized. During the main loop the MSP waits for interrupts while updating the LCD display, updating output to the regulator, sending data to the other microcontroller, and sending data through the USB.

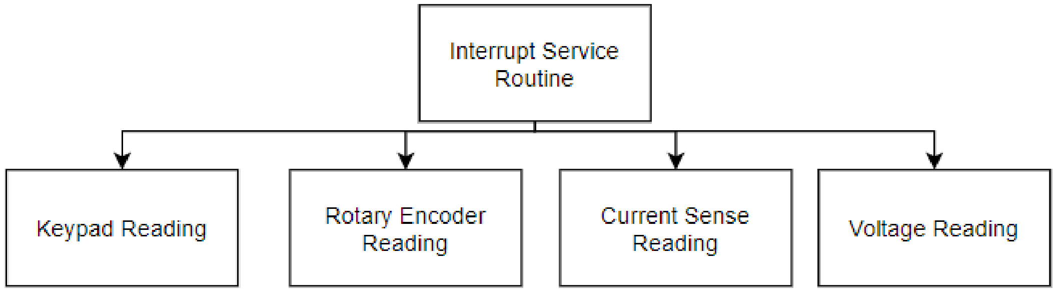


Figure 3: The image above shows the logical flow of the interrupt service routine (ISR) in software. Since the interrupts are triggered by hardware components (keypad, current sense reading) and aren't programmed in the main loop, the ISR is shown separate from the rest of the software flowchart above.

## System Models

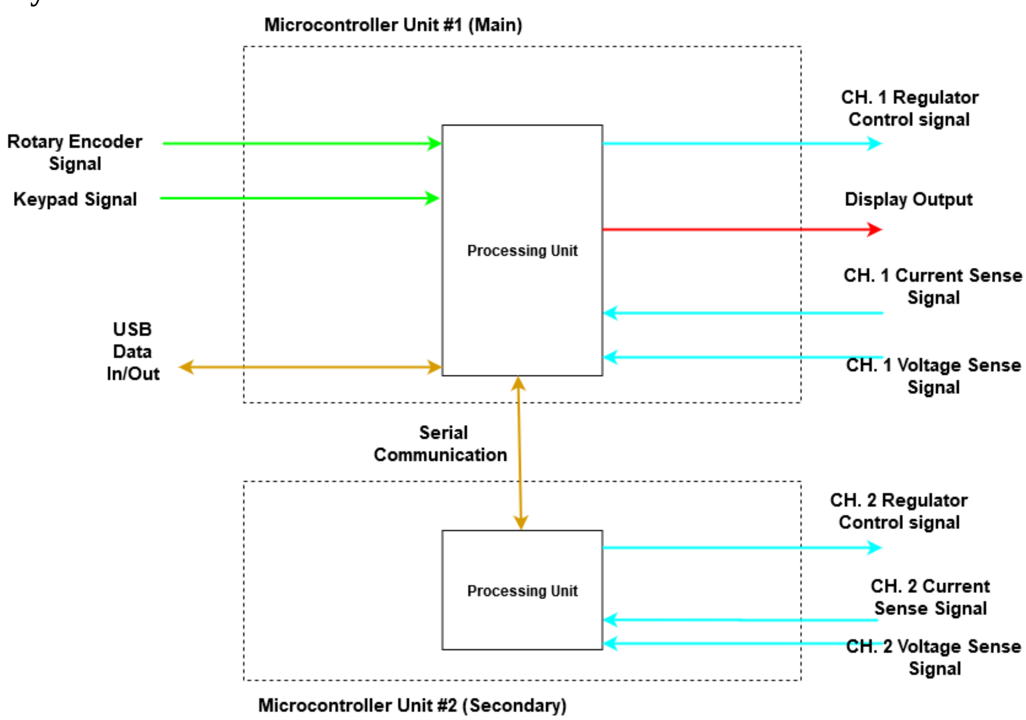


Figure 4: The above image is a level 2 block diagram architecture of the processing units interfacing using serial communication.

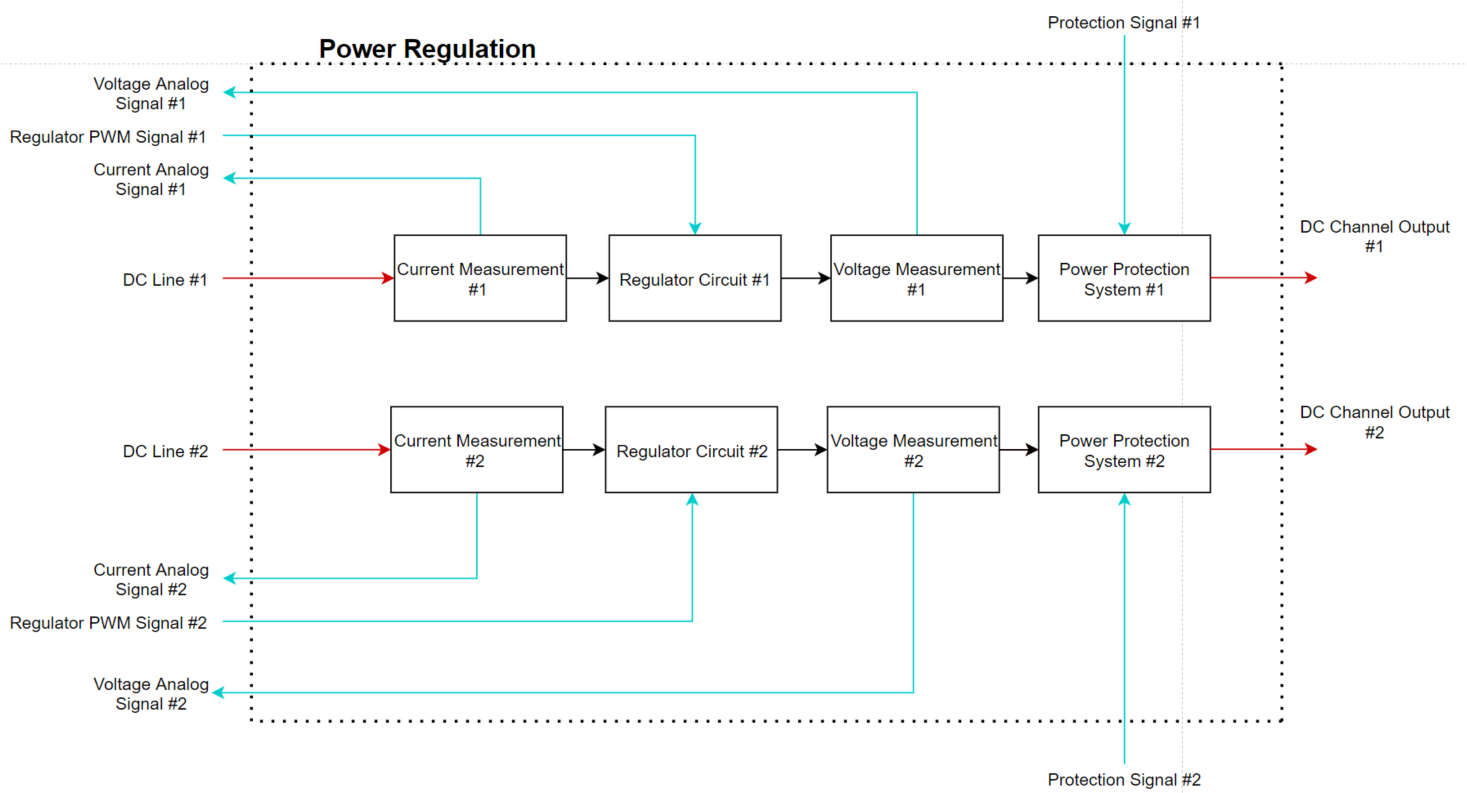


Figure 5: The above figure demonstrates the level 2 architecture of the power supply.

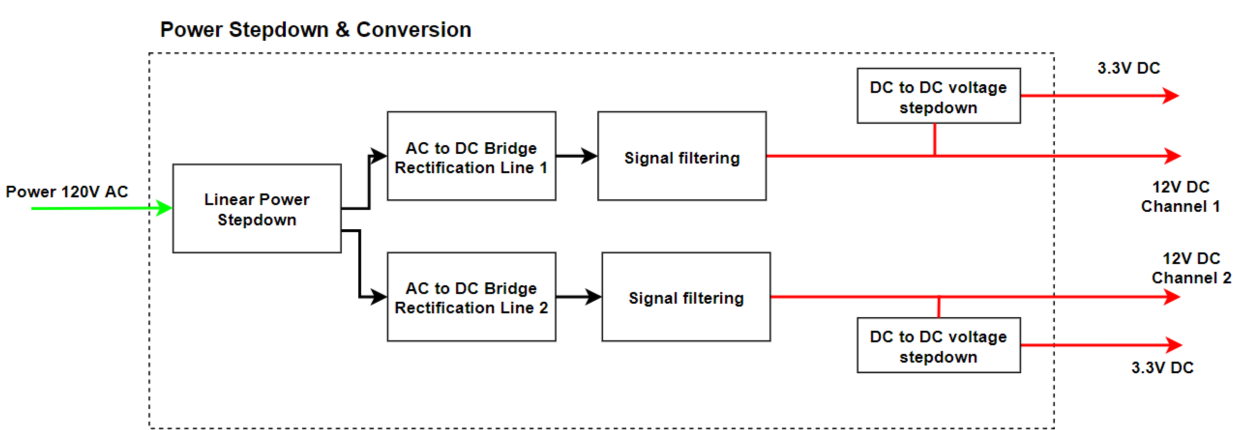


Figure 6: The above level 2 architecture shows the power Step-Down & Conversion.

## Critical Elements

**Character LCD** - For the display on our power supply, we've decided to use a 4 line display with 16 characters per line. This allows us to display measured current and voltage as well as set current limit and voltage for each channel with enough space for our specified measurement accuracy.

**USB Client** - The USB client allows a user to set current limits, as well as voltages for each channel through a serial connection using any serial communication software. Physically, the user can connect through a full-size USB type B connector on the back of the unit.

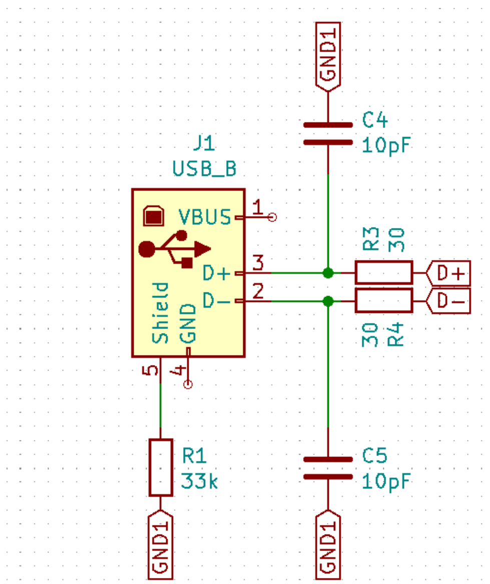


Figure 7: The schematic above shows the USB interfacing with the MSP.

**Current Sense-** Since our power supply contains an INA225 for overcurrent protection, the current is ensured to not exceed 500 mA and provides safe circumstances for operation.

**Regulator Circuit** - The regulator circuit is the main part of what makes this power supply cheap, but still accurate and useful for students and hobbyists alike. The main voltage regulation is done by a pair of Analog Devices LT3080's. These linear regulators take the 12VDC output of our two full-bridge rectifiers and with a PWM driven signal, rectify the output to anywhere from 0.2 to 10.5VDC. These rectifiers are rated for 1A, and work well with our maximum current of 500mA. To drive our 3.3V and 5V components, a pair of Texas Instruments L7805's feed our 5V which is also used as the input to our MCP1700T 3.3V regulators to drive the MCUs.

**Keypad** - The keypad is made up of 15 individual push buttons. The keypad is a critical component because it allows the user to quickly enter precise values for each channel. The MJTP button was chosen due to its cost effectiveness and small size. It is shown next to the buttons used in 447 labs for a size comparison.

Figure 8: The image above demonstrates a MJTP1234 button (right) which was used in our final prototype.

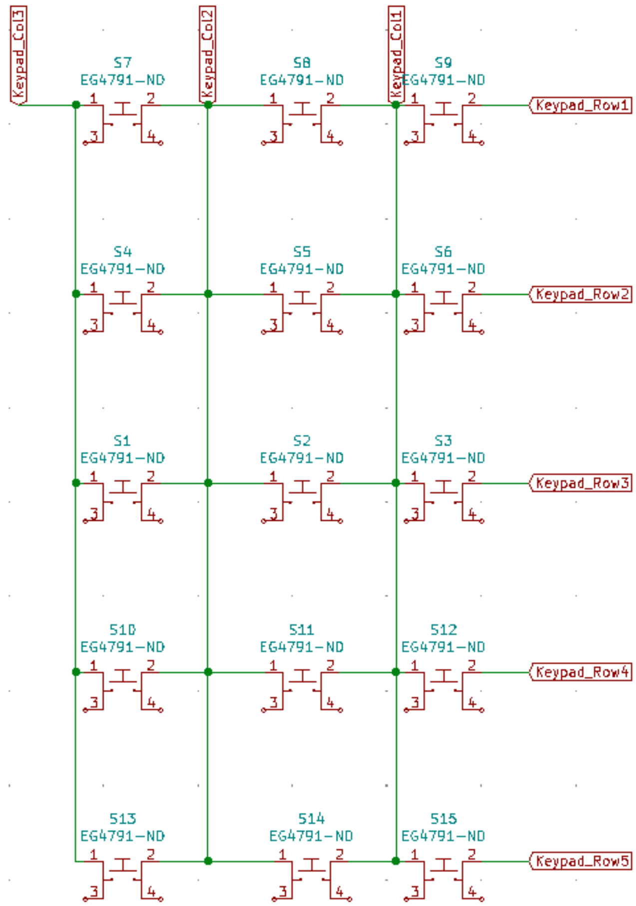


Figure 9: KiCad schematic of the keypad in a 3x5 Matrix.

**Rotary Encoder -** The rotary encoder allows the user to adjust the output in steps, rather than entering a specific value. The benefit of a rotary encoder over a potentiometer is that it will not interfere with a user typing a value in with the keypad or over the USB connection. The rotary encoder will be especially useful in labs where multiple voltage inputs and outputs must be recorded.

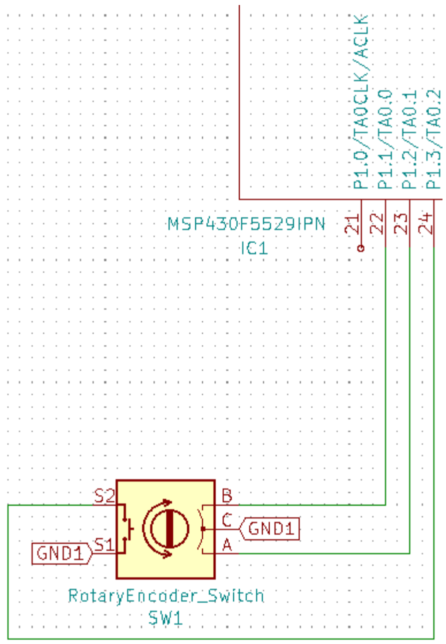


Figure 10: The schematic of the rotary encoder interfacing to the MSP is shown above.

**Regulator Control Circuit** - The regulator control circuit consists firstly of a pulse width modulation signal originating from the channel's respective MCU. This PWM signal then goes through an RC low-pass filter to turn the square wave into a fixed DC voltage. To control up to our regulator's maximum output, we use an operational amplifier in a non-inverting amplifier configuration to boost the PWM's maximum output from 3.3VDC to the regulator's input voltage of 12VDC.

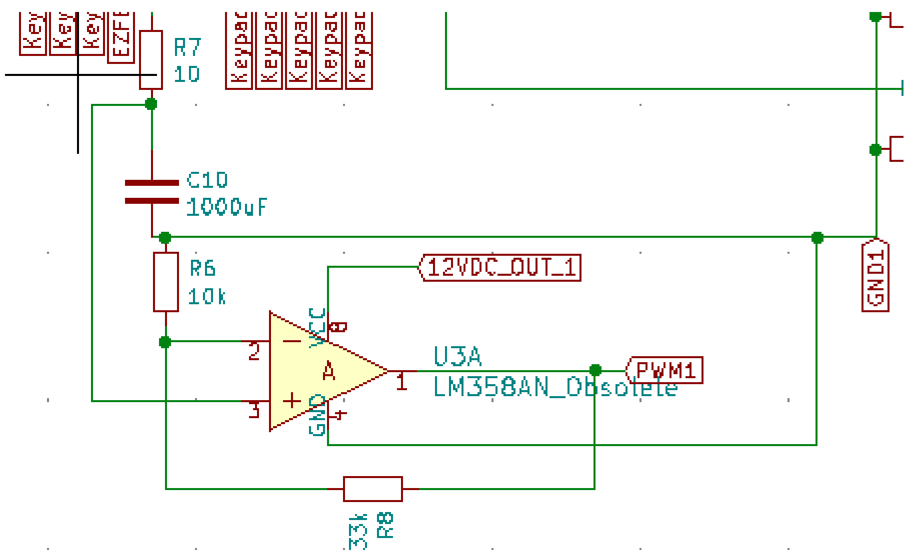


Figure 11: KiCad schematic RC filter and Op-Amp used to control the Regulator

**Microcontrollers -** Because there are two completely isolated power outputs, we used two separate microcontrollers. The main MCU handles all inputs, USB communications, driving the LCD, as well as driving the regulator for channel 1, while the second MCU controls the output of channel 2. Because the main MCU controls much more and needs to support USB serial communications, we used a Texas Instruments MSP430F5529.

Figure 12: The development boards of both our main MCU and our secondary MCU.

**Analog-to-digital Converter** - The ADC is tasked with reading the current value from the INA225 Current-Shunt Monitor and reading the voltage output from the LT3080. These analog signals are first sent into a voltage divider to step down the voltage and then goes into a 12 bit ADC on the MSP430 microcontroller. The output is then compensated from the step down in voltage by multiplying and then used as a variable in the system.

**Physical Design -** Our physical design of the unit was determined by gauging the size of our components, as well as looking at similar units on the market. It was important to us that none of the inputs or outputs were on the top of the unit, so that in a lab setting other lab equipment could be stacked on top of our power supply.

# Experimentation

### Character LCD

The Character display was programmed using general-purpose input/output pins to send commands to the screen. Referencing the data sheet, Specific actions were sent from the microcontroller to the SPLC780D dot-matrix LCD controller on the LCD screen. By providing simple commands to the board for example, Cursor, Entry Mode, and Clear commands, we can test the screen to make sure it provides the right output actions on the display. This was verified using an oscilloscope to capture the time of each signal.

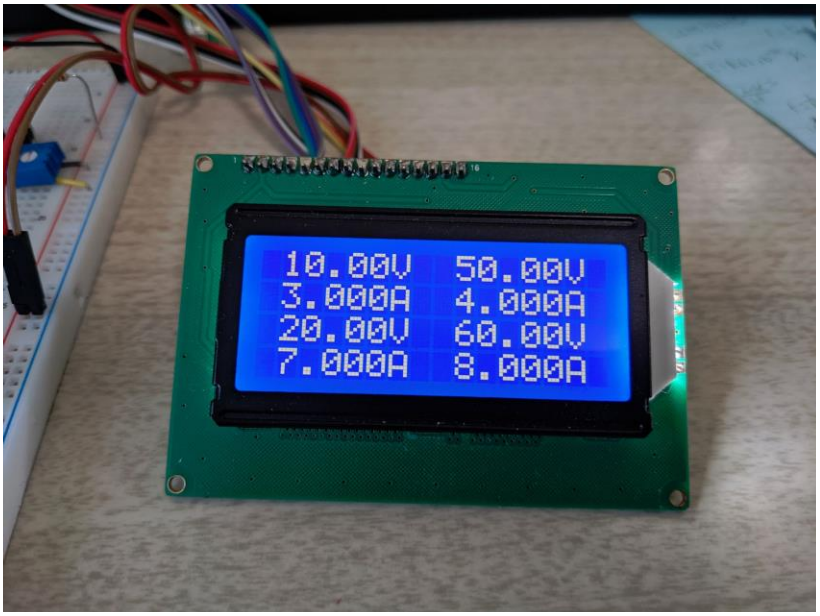


Figure 13: Note: Values displayed were for testing purposes only

### Pulse Width Modulation Signal

The pulse width modulation signal is filtered and amplified and used in place of a potentiometer on the SET pin of our LT3080s.

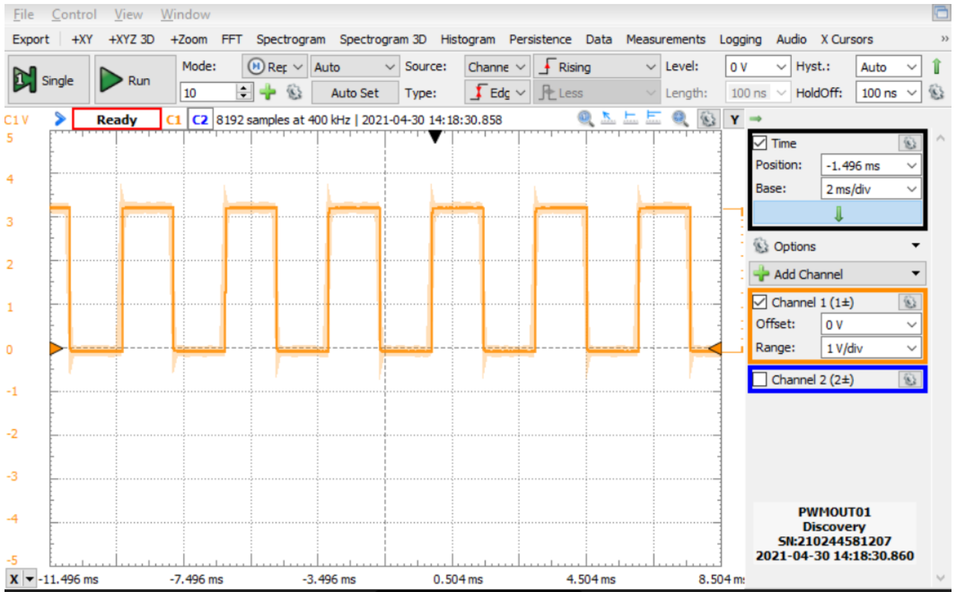


Figure 14: The above image shows the pulse width modulated signal at 3.2 volts.

## USB Client

The USB was used to send communication signals between the MSP430F5529 microcontroller and the user's terminal to send data between the MSP430 and a user's terminal.

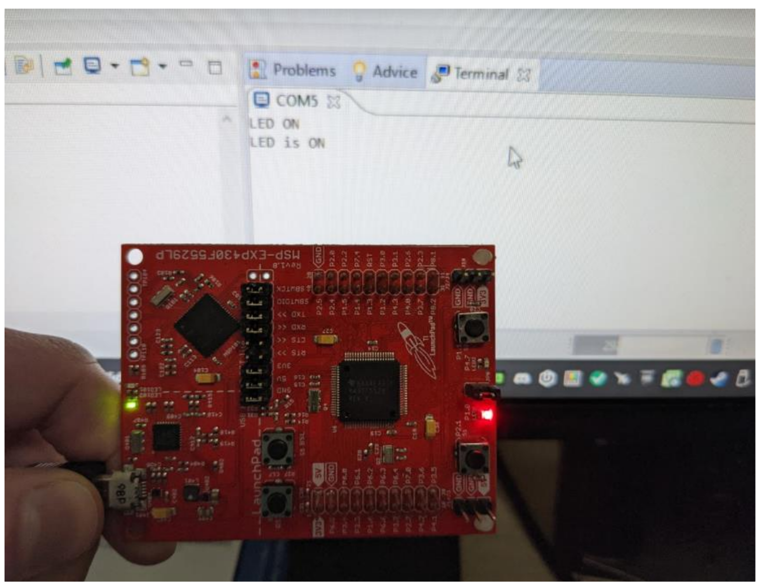


Figure 15: The picture above shows registration within the terminal that the MSP430 lights are ON.

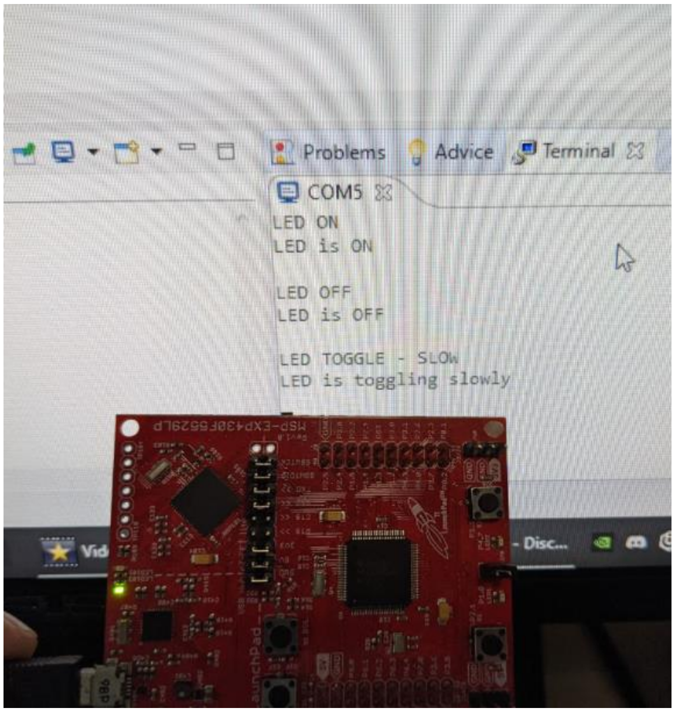


Figure 16: The image above shows communication through the USB of LED activity.

## User Interface Components

### Keypad

The keypad for one of the components of the user interface was initially tested both with individual buttons and a matrixed keypad. However, after the testing phase was complete for the keypad, the MJPT1234 buttons were soldered onto a perf board. The soldered perf board is integrated into our final design to hold the buttons together for the front interface.

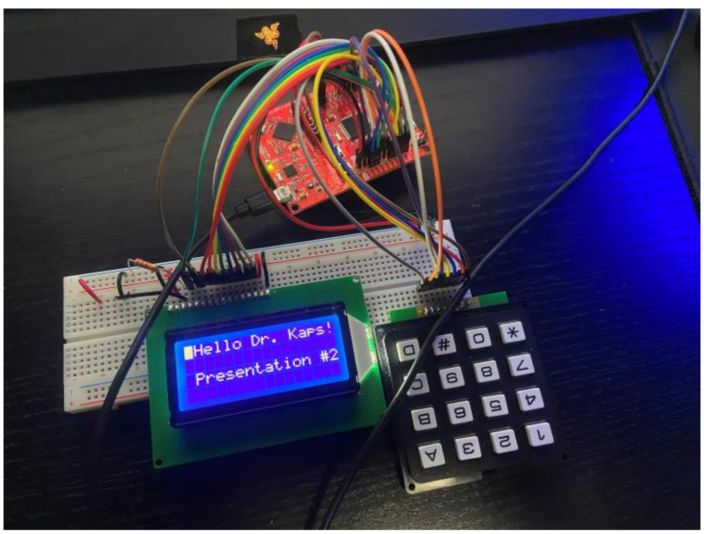

Figure 17: The above picture demonstrates the keypad interfaced to the LCD to produce output. NOTE: The keypad used in the above photo was for testing purposes and not implemented into the final design.

**Rotary Encoder**

The rotary encoder was tested by writing a simple interrupt routine on the MSP430. Using the two built-in LEDs on the Launchpad, we were able to light up the left LED if the knob was turned left, the right LED if the knob was turned right, and clear the LEDs if the push button was pressed. The precision of the rotary encoder was precise enough to change the voltage by 0.01 V and current by 1 mA.

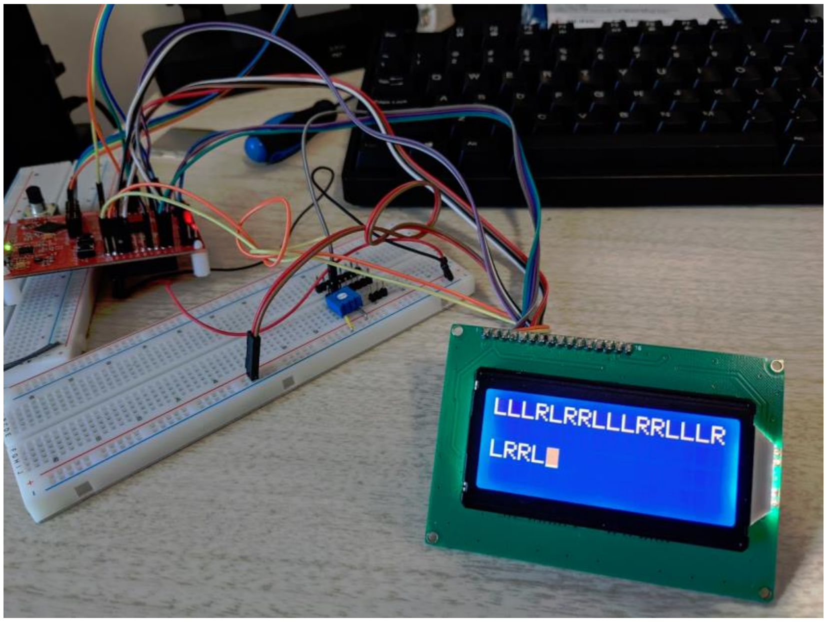


Figure 18: During testing, the display printed ‘L’ if the rotary encoder was turned counter-clockwise and ‘R’ if the rotary encoder was turned clockwise

**Analog to Digital Converter**

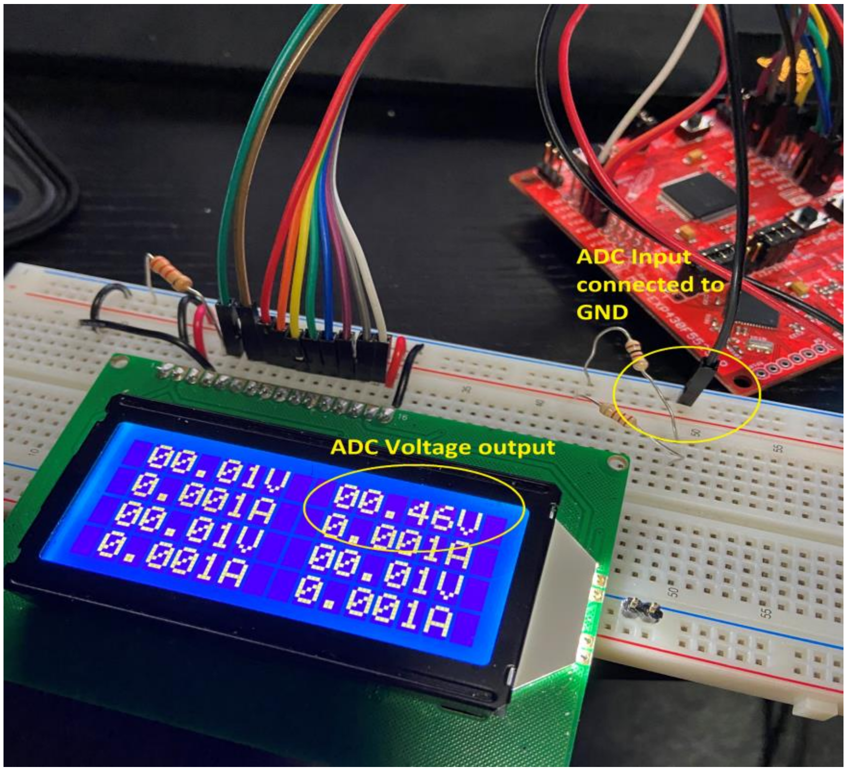


Figure 19: ADC Output test to GND. 3.3 Voltage as REF

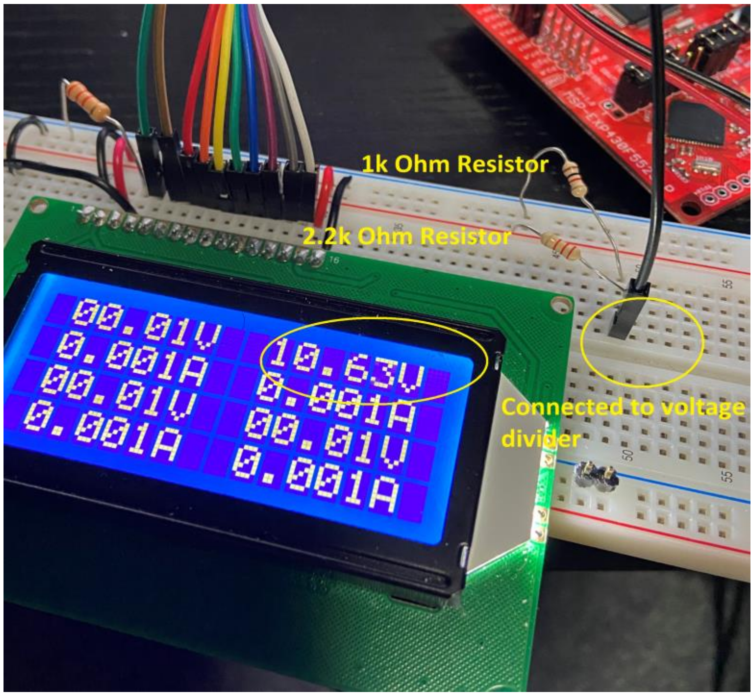


Figure 20: ADC Output test to 5V as. 3.3 Voltage as REF

**Regulator Circuit**

The Regulator circuit was problematic in the early experimentation phase. This component of the circuit was tested using a potentiometer to adjust the current through the set pin of the regulator. When looking at experimental results to the theoretical on the data sheet, the output was off due to lack of current on the output in the lower range of Voltage outputs. This issue was resolved by using a constant current on the output.

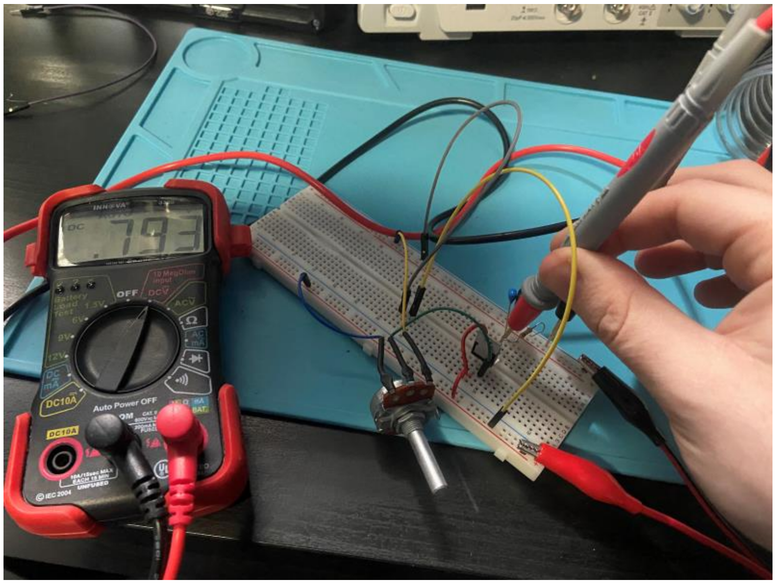

Figure 21: The above figure shows testing of the LT3080 Regulator.

**Regulator Control Circuit**

The regulator circuit was tested using several iterations of the regulator circuit configuration. Early testing was done with a potentiometer as the input to the LT3080's SET pin, rather than the PWM output. We then moved on to testing with the PWM output of the MSP430. This output was tested with several configurations of an RC filter as well as several configurations of a non-inverting operational amplifier. The output of the opamp was then fed directly into the SET pin of the LT3080. We used an Analog Discovery to plot and monitor the signal at many points including the raw PWM signal, the filtered PWM signal, the amplified signal, and the output of the LT3080. Once the results were verified, we moved on with our design.

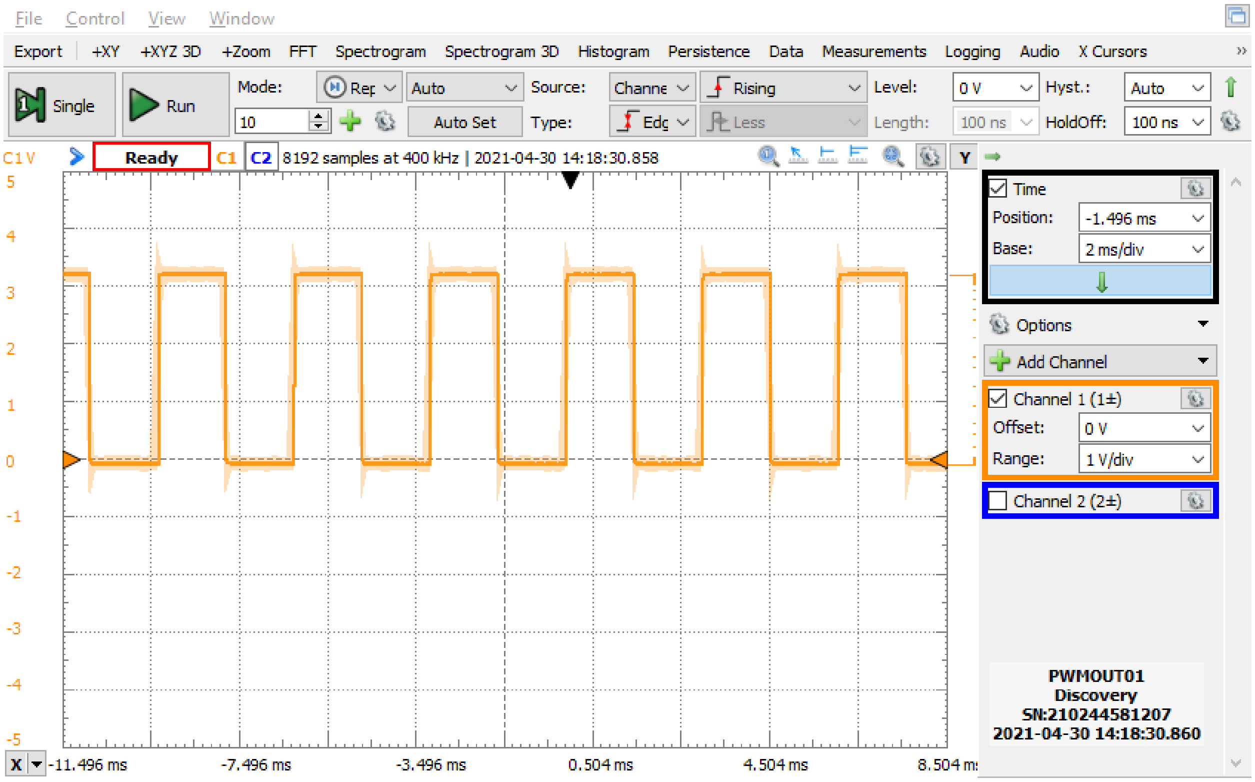


Figure 22: The yellow line shows the output of the PWM signal before it is filtered.

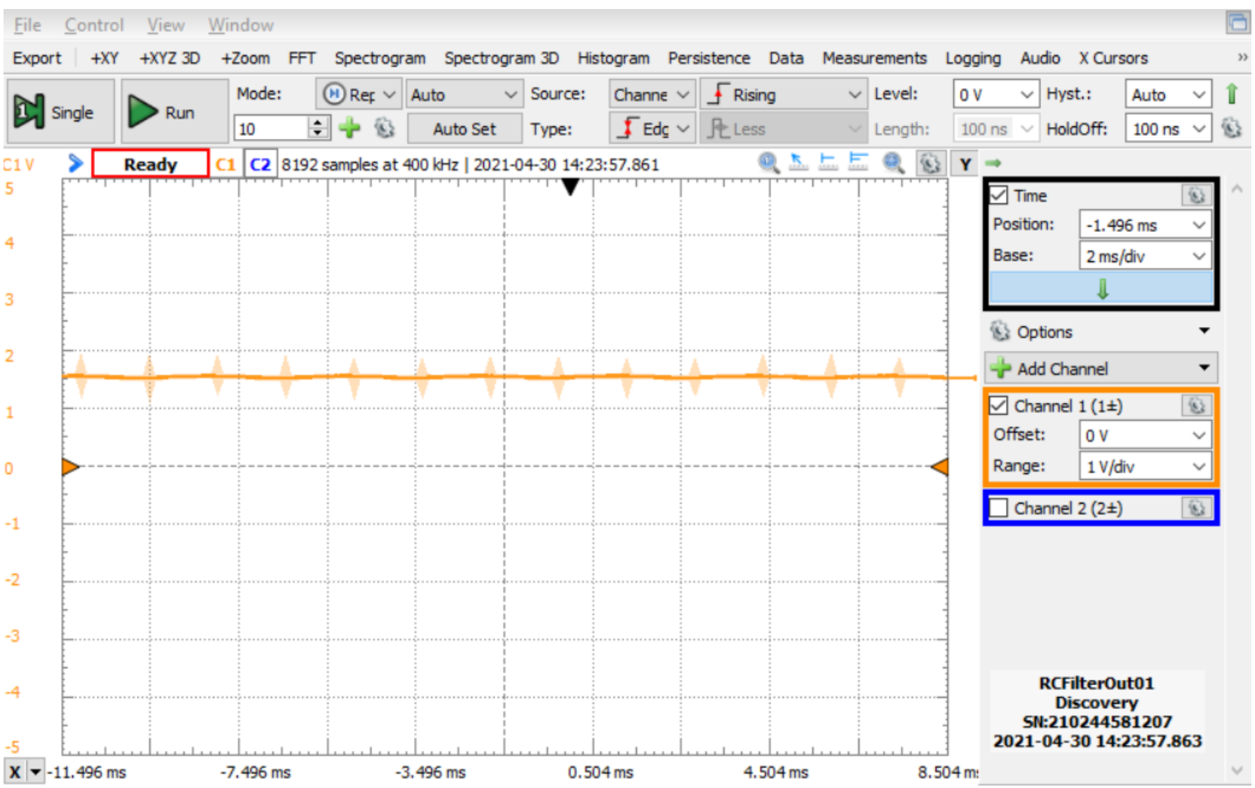


Figure 23: The above image shows the filtered PWM signal. This would be sent to the input of the op-amp.

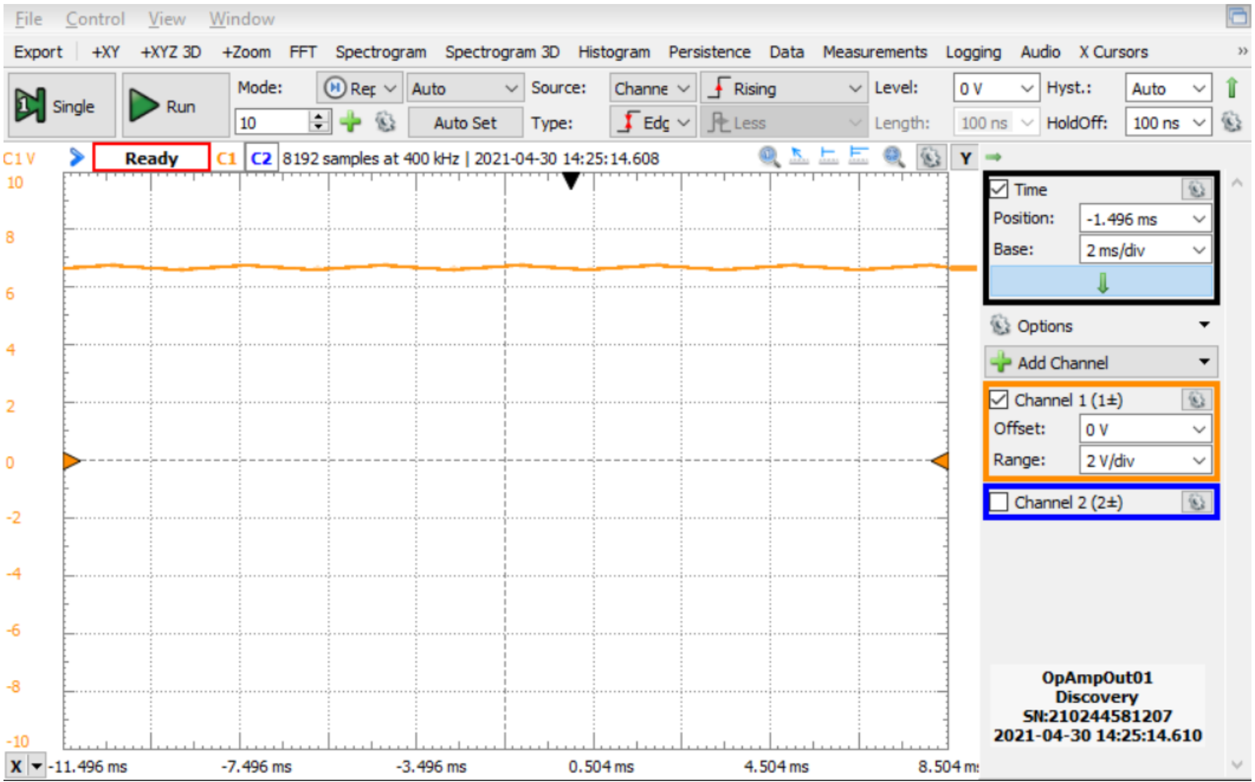


Figure 24: The above screen capture demonstrates the op-amp after amplifying the filtered PWM signal.

### Microcontrollers

The microcontrollers were tested not only for standalone components but in conjunction with every other piece of the design, as they are a critical part of our design. The majority of the testing was done with the MSP-EXP430F5529LP Launchpad. This development board allowed us to test not only inputs and outputs of digital signals, but also the analog inputs and PWM outputs. This made it much easier to quickly verify code designs as well as use simple programs to test how hardware reacts to different inputs. This board also allowed us to test different USB communication methods, as it can act as a USB client, while still sending debug data to the host PC.

### Physical Design

The design for the front panel was first developed by our team and then went through several revisions. The first was with helpful input from Dr. Kaps. The second round of changes was when the physical prototype was being modeled in Autodesk Inventor. The final round was when the unit was being physically assembled and a few unforeseen physical constraints had to be addressed, the result is what you see below.

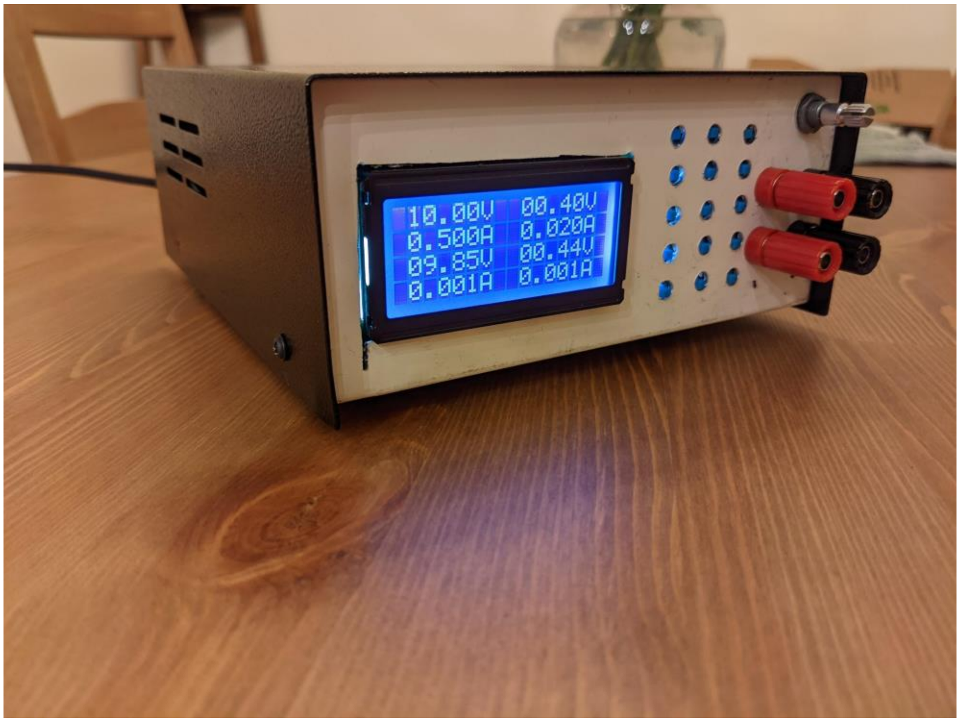


Figure 25: The font panel design of the initial prototype unit.

Figure 26: The case above is displayed to show its air ventilation cuts into the side frame.

Figure 27: The image above shows the back of the case. The power source is plugged into the back. The orange button is used to turn on and off the case. The green terminal connects to ground, to ground the system.

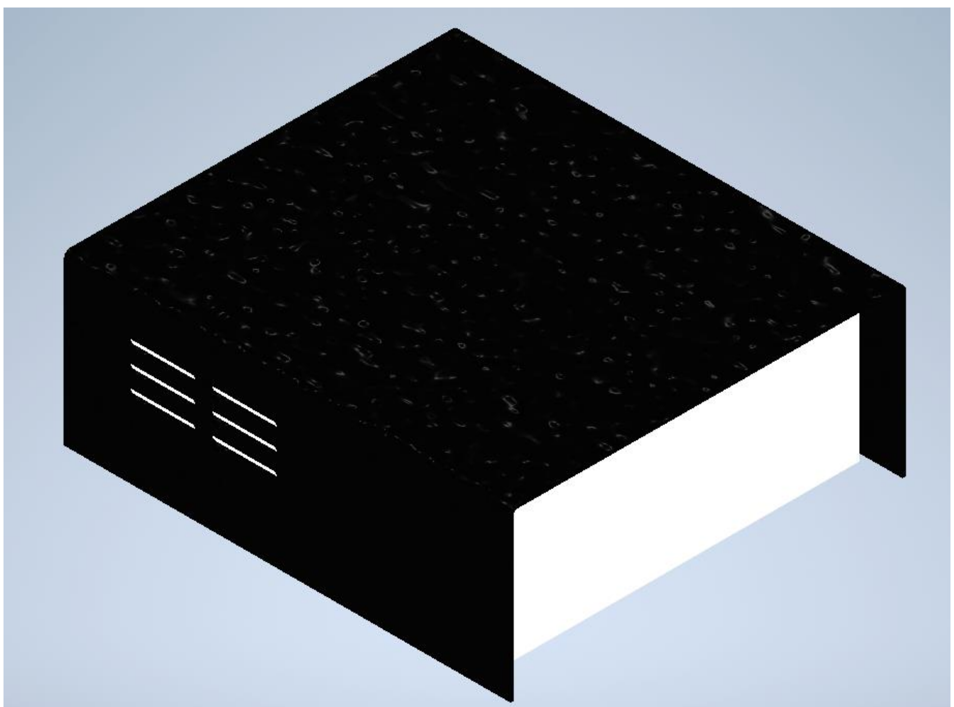

Figure 28: Autodesk Inventor sheet metal model of power supply case

# Collected Data

## Pulse Width Modulated Signal

| PWM Duty Cycle (%) | Vout (V) |
|---|---|
| 0 | 0.32 |
| 1 | 0.32 |
| 2 | 0.32 |
| 5 | 0.574 |
| 10 | 0.776 |
| 15 | 0.992 |
| 20 | 1.252 |
| 25 | 1.367 |
| 30 | 1.675 |
| 35 | 1.882 |
| 40 | 2.357 |
| 45 | 2.733 |
| 50 | 3.3 |
| 60 | 4.835 |
| 70 | 7.506 |
| 80 | 8.055 |
| 90 | 9.963 |
| 100 | 10.546 |

Table 1: The above table demonstrates the duty cycle % of time the duty cycle is on at a certain voltage.

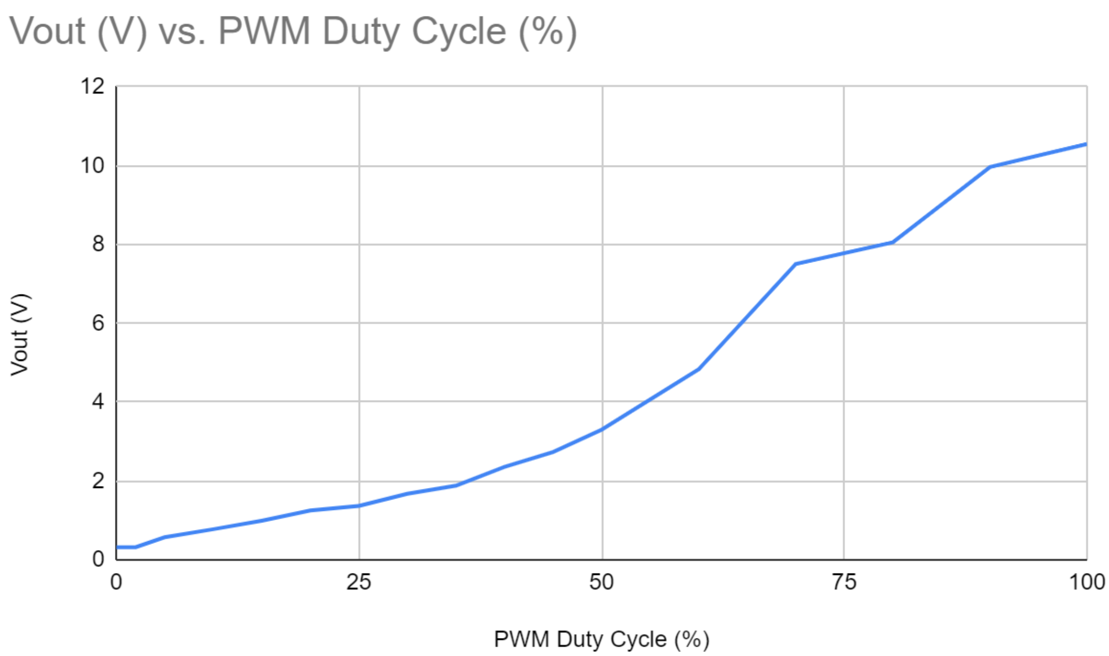


Figure 29: The experimental results of testing the LT3080 Regulator with PWM for input control

## Regulator Data

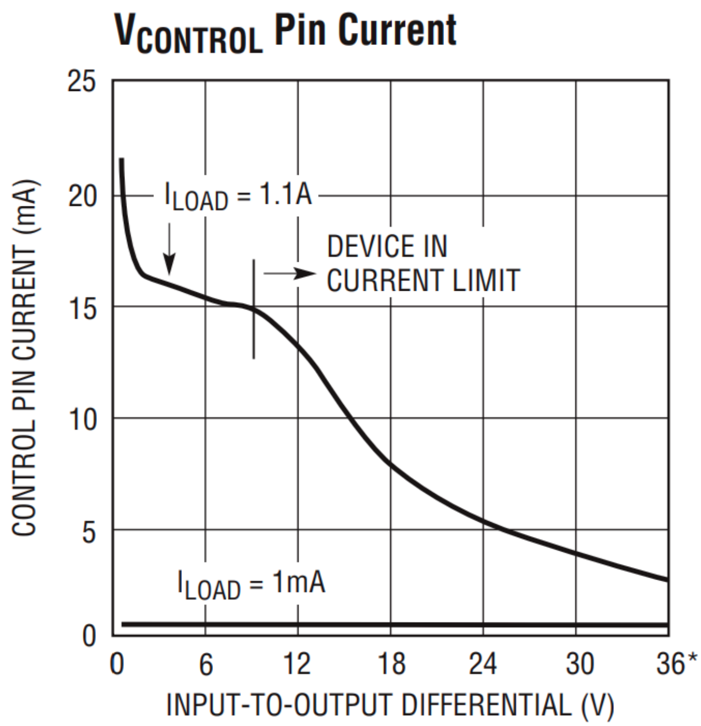


Figure 30: The expected theoretical results from figure 2 are graphed above. Since our input was a fixed 12VDC, only the 0 to 12 range of the graph is important to our design.

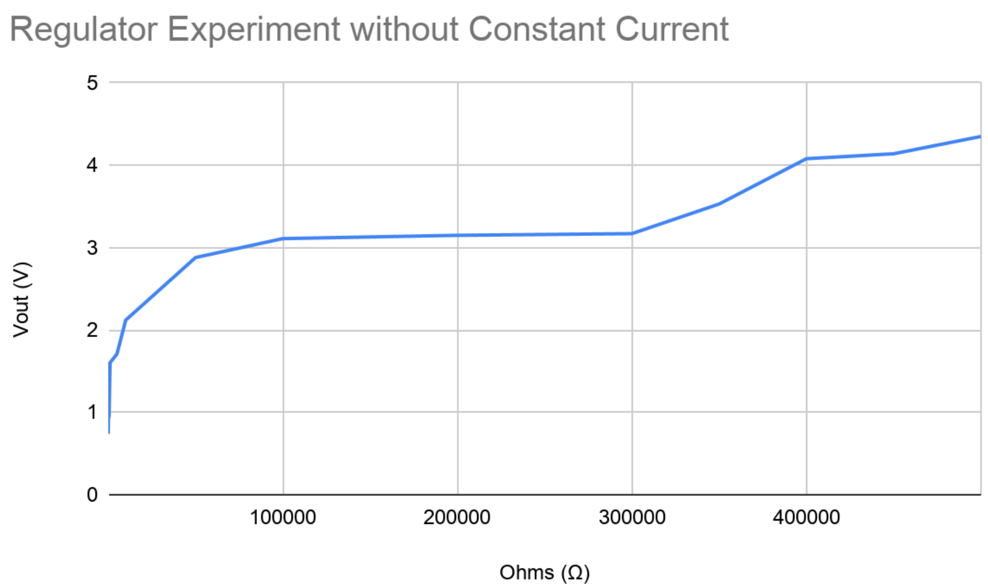


Figure 31: The experimental results of testing the LT3080 Regulator.

# Experimentation Validation using Evaluation Criteria

### Proof of Success

As demonstrated above in the experiment section, schematic design, and data collection many of the aspects of the voltage regulator are working correctly. Our design is sound and our individual parts have been shown to be working as expected. Many of our individual components have been tested together as well. Our design was able to fulfil many of the specifications that were assigned to us at the beginning of the Fall 2020 semester. More specifications can be found below in the 'Comparison with Requirements Analysis'.

### Comparison with Requirements Analysis

1. Benefit students and hobbyists

   The programmable two channel power supply is beneficial both to students and hobbyists. The final cost of the prototype costs $107 while the mass produced version ( <1000 quantity) costs $60.48. Due to the lower cost than current market available power supplies while maintaining rich featurability this requirement is met.

2. Align with GMU ECE lab requirements

   The product aligns with the majority of GMU ECE laboratory requirements. The labs in ECE 101, 285, 286, and 231/331 are able to be met since they utilize less than 10 Volts. All labs in ECE 334 are also able to be accomplished except for one lab which uses up to 20 Volts.

3. Cost < $100

   This requirement is mostly met because when the power supply is mass produced the total cost is $60.48. However, the total cost to design one individual power supply is slightly over $100 at $105.41. This price difference is only $5.41 and would not provide much inconvenience to the customer compared to the current price range of $222 up to $973.

4. Voltage per channel adjustable between 0-10V

   The voltage per channel is mostly adjustable between 0 and 10 Volts. Our device allows the user to go slightly above 10 Volts to around 10.5 Volts. However even with the constant current attached to the output the regulator circuit is not able to output below

0.3 Volts.

5. Maximum current per channel at 500mA

   For this part our team designed a schematic and researched components for current protection so that the device would not go above 500 mA. However, this was not tested enough to be integrated into the final design

6. Output adjustable using a keypad or a knob

   Both the keypad and rotary encoder components are fully working.

7. A current limit should be settable for each channel

   This was not accomplished due to time constraints.

8. Digital readouts for voltage, current, and current limit per channel

   The LCD is able to display the set current, set voltage, measured voltage, and measured current for both channels. The code to collect this data was not entirely completed and tested to our satisfaction.

9. Digital readouts should be precise to a minimum of 0.1 V/10 mA

   This was achieved because the voltage readouts are precise and align with a multimeter when testing the power supply. The readout for current is precise to under 10 mA and the voltage precision is precise under 10 mA.

10. Device switches off when current limit is reached

    Our design accounts for this by using a latching relay at the outputs and a current monitor to constantly check if the measured value exceeds the set maximum.

11. Will be controllable from a USB connection

    This requirement was achieved, but not with full SCPI compatibility.

12. Use a low noise regulator

    This requirement was achieved because a LT380 was used for the regulator. The maximum noise for the regulator circuit was 0.003% of the voltage at maximum.

13. The set voltage should be accurate to 0.1V

    This step was achieved and is shown in the regulator testing section.

14. The set current limit should be accurate to 1mA

    This step was achievable based on our design and was thoroughly planned for, but was not realized in the final prototype.

## Other Issues

One issue we faced was attempting to rely on prewritten MSP430 libraries to reduce time in writing code. Using existing libraries would also decrease the software's testing time since it had been thoroughly tested. However, when using the LCD_HD44780 library for the LCD, several issues increased the estimated time for developing software. When interfacing the library with the MSP430 and LCD, most of the time text would not output. However, on a rare occasion that text did output, only the first and third LCD text lines out of the four available four were accessed.

An additional issue we faced was obtaining the correct output for the LT3080 regulator. During initial testing using a potentiometer, voltage lower than 0.74V couldn't be obtained. This issue was due to a lack of maintaining constant current at the output of the circuit. To maintain a constant current, an LM334 constant current source was added to the regulator circuit's output.

On one occasion, a potentiometer, which was being used as a stand-in for the set signal to the LT3080, smoked and melted. However, this did not cause any long-term problems or damage to the other components. Other components such as resistors, and buttons broke during the debugging process. Luckily this did not cause damage to central components but did impact the cost of prototyping this system.

There were also several encountered issues relating to the specific MSP430s our team used. Different variants of the MSP40 have varying pros and cons. To lower cost and use a less expensive microcontroller, our team used a MSP430F5529 which only costs about 15 dollars from Digi-Key. When programming this microcontroller we realized that only ports 1.0-1.9 and 2.0-2.9 have interrupt vectors allowing for more efficient inputs. Our team did not expect this, resulting in additional debugging and code modification time.

Another issue came due to the second MCU not having a launchpad version. Launchpads ease the wiring process and streamline development. Without a launchpad, more time is necessary to debug issues that arise. To fix this, we decided to use a different MSP which had a launchpad variant.

Difficulty also presented in ensuring that our product remained within $100 to $150 in total cost. Since we built and tested the product while editing the schematic, additional parts were ordered, increasing prototyping cost. There were also high shipping costs to get the product as fast as possible. During the testing process, we decided to buy different/additional resistors or protection pieces. When we designed the power supply last semester, we budgeted using the lowest-cost components possible. However, using the lowest-cost components adds extra development time or even requires adding additional parts to make up the functionality of the high-cost components.

Due to Covid-19, additional problems arose in getting components delivered within a short time frame. Since the virus required that the post office take extra precautions in cleaning packages and social distancing, shipping time increased for the majority of our products. A high amount of time went to waiting for certain parts, such as the LT3080. Therefore, less time was devoted to building and debugging the circuit. A majority of the products our team ordered came from overseas locations, compounding delivery time.

Distance learning and virtual communication were another challenge our team faced this semester. Due to Covid-19 and distance learning challenges, our team could not meet with all individuals present in-person at the same time. Some of our team members lived in different states causing communication to be constructed virtually over sites such as Zoom and Discord. This made testing and interfacing components difficult compared to an in person setting. However, this strengthened our team's ability to use online collaboration resources such as GitHub.

In using online collaborative tools such as GitHub, a few challenges arose. While GitHub is generally an easy platform to use, it may be less intuitive compared with other online collaborative tools, such as Google Docs. This caused a few minor problems such as team members forgetting to push the most recent code online, leading to other members not having the most updated code versions or schematics.

Lastly, the most intensive issue we faced was staying ahead of schedule. Due to all team members taking a full course load while managing senior design, we had to maintain ahead of schedule to manage the project. It was more difficult to collaborate if one team member had a test coming up that they needed to devote more time to. Waiting for components to arrive in the mail also increased waiting time to the schedule that was not accounted for previously. Our team also did not expect certain debugging and code writing processes to take as long as they did. Since we originally planned to use prewritten libraries for the MSP, running into errors with these libraries was surprising and added time to the schedule.

## Administrative Analysis

Project Progress Discussion:

The progression of the project is coming along well. All the components have been finished and thoroughly tested/debugged. Having more time would have been helpful to devote to PCB design, PCB printing, and interfacing the PCB to the rest of the device.

Completion of Tasks Successfully:

| **Task** | **Completed** |
|---|---|
| Schematic Revisions | ✔ |
| LCD Software | ✔ |
| USB Connection | ✔ |
| Regulator Circuit | ✔ |
| Keypad | ✔ |
| Rotary Encoder Knob | ✔ |
| PWM Signal | ✔ |
| Interfacing Software | ✔ |
| PCB Design | ✕ |
| Population of Fabricated PCB | ✕ |
| System Final Assembly with PCB | ✕ |

Table 2: Planned tasks which were or were not accounted for.

Changes Made to Original Schedule:

Originally, we planned to have the components interconnected to PCB within the final development case. Due to time constrictions, the PCB will be designed by the deadline, but will not be printed to interface the remainder hardware of the project.

Additional (non-planned) activities:

There were limited non-planned activities necessary to design and build the power supply. The only non-planned activities occurred when a specific approach took too much time / would not work.

BOM Cost:

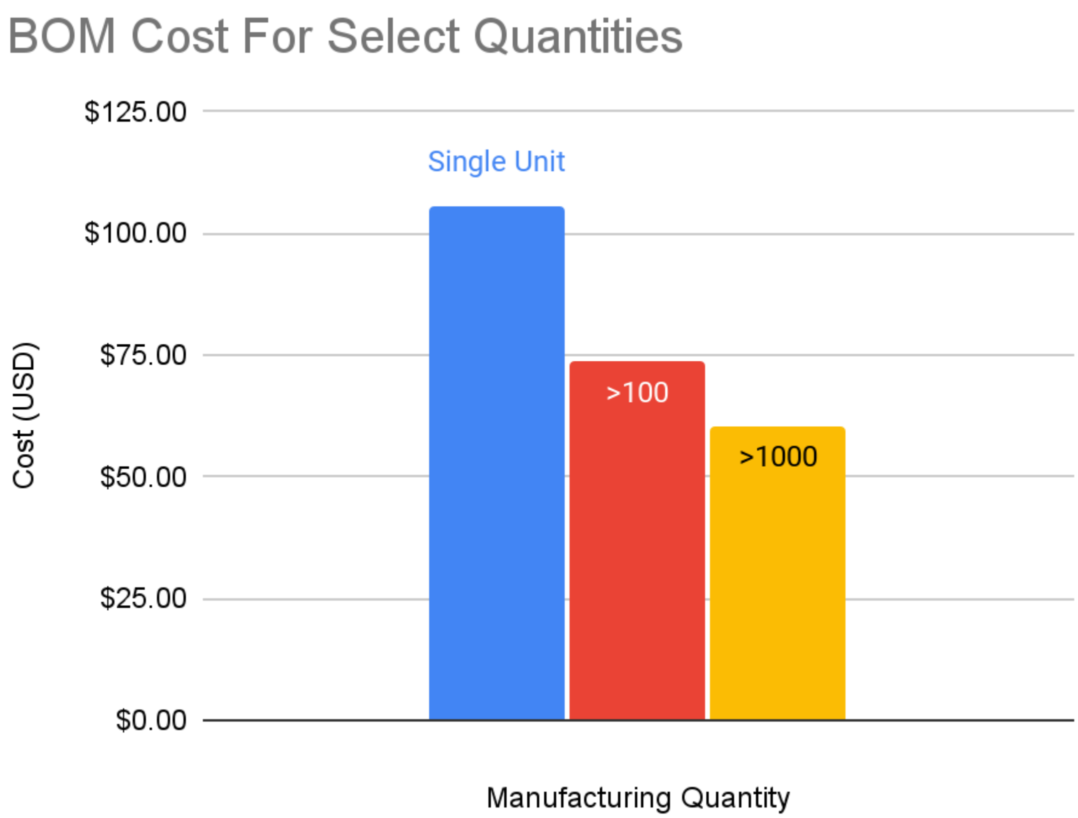


Figure 32: The above graph shows the BOM Cost vs Quantity.

The final bill of materials cost for a single version of our power supply came out to $105.41, which is slightly above our target of $100. Although as shown above, the cost is significantly reduced when built in quantities between 100-1000 at just $73.66. This is even further reduced to $60.48 when ordering in quantities greater than 1000.

Man-Hours:

| **Group Member** | **Total Hours Spent (Fall)** | **Total Hours Spent (Winter)** | **Total Hours Spent (Spring)** | **Total** |
|---|---|---|---|---|
| Harmon Turner | 120 | 10 | 124 | 254 |
| Allison Scanlan | 110 | 4 | 116 | 230 |
| Case Hassak | 108.5 | 3.5 | 123 | 235 |
| Owen Bates | 108 | 4 | 118 | 230 |
| **Total** | | | | **958** |

Table 3: The above table shows hours spent on the project over spring, winter, fall, and spring. The total amount of hours was about 958.

## Lessons Learned

**Additional Knowledge and Skills Learned:**

During the course of this project, a wide range of skill sets was developed. Last semester during the planning phase, our team increased our ability to research for projects which occurred over a long period. During ECE 492, we also used flowchart software such as draw.io.

This semester during ECE 493, our team had increased interactions with difficult software and hardware. In laying out and perfecting the schematic, KiCad was the main software our team relied upon. We developed more skills using KiCad including learning keypad shortcuts and designing new components. We also had several meetings with our faculty supervisor focusing on schematic fine-tuning and using KiCad with increased proficiency.

During the development of our project, our team used several pieces with which we did not possess complete familiarity. We needed to read data sheets to learn the specifics about each component. As an example, we were surprised when the MSP430F5529 only contained interrupts along 1.0-1.9 & 2.0-2.9 ports. This taught our team the importance of scanning a datasheet ahead of time.

A major requirement of our project included performing budget analysis to remain low cost. To reduce cost, our team spent more time researching a wide variety of components and comparing them to decide which piece offered the highest result to cost ratio. We had to keep the receipts of the pieces and budget expenses to ensure we did not exceed the cost limit.

Our team also worked with MSP430 to develop most of the components for our project including the rotary encoder, keypad, and LCD screen. Originally, we attempted to integrate libraries into the design and while this was unsuccessful, we still learned more about libraries and their complexity. When integrating a library, we realized it is often harder to debug since the libraries contained so many files.

Additionally, at the start of our project, our team possessed limited knowledge of PCB design. Only one team member had taken a PCB design lab during our second semester, which was not as thorough as we would need to design a PCB of this complexity. Our team needed to research PCB design methodology and self-teach most of the protocols we used in this design process.

**Teaming Experience:**

The teaming experience went well but was more challenging due to covid. Due to Covid, all team members were in a different location. This increased difficulty in terms of interfacing the pieces together since they were all stored in different locations. Our team needed to double-check with each other on parts they weren't working on before the interfacing could occur.

The most critical part of the teaming experience was improving our time management skills and sticking to a schedule. Our team created several schedules during this semester and revised them accordingly depending on how long certain debugging processes took. We learned that it is crucial to incorporate extra time into a timeline for unexpected bugs and surprises. Another important lesson was the importance of regular meetings when working in a remote group.

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Appendix A: Proposal (ECE 492)

# Programmable Two Channel Lab Power Supply

# Project Proposal

Team Members:

**Harmon Turner, Allison Scanlan, Case Hassak, Owen Bates**

Faculty Advisor:

**Jens-Peter Kaps**

ECE 492-001

Date: October 13, 2020

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# 1. Executive Summary

We aim to design and assemble a 2-channel bench power supply that combines the best market features for a $50 to $100 cost to the consumer.  Workbench power supplies are tools that enable programmable voltage and current output using an AC-DC converter. By providing a precise power output at a low cost, workbench power supplies become more accessible to an average electronics user. Some of the features the end product will include are a high quality linear transformer, 2-channel output, current and voltage readings/limits, a keypad and rotary encoder to directly enter the specified output values, and control through a USB serial connection.

The problems with current market available 2-channel DC power supplies fall into three categories: accuracy of power output, cost, and available features.  Many available power supplies that satisfy the features we aim to include are generally cost-prohibitive to students and even hobbyists.  Most power supplies on the market also output a larger voltage and current range compared to what students need to perform tasks for lab projects. Our power supply would be able to satisfy all laboratory DC requirements for ECE classes 101, 285, 286, and 334 with the exception of one lab. There are not any power supplies on the market which include the specific features of our product.

Due to COVID-19, engineering students are enrolled in online labs and require additional power supplies to complete their labs and assignments. For all the electrical & computer engineering labs at George Mason University, all but one require voltages lower than 10V or can be easily modified with this limit in mind.  Also, with a maximum current of 500mA, the power supply is much safer to handle at home than power supplies with higher current/voltage outputs. Our project can deliver the needed power requirements for labs, while providing a safe power output at an affordable price.

This power supply will be composed of two systems. The primary system is the main PCB which controls user specified input and output, while the secondary system operates internally to control voltage regulation. Specifically, the main PCB contains a microcontroller unit which interfaces with user inputs, usb serial input, output display, and I/O bus to interface to the secondary board. The secondary system will contain a smaller microcontroller processing unit. This will use a transformer to perform power regulation and to control the output of the two DC channels.

# 2. Problem Statement

## 2.1 Motivation and Identification of Need

DC workbench power supplies can be used in many engineering applications where power needs to be provided to a circuit. Our project focuses on students as one of the main target groups. This product would be helpful in times like COVID-19 where students have to take classes online or even when students are taking labs in person, as a way to work on labs when the rooms are not available. One of the problems with other power supplies on the market is the extreme overpowered nature of power supplies for students' needs. Going through the electrical and computer engineering labs at George Mason University, we have seen that students rarely need more than 10 volts and 500 mA per channel. In the rare occasions that more current or voltage is needed, labs could be easily modified with this limitation in mind without affecting the learning goals of the labs. Also, most labs require more than a single channel, especially in labs with operational amplifiers. Additionally, the specific features our product aims for would assist in creating a friendly user experience for students and beginners. Supplying both a keypad and rotary encoder will allow for precise and simple input to the power supply. Allowing the power supply to be programmable would allow various lab experiments and results to be easily saved to resume at a later time.

Another group we are targeting is electronics hobbyists. Hobbyists often have similar needs to the students that we've outlined above. There is a high demand for low-cost, feature-rich bench power supplies in the hobbyist market. This is evidenced by the abundance of DIY power supply plans available on the internet. Many of these plans use an ATX power supply to achieve cheap and easy regulation, at the cost of higher minimum voltages and higher noise on the output. Our design would create an alternative to these DIY projects, as well as the commonly used cheap chinese power supplies that have low-quality components and build quality. It would also cover their needs as most hobbyist projects depend on maximum voltages around 12 volts, which could be achieved by using both outputs of our power supply, but most projects depend on low voltages for digital applications, such as 5 or 3.3 volts. Our design would also allow for tinkering via the USB serial port, which is a feature that we found to be completely unavailable in our targeted price range.

Our market review shows the lack of products that meet our critical requirements. One of these requirements is the cost to the consumer. Most products that achieve accurate voltage with the ability to interface in several ways (keypad and USB control) cost upwards of $400. This is not a reasonable price for students who are already often required to spend money on lab kits. Our power supply would offer a simple and efficient solution to this problem.

### 2.2 Market Review

When creating a low cost product, it is important to analyze the market to ensure there are few, or no competitor products on the market. The following table shows the commercially available products either with similar features, or similar target prices to our project.

| **Model** | **Image** | **# of Channels** | **Voltage Range (Volts)** | **Maximum Current (Amps)** | **Input Methods** | **Maximum Power** | **Maximum Ripple and Noise (µVrms)** | **Meter Accuracy (percent)** | **Serial** | **Price (USD)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Minleaf LONG WEI K3010D |  | 1 | 0-30 | 10 | Rotary Encoder | 300 W | 10,000 | 0.05% | No | $54.99 |
| HYELEC HY5003M(L) |  | 1 | 0-50 | 3 | Keypad | 150 W | 500 | N/A | No | $73.70 |
| Global Specialties 1310 |  | 3 | 1.3-20 | 0.25 | Rotary Encoder | Not found | 1000 | 0.05% | No | $222.83 |
| Siglent SPD1168X |  | 1 | 0-16 | 8 | Rotary Encoder | 128 W | 350 | 0.03% | Yes | $259.00 |
| Rigol Technologies DP711 |  | 1 | 0-30 | 5 | Keypad & Rotary Encoder | 150 W | 500 | 0.05% | No | $299.99 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Keysight U8001A |  | 1 | 0-30 | 3 | Rotary Encoder | 90 W | 1000 | 0.35% | No | $451.00 |
| **Model** | **Image** | **# of Channels** | **Voltage Range (Volts)** | **Maximum Current (Amps)** | **Input Methods** | **Maximum Power** | **Maximum Ripple and Noise (µVrms)** | **Meter Accuracy (percent)** | **Serial** | **Price (USD)** |
| Tektronix PWS2326 |  | 1 | 0-18 | 5 | Keypad | 90 W | 3000 | 0.05% | N/A | $597.00 |
| Keysight E3630A |  | 3 | -20-20 | 0.5 | Rotary Encoder | 50 W | 350 | 0.50% | No | $699.00 |
| Keysight E3620A |  | 2 | 0-25 | 1 | Rotary Encoder | 35 W | 350 | 0.50% | No | $699.00 |
| Keysight E3640A |  | 1 | 0-20 | 1.5 | Rotary Encoder | 30 W | 350 | 0.05% | Yes | $973.00 |

## 2.3 Conclusion

From observing the lab power bench supplies on the market, it is clear that while some products have overlapping qualities with the power supply we seek to build, there are none that meet the exact specifications/requirements. Most of the reviewed products have ample voltage and current ranges similar to our desired product. However, the input methods are varied. Most reviewed power supplies only have one method of input; either a rotary encoder or a keypad with few being USB programmable. The lower cost supplies also have higher noise than the standard low noise standard of 350 uVrms. Our power supply aims to supply the best combination of the above features while maintaining a low cost.

# 3. Approach

## 3.1 Problem Analysis

There are many obstacles to overcome for this project to be successful. First, the project must be completed using parts which cost under $100 total. The project must have an output that ranges from 0-10V and keep the current at a maximum of 500mA. This will require a voltage regulating circuit that can be controlled and read by the user easily. The voltage regulator must keep a constant voltage as long as the load is under 500mA. Limiting ripple noise is another larger challenge of this project as we aim to keep this noise as low as possible. Also, the output current must be settable for each channel and able to switch itself off if maximum current is reached. When selecting components for this project we will also need to select parts that are able to perform their task and to not break down over a short period of time.

## 3.2 Prefered Approach

The preferred approach would be to design a two channel power supply that is computer controlled with a voltage output that is adjustable using a keypad and a knob. The input to the system will be a standard 120V outlet connection that is stepped down using a 120V to 24V transformer. The voltage will then go through a bridge rectifier to convert the voltage from AC to DC. The two channels will allow for increased voltage or current through connecting them together if needed. A DOT matrix LCD display will be used as a display and the system will have holes and possibly a cooling fan for temperature control. Our supply will also use a serial interface that is computer programmable.

## 3.3 Alternative Approach

### 3.3.1 Center-Tapped vs Two Discrete Secondary Windings

Most power supplies used in laboratory settings have more than one variable output channel. One of the benefits to having several discrete output channels is the ability to connect them either in series or parallel to allow for higher current or voltage than a single channel could provide. To achieve this, the internal layout must have the two channels be completely discrete. The transformer must have two separate windings, one for each channel, rather than having a larger secondary winding, with a center tap to achieve a ‘positive’ and ‘negative’ voltage on either side of the center. Using a center-tapped transformer may reduce the complexity, and possibly, the overall cost of the final product. At this time we are planning to use a main transformer with two discrete secondary windings, but are keeping both options in mind for later testing.

### 3.3.2 TFT LCD vs Dot Matrix LCD

A TFT LCD is a higher quality and is able to display more than a Dot Matrix LCD. This causes the TFT LCD to cost more than the Dot Matrix LCD. For our project both displays could perform any task needed.

### 3.3.3 Multiple Microcontrollers vs Single Microcontroller

Multiple microcontrollers can make the components they control operate more efficiently since each controller is dedicated to fewer functions. A single microcontroller would be less expensive but potentially harder to design. A signal microcontroller could also result in more bugs and time needed to devote to debugging. If our product is mass produced, a single microcontroller would save a significant amount of money, opposed to multiple controllers.

## 3.4 Introduction to Background Knowledge

### 3.4.1 Overview

When designing and working with lab power supplies, it is important to understand the specifications, and which internal parts affect the specifications. This can range from simply knowing how the number of channels affects the internal layout and price, to knowing how linear and switching regulators affect the noise on the output.

### 3.4.2 Power Supply Specifications

Most lab power supplies on the market focus on the following eight factors to indicate their quality and accuracy.

*Channels:*

The channels of a power supply indicate how many discrete power outputs they have on-board. Many power supplies have either one or two variable power channels, while some may have an additional fixed, usually 5 volt, channel for digital components. Most power supplies, our design included, allow the channels to be coupled together either in series or parallel to allow for more voltage or current for a single application. Also, having two floating channels is useful in applications with operational amplifiers, as these channels can be used to create a positive and negative voltage.

*Voltage Range:*

The voltage range is the range from the minimum voltage that can be variably controlled, to the maximum. Most power supplies we included in our market review can achieve a minimum voltage output of 0 and max out around 20 to 30 Volts.

*Maximum Current:*

The maximum current rating on a power supply is the maximum current it can achieve at any given voltage on the variable output channel. This value can vary drastically from power supply to power supply and is more important to driving larger projects than would generally be done in an electrical & computer engineering lab.

*Input Methods:*

The input methods are the ways a voltage and current limit can be set in the power supply. Most power supplies in our market research have a single input method, which is a knob. Oftentimes, these knobs are flanked by a series of buttons to change what the knob controls. Another, less common input method is the keypad, which can be used to type in specific values directly to the power supply, which can sometimes be faster than dialing in with a knob. The final input method we observed in the power supplies research for our market review is the serial interface, which is laid out in detail below.

*Maximum Power:*

The maximum power is the max rate at which electrical energy can be transferred by the power supply. Therefore the power is calculated by multiplying the voltage with the current. The max power of the market reviewed power supplies ranges between 35 - 150 Watts. Since the ideal max power of our device will be 5 W (0.5 A * 10 V), our power supply will operate at a lower maximum power compared to other products. If the power supply operates at a power higher than the max power, the device may not function properly or could damage the internal components.

*Maximum Ripple and Noise:*

Maximum ripple and noise both contribute to variance in the signal. Generally, from the market analysis higher priced lab power benches produce lower maximum ripple and noise while the opposite is true for lower priced lab power benches. The majority of analyzed products have maximum ripple and noise ranging between 350 -500 μVrms, but some go as high as 10,000 μVrms. Ideally we are aiming for a ripple and noise maximum that is comparable to those that ranged between 350-500μVrms.

There are several factors which contribute to ripple voltage. The first is noise due to internal thermal changes within the power supply. This type of noise is Gaussian distributed through the frequency domain and is therefore less likely to occur in DC power supplies. Additionally, noise can occur due to a partial leftover AC signal from the full-wave rectification after the transformer. This can be reduced with capacitors and filtering. Parasitic capacitance (unwanted capacitance between parts of an electronic circuit) can also contribute to noise. This is harder to avoid but can be reduced through thoughtful design of the PCB layout.

Noise is more variable and harder to predict compared to ripple. Noise is usually caused due to ringing in inductances due to larger changes in di/dt occurring in the switching converter. Noise frequency is much higher than ripple frequency and can go up to values in the MHz range. Noise occurs in short intervals when there is switching activity in the converter, resulting in what mirrors higher peak and valley effects on the ripple waveform. This is demonstrated below in figure 1.

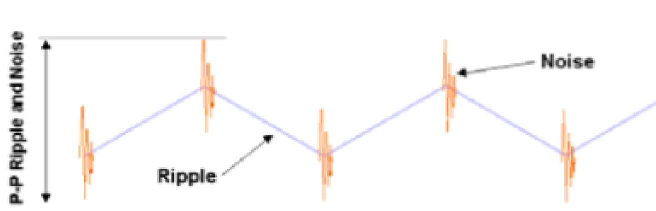


***Figure 1. Ripple Waveform [10]***

*Meter Accuracy:*

Meter accuracy is an important feature that displays the precision of output voltage and current. The voltage will be displayed as xx.xx Volts while the current will be displayed as xxx mA. From the analyzed products in the market review the median percent error is 0.05% with the best quality products ranging down to 0.03%. In order for our power supply to achieve the ideal percent error proper testing will be done as outlined below in the testing section.

*Serial Interface:*

One of the main features of our design is the ability to write custom programs to interface directly with the readings and outputs of the power supply. Few power supplies, without getting into the very high end, include the ability to to interface with the power supply in this way. Some allow this interface through the use of a DB9 serial port, which few modern computers still have, and therefore would require an adaptor to be used. Other, more modern power supplies use a standard USB port to achieve this functionality.

### 3.4.3 Power Supply Components

*Transformer:*

The transformer is a critical part of the design of a power supply. The quality of the transformer can influence noise and other problems within the chain of components in the power supply. The transformer will accept a 120 AC volt supply and decrease the voltage down to a set voltage between 0 and 10 volts. The step down transformer has two coils with different turn ratios. More turns are present on the primary coil compared to the secondary coil which reduces the induced voltage through the secondary coil and hence the voltage output. A bridge rectifier will be attached to the end of the transformer in order to convert to DC voltage.

*Regulators:*

The voltage regulator sustains the current drawn by the load by altering voltage respective to load changes in order to maintain voltage at a constant level. Voltage regulators are commonly found in already built integrated circuits, specifically 78XX or LM78XX. These ICs combine three Zener diodes, 17 transistors, a heat sink, and multiple resistors. The heat sinks assist in limiting the excess power drawn by the regulator when manipulating the current. Generally, regulators come in two varieties, linear and switching. Each has their own advantages and disadvantages. Switching regulators are much more efficient, and often cheaper, than linear regulators, but come at the cost of more noise. Our application needs relatively low noise, so we will be attempting to make linear regulators fit in our budget, but may also use a combination of both to achieve the best noise to price ratio.

*Overcurrent Protection:*

Overcurrent protection devices protect the power supply and external components by opening the circuit when current reaches a max value. The protection may also cause the power supply to turn off if the current spikes to cause a dangerous temperature rise potentially damaging conductors. Magnetic circuit breakers, fuses, and overcurrent relays operate as types of overcurrent protection.

### 3.5 Required Specifications

- Should cost between $50 and $100
- Voltage per channel should be adjustable between 0-10V
- Maximum current per channel should be 500mA
- Output should be adjustable using a keypad or a knob
- A current limit should be settable for each channel
- Digital readouts for voltage, current, and current limit per channel
- The digital readouts should be precise to a minimum of 0.1 V/10 mA
- May display whether output current reaches current limit
- Should switch off when current limit is reached
- Will be controllable from a USB connection
- Should use a low noise regulator
- The set voltage should be within ADDERROR% of the set voltage
- The set current should be within ADDERROR% of the set current

# 4. System Design

## 4.1 System Functional Decomposition

### Level-0

This basic level-0 diagram represents the start of this system's decomposition. To understand the overall solution of this system, we have to understand the lab bench system inputs and outputs. In figure 2,  the keypad, rotary encoder, computer USB serial, and 120V AC are shown as input to the system while the DC outputs, display and output data over USB serial are demonstrated as the outputs.

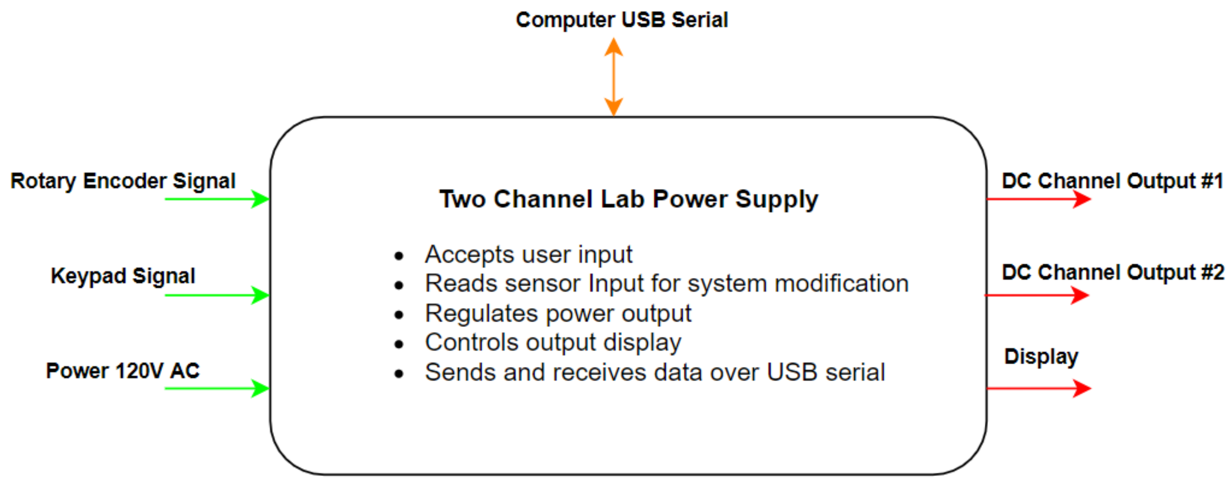


*Figure 2. Two Channel Lab Power Supply Level-0*

### Level-1

After understanding the system at Level-0 of inputs and outputs, the next step is to decompose further for the function makeup of the system. For this system, we included the user system configuration, microcontroller unit, power step down & conversation, sensors, and power regulation. Each function has inputs that get processed into various outputs and sent out to different functions. More detail is provided in figure 3.

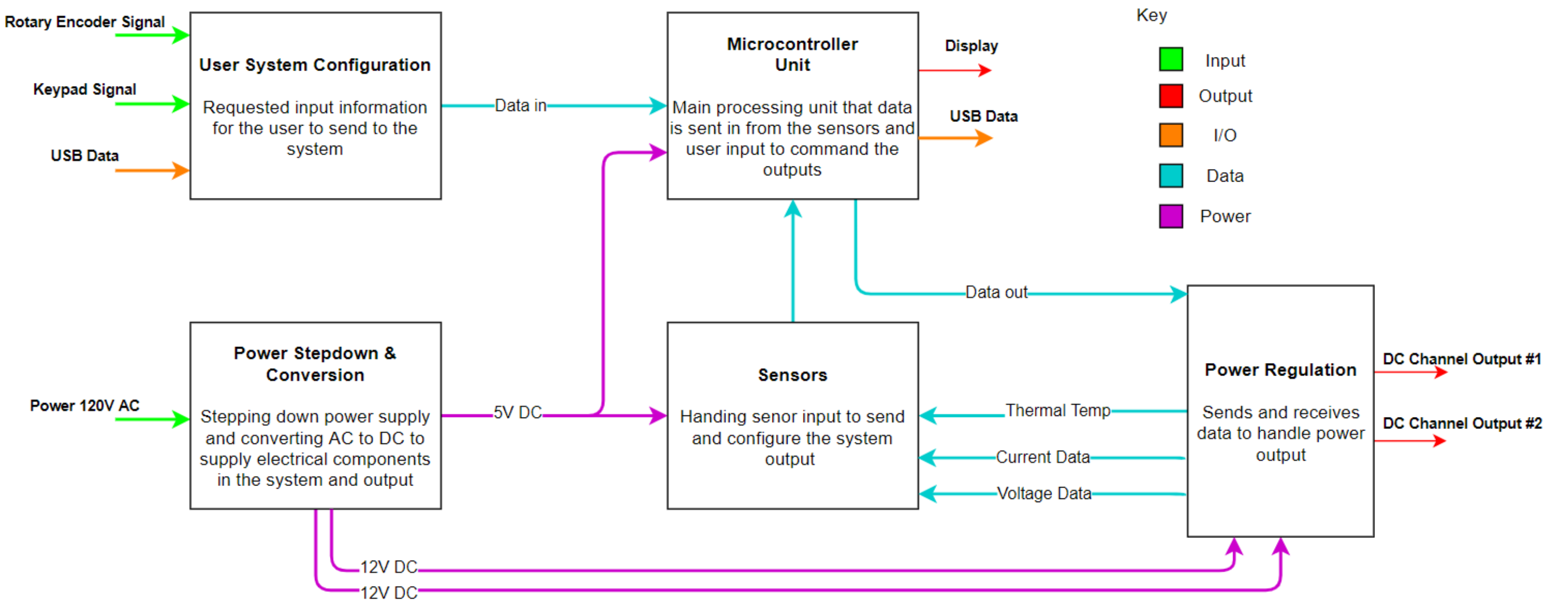


***Figure 3. Two Channel Lab Power Supply Level-1***

### Level-2

After understanding the system at Level-0 and Level 1, the next step is to decompose further to understand how each element and function make up a section in level 1. This detail can help us understand where inputs and outputs are being produced in the system. We can see the main microcontroller unit, power regulation, sensors, and power step down & conversion functions at a lower level. More detail is provided in figure 4-7.

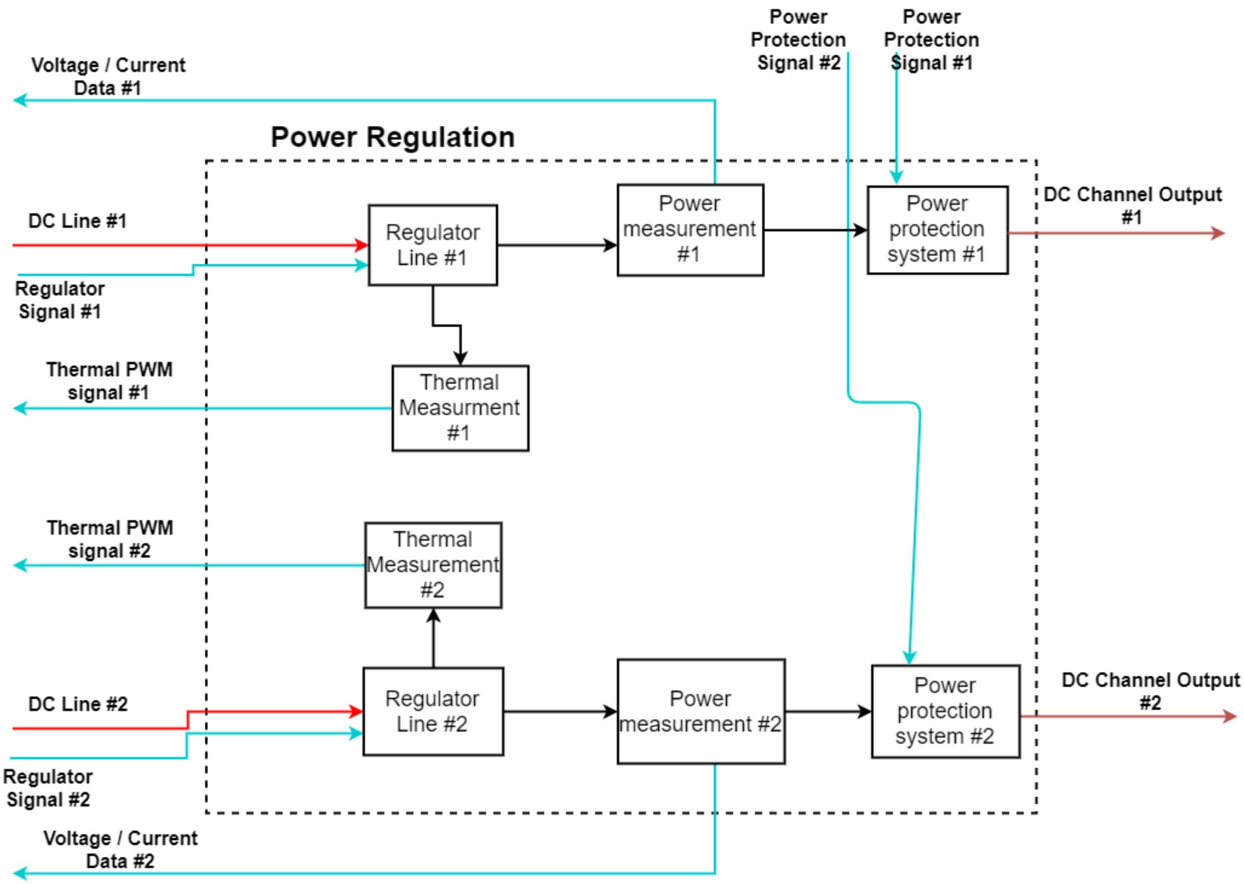


*Figure 4. Two Channel Lab Power Supply Level-2 Power Regulation*

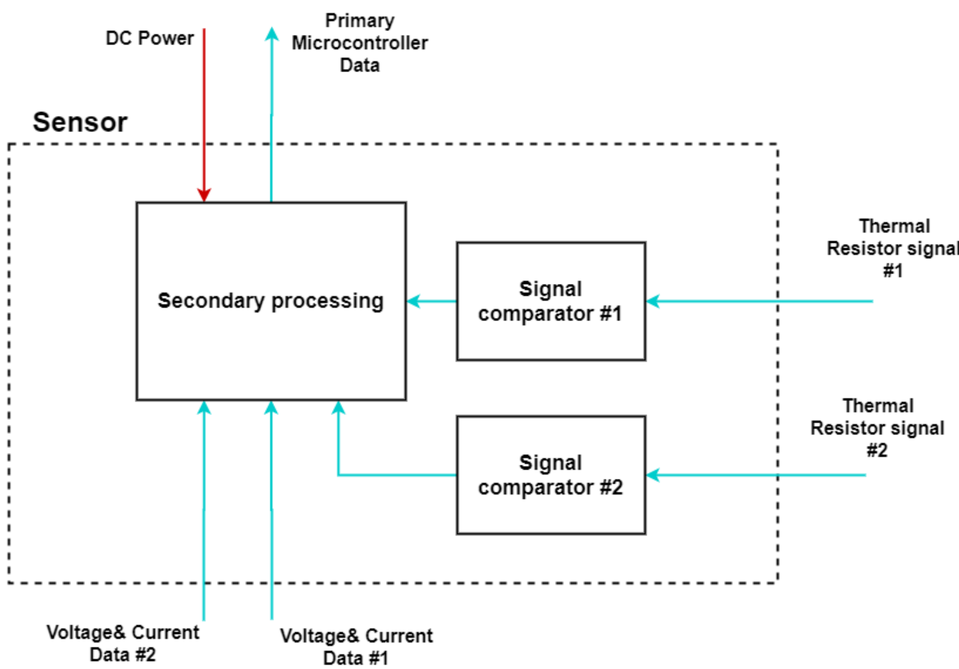

*Figure 5. Two Channel Lab Power Supply Level-2 Sensor*

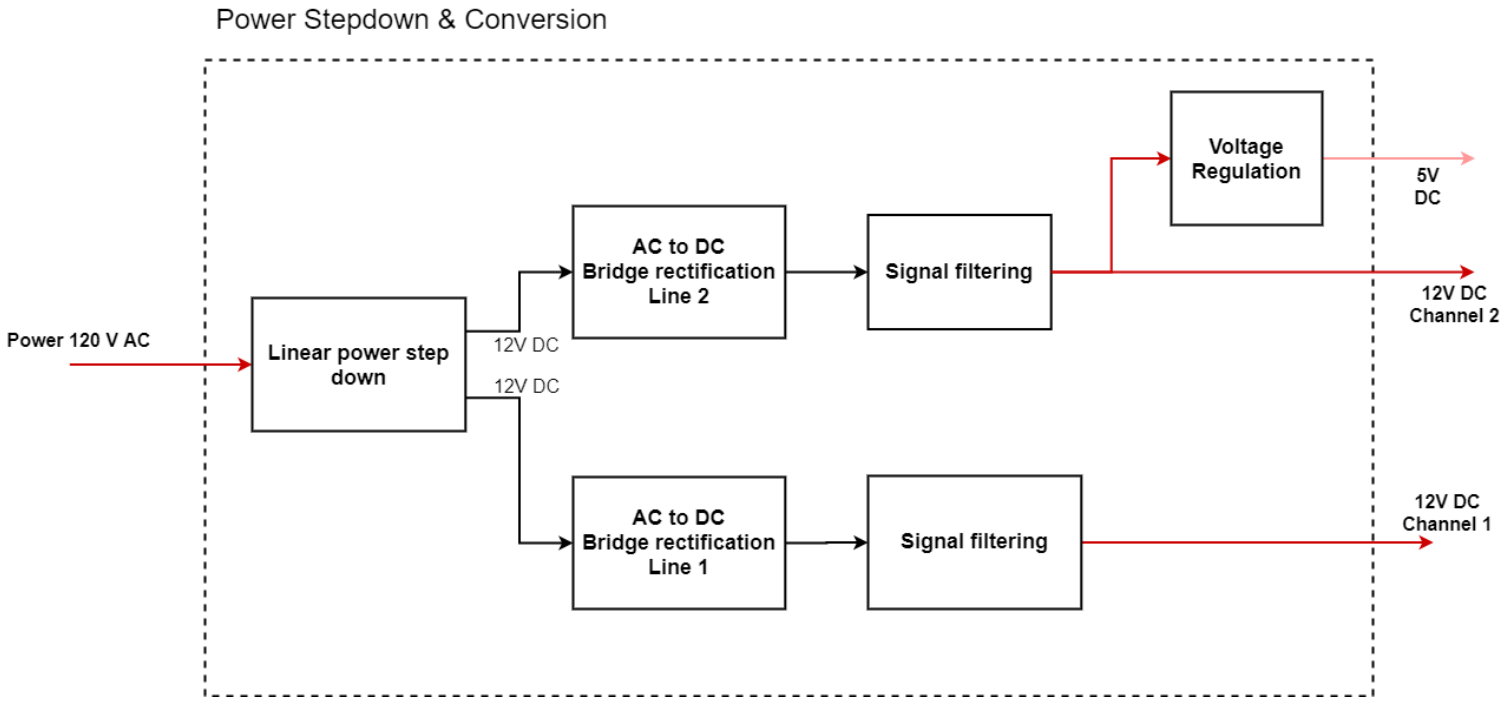


*Figure 6. Two Channel Lab Power Supply Level-2 Power Step Down & Conversion*

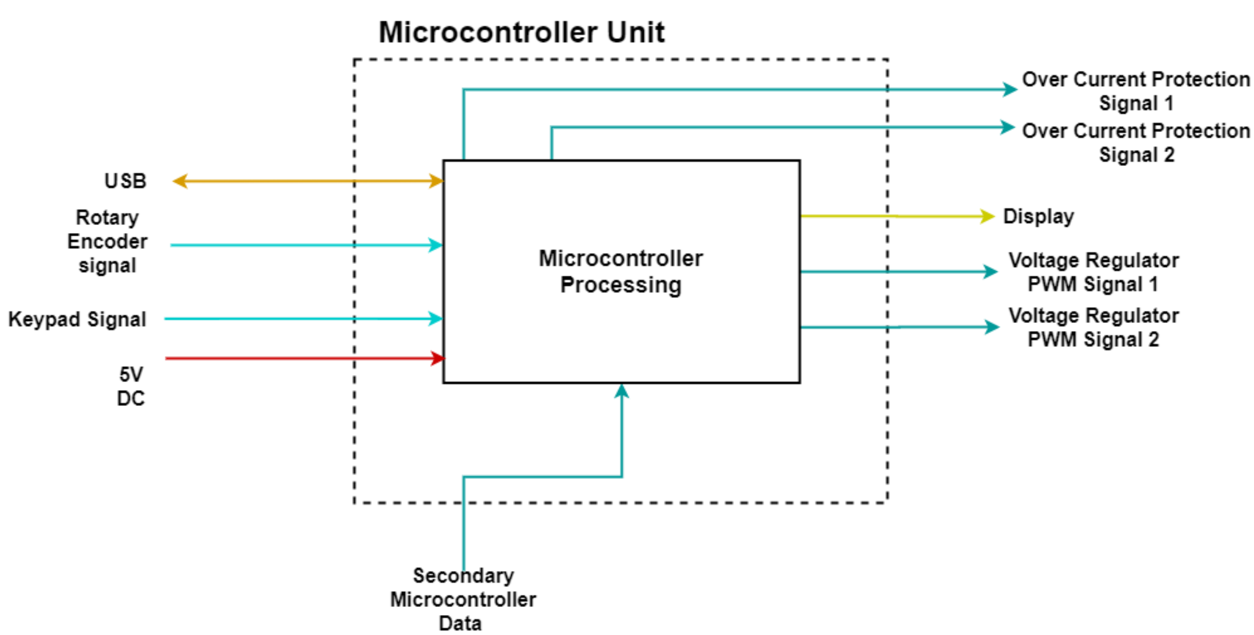

***Figure 7. Two Channel Lab Power Supply Level-2 Microcontroller Unit***

## 4.2 System Architecture

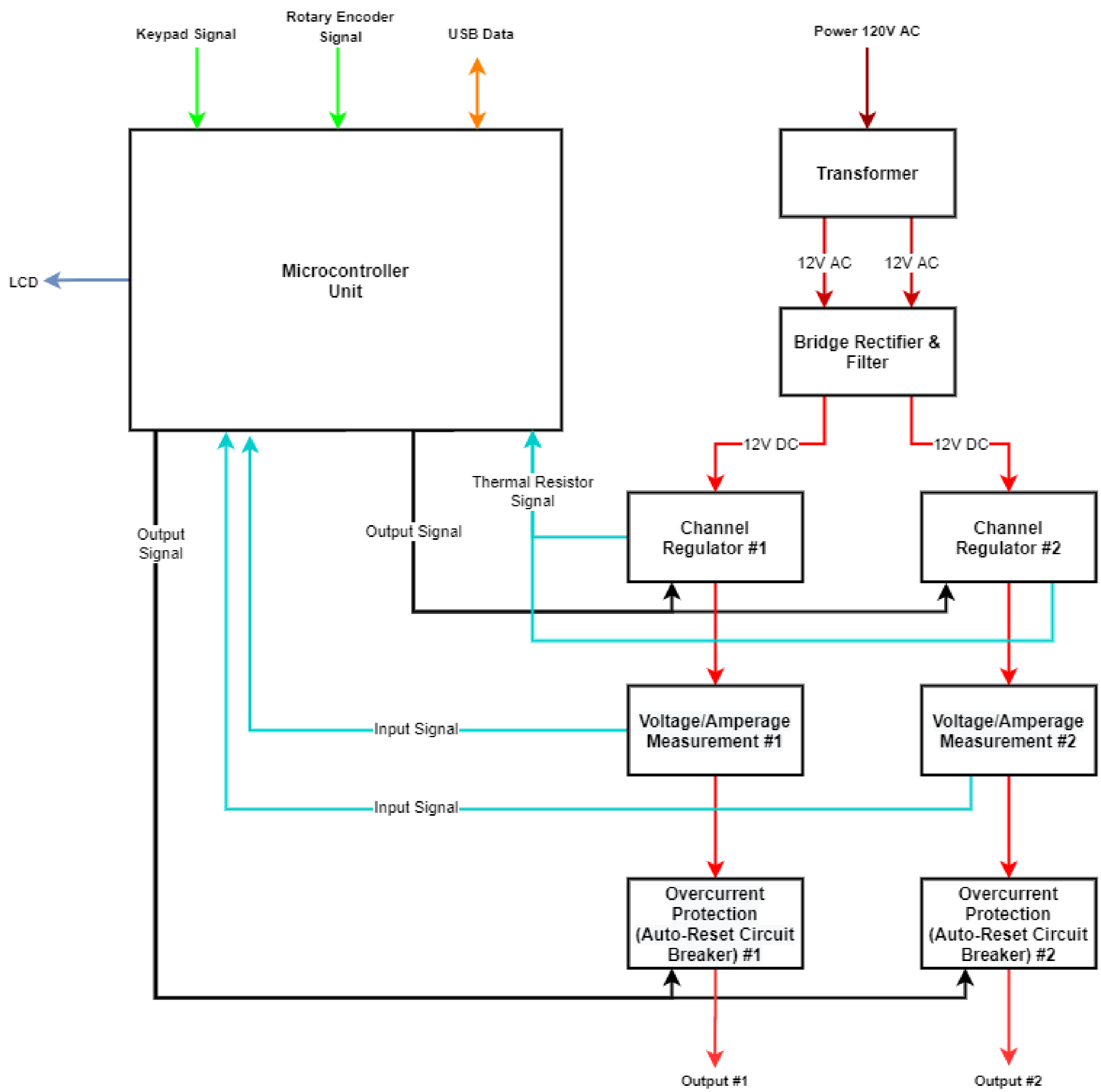


*Figure 8. Physical Architecture*

# 5. Preliminary Experiment Plan

## 5.1 Overview

Testing will need to be conducted in order to thoroughly verify the functionality of this device. To ensure correct operation, the software and inner functions of the device will be tested first. This requires testing and debugging the microcontroller program code. The second approach is to ensure the product works as a whole in a black box format. This means ensuring that the display is correct and the controls can adjust the voltage and currents to the desired settings.

## 5.2 Microcontroller I/O System Testing

The microcontroller will be built early on in the project's development and it will be tested by ensuring the code allows the desired outputs based on the given inputs. The testing of the microcontroller unit will be broken into two parts. First part is input testing and the second will be output testing.

*Input Testing:*

To test input values print statements and an oscilloscope will ensure each signal is being inputted correctly. By using print statements, the input signal can be seen from the rotary encoder, keypad, and USB data. This will confirm that the microcontroller unit is receiving the proper signals. The next part of the input testing is testing sensor input. By using the oscilloscope to see the sensor input signal, this can be compared to the datasheet. After this signal can be printed out from the microcontroller to test if the sensor is being properly interfaced.

*Output Testing:*

To test the output signals this will be broken into two parts. The first part is to test specific cases and have expected outputs. For example, A test case would have the function input for the power supply to be 5V and 0.25A on channel one and ensure the output signals to voltage regulator #1 is being sent. Using the oscilloscope will help us see the proper signal is being provided. We would also want to make sure the display is receiving the right output and that the overcurrent protection device is functioning properly. The current in the output should not be going over the max limit of 0.5 Amps. It also ensures that surges in current are avoided, flows in the correct direction, and has the correct polarizing signal. The second part will test the rare cases that occur from system input. This will involve providing invalid data to the system to ensure the functions with invalid data have the proper catch statements to prevent the output from breaking.

### 5.3 Power Output System Testing

To test the Power Output of the System a multimeter will be used to confirm the generator is displaying the correct results.

*Ripple & Noise Amplitude*:

As a baseline for the measurements the output of the power bench will be tested first without any filters (capacitors /low pass filters).  Using an oscilloscope to analyze the DC output will allow a visual view of the ripple and noise levels.  The Noise peak to peak value is the measurement from the lowest voltage point to the highest. Various RC circuits can be added before the output in order to create a low pass filter which still allows the highest max voltage to pass through.  Additional capacitors can be added to reduce ripple and noise.  Using the microcontroller we could program digital resistors and capacitors to limit noise and ripple.

*Stable output/ Load Regulation*:

Load regulation is a measurement of the ability for the output voltage to be maintained when the current changes. This ideal load regulation variation is very small, at approximately 0.01% or 2mV above the maximum voltage.  The best way to test for load regulation is to get a load resistor which will allow the minimum load, maximum current and nominal load.  This should be connected to the output terminals.  Once the measurements are completed the load regulation can be calculated with the formula below:

*%load regulation = V (full load) - V(minimum load) / V (nominal load) * 100%*

*Meter Accuracy*:

The goal voltage output for this power supply is between 0 - 10 Volts, however it is also important to ensure precision at each output voltage.  In order to test the voltage accuracy, the input voltage should be set to the nominal requirement for the power supply.  Next, the output voltage should be set to the maximum value, or 10 Volts. Once the output voltage is measured with a calibrated voltmeter the below formula can be used to determine the output voltage accuracy (OVA):

$$OVA\ (\%) = (V_{out} - V_{nom}) / V_{nom} * 100$$

*Smooth Turn on/off Without Spikes*:

Since the power supply is using a step-down transformer to convert AC voltage to DC voltage, there is a possibility of spikes when turning on/off the device. When the switch is closed, inductor current increases, however when the switch turns off the voltage spikes as the inductor attempts to maintain current. Since the inductor is using its potential to construct its magnetic field it is not able to maintain the current. The diode then conducts current from the inductor into the capacitor. Spikes with high voltage amplitudes can cause damage to the power supply or components the user is examining. Therefore, it is ideal to limit spikes as low as possible.

In order to test the voltage spikes, a multimeter will be attached to the power supply's output terminals. An oscilloscope will be used to visually measure the spike when turning on and off the power supply. Voltage spikes should be less than 3 nanoseconds in length otherwise they are called a voltage surge. Voltage surge range protection is available to limit electrical charge exiting the system. This protection is able to remove the excess charge through various methods including an earthed lead.

*Transient Response Time*:

The load regulation enables the power supply to continuously adjust in order to provide the proper voltage. However, this adjustment doesn't happen instantaneously, and is known as the transient recovery time. This is rated between two levels of the rated loads. It is measured from the moment the load is charged to when the voltage returns.

In order to test the transient response time the input voltage should be adjusted to the nominal value. The power supply should be programmed to step the load change value. The oscilloscope should be triggered while the load is switched over the programmed range. The transient recovery time can be measured with the oscilloscope.

# 6. Preliminary Project Plan

## 6.1 Overview

This project will be worked on in a specific order to ensure each function works before all parts are combined. First, we will start by developing and testing some of the core code that will be written to the microcontroller. While one part of the team is testing the programming and testing the microcontroller, another will be working on the regulators and testing the design. Our design calls for regulators that can handle zero to ten volts and up to 500 milliamps per channel, where there is one regulator per channel. Once we have the regulators connected and wired up to the input power supply, we will manually test them on a breadboard before moving on to a printed circuit board or connecting the microcontroller to control them. When we are satisfied with the performance of the regulators, we will introduce the microcontroller to not only control the voltage level and turn the output on and off, but also to monitor the voltage and current leaving the regulator, which will enable the functionality our design calls for. When all components are assembled and tested on a breadboard, we will begin to plan and design a PCB to house all the required components. We will then work on specifics of the physical layout and shift the components around to decide the best layout. To get the most efficient layout, we will be designing not only for space efficiency, but also with the ability to remove the parts and repair anything that may be broken or malfunctioning. The case will feature a dot matrix LCD, a keypad, and two rotary encoders on the front. On the back, there will be holes for airflow and possibly a fan, if deemed necessary during testing, a female USB type B connector and a standard AC input.

## 6.2 Allocation of Responsibilities

The aspects of the physical testing and building phase will be carried out by all team members. Owen Bates and Allison Scanlan will be responsible for the physical design and assembly of the power supply. Harmon Turner and Case Hassak will be responsible for writing the software that will control the power supply and run on the main microcontroller. Owen Bates and Harmon Turner will be responsible for designing and building the regulators and sensors that communicate with the main microcontroller. Case Hassak and Allison Scanlan will be responsible for technical drawings and documentation. By the end of this semester we should have the design for the project complete. Once a design is made we will move forward with the building next semester. By the beginning of next semester we should have a list of parts to purchase as a group that we will review and go over. By the end of January we should have parts ordered. Code for the microcontroller, as well as the regulator working should be complete by February 15th. Once this is complete work on the printed circuit board will begin and hopefully within two weeks of the regulator working we will have the parts soldered onto a custom PCB. By March 15th we should have the display connected and working to display outputs from the system. By the end of March everything should be working individually and all that will need to be done is to have the parts put together and to add a cooling system and housing. Then by the middle of April we hope to have a complete project that we can work on improving if there are any issues we notice. The full project should be completely ready by the beginning of May and any extra time we have can be used for if a specific portion of the project takes longer than expected.

# 7. Potential Problems

## 7.1 Required Knowledge and Skill

This project requires a lot of new information and skills to be obtained. Learning how to combine these components to make one machine that functions smoothly for the user will be the main thing to figure out. How to program the display screen to show the outputs of the power supply and how to program the 4x4 keypad to have specific functions relating to the power supply will also be required. Another obstacle will be figuring out how to best model this project.

## 7.2 Risk Analysis

Potential hazards with this project include the risk of having an unreliable product. If this product is not soundly built it will not matter that it is cheap, since it would not be dependable. Another potential problem could be the safety of the design. If this project is not built to be just as safe, if not more safe, than the power supplies on the market, then it will not be worth building. Other risks include it being too confusing comparatively to other power supplies, so this design must be simple and user friendly in order for people to want it. Finally we want to make sure the voltage output is linear and not a sudden power spike. Having a power spike when a user turns on the power supply can damage the load and make the power supply unreliable for lab use. We also must be sure that the regulator is stable and if it is not a backup plan that may involve adding a base load or some capacitors may be required.

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Appendix B: Design Document (ECE 492)

# Programmable Two Channel Lab Power Supply

# Design Review

Team Members:

**Harmon Turner, Allison Scanlan, Case Hassak, Owen Bates**

Faculty Advisor:

**Jens-Peter Kaps**

ECE 492-001

Date: December 7, 2020

# 1. Needs and Requirements

We aim to design and assemble a 2-channel bench power supply that combines the best market features for a $50 to $100 cost to the consumer. Bench power supplies are tools that enable programmable voltage and current output using an AC-DC converter. By providing a precise power output at a low cost, bench power supplies become more accessible to an average electronics user. Some of the features the end product will include are: a high quality linear transformer, 2-channel output, current and voltage readings/limits, a keypad and rotary encoder to directly enter the specified output values, and control through a USB serial connection.

The problems with current market available 2-channel DC power supplies fall into three categories: accuracy of power output, cost, and available features. Many available power supplies that satisfy the features we aim to include are generally cost-prohibitive to students and even hobbyists. Most power supplies on the market also output a larger voltage and current range compared to what students need to perform tasks for lab projects. Our power supply would be able to satisfy all laboratory DC requirements for ECE classes 101, 285, 286, and 334 with the exception of one lab. There are not any power supplies on the market which include the specific features of our product for our targeted price.

Due to COVID-19, engineering students are enrolled in online labs and require a power supply at home to complete their labs and assignments. For the electrical & computer engineering labs at George Mason University, all but one require voltages lower than 10V or can be easily modified with this limit in mind. Also, with a maximum current of 500mA, the power supply is much safer to handle at home than power supplies with higher current/voltage outputs. Our project can deliver the needed power requirements for labs, while providing a safe power output at an affordable price.

This power supply will be composed of two systems, power regulation and user control. The power regulation system will take AC input from the wall and step it down to a more reasonable voltage. This voltage will then be rectified and fed into a linear voltage regulator. These two outputs will then be made available to the user via the front of the unit. The secondary unit will allow the user to select and control the power output. This will be achieved through two microcontrollers. The first MCU will be responsible for channel one as well as interfacing with the user. These interfaces will be: a keypad to directly enter values, a rotary knob to adjust values quickly, and a USB connection to input values digitally. The second MCU will be responsible for interfacing with the first MCU to control the power output and relay current and voltage information on channel two.

Project Requirements:

- Cost between $50 and $100
- Voltage per channel should be adjustable between 0-10V
- Maximum current per channel should be 500mA
- Output should be adjustable using a keypad or a knob
- A current limit should be settable for each channel
- Digital readouts for voltage, current, and current limit per channel
- The digital readouts should be precise to a minimum of 0.1 V/10 mA
- May display whether output current reaches current limit
- Should switch off when current limit is reached
- Will be controllable from a USB connection
- Should use a low noise regulator
- The set voltage should be accurate to 0.1V
- The set current should be accurate to 1mA

## 2. Design architecture

### 2.1 Level-0:

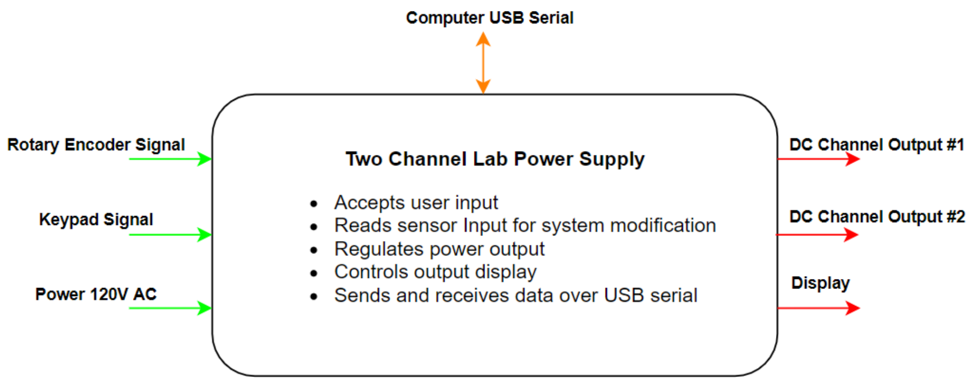



***Figure 2. Two Channel Lab Power Supply Level-0***

### 2.2 Level-1:

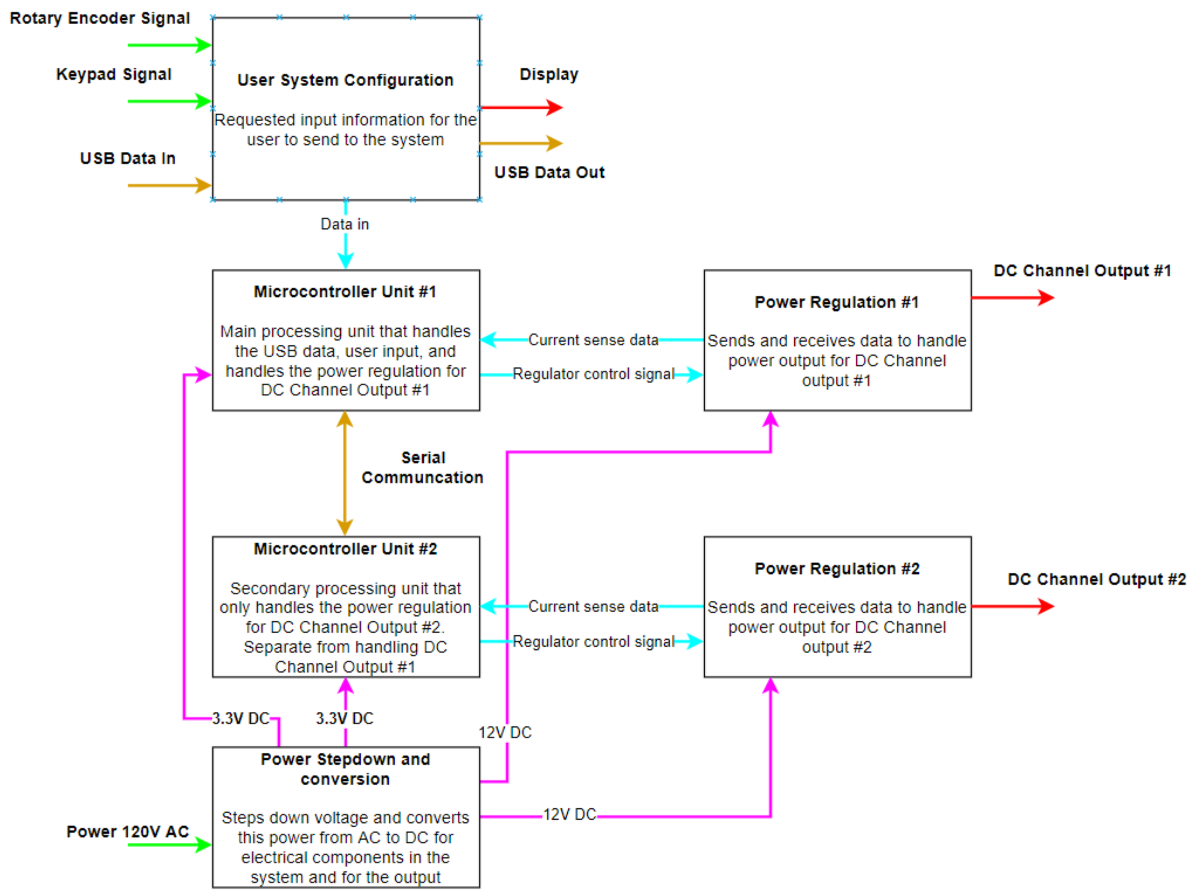
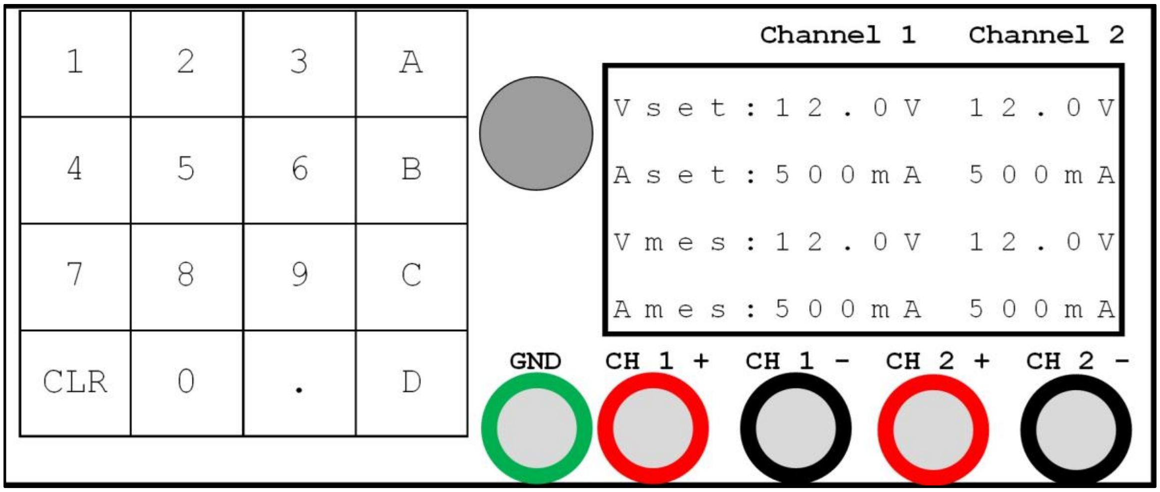



***Figure 3. Two Channel Lab Power Supply Level-1***

## 2.3 Physical Design:




This is our first revision for the front panel of the power supply in the given case. The current design is a little cramped, but will be functional and allow for the supply to be stored in small places or kept on a desk without taking up too much space. This is especially important for use by students working at home, who might not have a whole workstation setup for lab work.

As shown, this design keeps the keypad, knob with built-in button, display, and outputs conveniently on the front of the case while keeping the AC power input on the rear along with the female USB type B connector. We opted for this approach rather than moving some I/O off of the front to allow the unit to be tucked into a smaller space and still allow the user to reach everything easily. The display will update several times per second to ensure timely readings of measured values. The knob will be always active and allow the user to ‘scroll’ from 0V to 12V in a linear fashion, each ‘notch’ will raise the value 0.1V, or 1mA for the current limit. This will be useful when fine tuning, and the keypad can be used to move between small and large values more quickly.

# 3. Background knowledge

## 3.1 Transformer:

The transformer will be connected between a 120VAC outlet and the two bridge rectifiers. The transformer is composed of two isolated windings, each with the same turn ratio. The initial alternating current signal flows through the primary coil, establishing a magnetic flux. The magnetic flux can be found using the sine of the angle of the voltage signal or the turn ratio. This magnetic flux induces a voltage across the secondary coil.

In construction of the bench power supply, one primary coil will be isolated from two (seperated) secondary coils. This will result in inducing two separate step down voltages into the secondary inductors. The turn ratio is the chosen transformer will reduce the 120 VAC source to 12 VAC volts across both inductors feeding into the bridge rectifier.

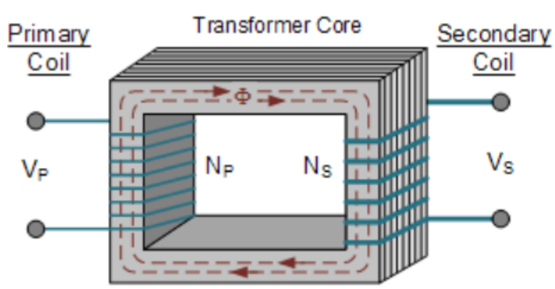



Figure 1: The above image displays the construction of a transformer.

Magnetic Flux (Φ): $\Phi = \Phi max \sin(wt)$

Assuming an ideal transformer and phase angles of $\Phi_P = \Phi_S$,

Turn ratio (TR) = Np / Ns = Vp / Vs

Determined by Faraday's Law:
Emf (E) = N* (dΦ/dt),
E = N* w * Φmax * cos(w*t)
Emax = N*w*Φmax
Erms = (N*w* Φmax)/√2

Vp (primary voltage), Vs (secondary voltage) = E (emf), Np ( no. of primary windings), Ns (number of secondary windings), Φ (flux linkage), TR (Turns ratio), w (omega)

## 3.2 Thermal Dissipation:

Calculating thermal dissipation (heat transfer) may be necessary at several locations within the circuit in order to avoid overheating. Since electrical components are not 100% efficient and heat is produced, it is important to know how much heat needs to be dissipated in the system. Having the voltage regulators run at cooler temperatures helps put less strain on the devices to make the components last longer. Using the thermal resistance equation, we can calculate how much heat is being produced, and from here use this equation to calculate the maximum power we need to dissipate.

Thermal Resistance equation:

$$\theta_{JA} = \frac{T_J - T_A}{P_D}$$

Where:

$\theta_{JA}$ = thermal resistance
$T_J$ = junction temperature
$T_A$ = ambient temperature
$P_D$ = power dissipation

Maximum power that the device can dissipate:

$$P_{DMAX} = \frac{T_{JMAX} - T_A}{\theta_{JA}}$$

## 3.3 Bridge Rectifier Circuit:

The bridge rectifier circuit is placed after the transformer and before the regulator. The bridge rectifier works by rectifying the transformer output of 12 VAC to 12 VDC. The diodes shown below in figure 2, are placed in a way which only allow current to flow in one direction. This creates the below purple signal (figure 2) above the x-axis. Since the diodes alone don't create a completely smooth signal, a capacitor is necessary to be added after the diamond arrangement of diodes. The formula for the created DC signal is detailed below.

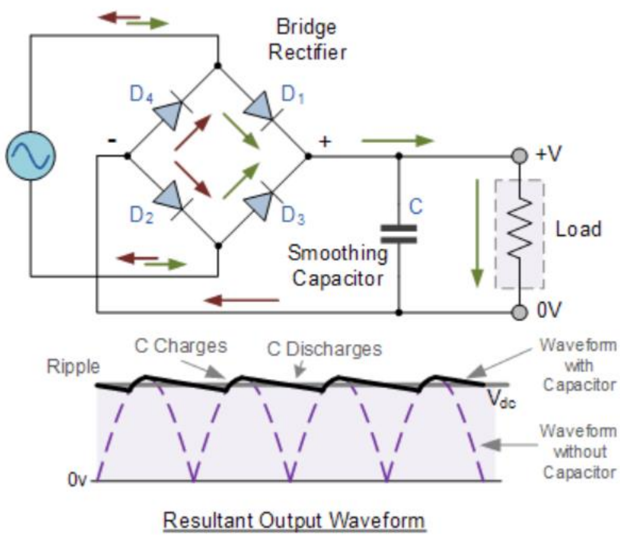



Figure 2: The above circuit represents that of a bridge rectifier circuit.

$V_{d.c} = 2*V_{max}/\pi = 0.9*V_{rms}$

## 3.4 Ripple & Noise:

Ripple and noise are attributes of the electrical signal throughout the circuit which decrease accuracy and reliability of the signal. Ripple is the intrinsic AC component of the signal. Generally, it occurs at low frequencies similar to that of the operating frequency. Noise is due to parasitic inductance within the circuit and occurs at a much higher frequency, usually within the MHz range. Noise will be induced individually by several of the components within the circuit, mainly the regulator. In contrast, ripple will be induced due to the original conversion of the signal from AC to DC after the bridge rectifier.

The ripple formula below is the induced ripple from the bridge rectifier circuit (figure 2).
$V_{(ripple)} = I_{(load)} /f*C$

f = frequency, C = capacitance value

A low pass filter (π filter) will be constructed out of two smoothing capacitors. The effect of this is seen in figure 2.

Noise will also be induced from the regulator (Noi)
$Noi = \sqrt{4*k*T*R}$

$k = 1.38 * 10^{(-23)}$ J/K , T = absolute temperature, R = resistor

## 3.5 Regulator:

The regulator that will be used within this bench power supply is the LT3080. This regulator is able to supply a wide range of output voltages based on a comparison reference. The reference current through the resistor allows the output voltage to be between 0 and 36 volts, which is well above our desired 12 volts. This device has some built in over-current protection, but continuous operation over the maximum junction operating voltage may cause permanent damage.

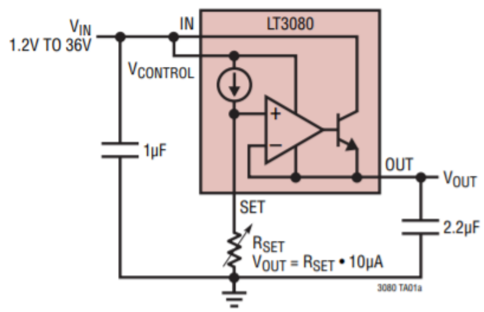



Figure 3: The above circuit shows a single resistor low dropout regulator.

## 3.6 Max Current, Voltage, Power:

Throughout construction and building of the power supply, testing and debugging will be necessary. The voltage and current will be tested at various points in the diagram to ensure that the values remain consistent with those outlined in the schematic. Additionally, current will be measured at various points to limit overheating and to test overcurrent protection.

Additionally the fundamental characteristics of Ohm's law are necessary for designing the circuit. Based on various resistor values implemented into the schematic the voltage and current can be modified. The below equations detail Ohm's law and the relationship between voltage, current, resistance, and power.

Ohm's law dictates the relationship: $V = I*R$

Power (P) = $R*I^2$ , V/R

## 3.7 Heat Sink:

The heat sink is designed to draw heat away from the components. The heat is generated by the components as outlined above in section 3.2. Below shows how we can use aluminum, copper, or steel to draw heat away from these components and spread it into the surrounding environment. This can either be a purpose built device or possibly just the case of the supply itself.

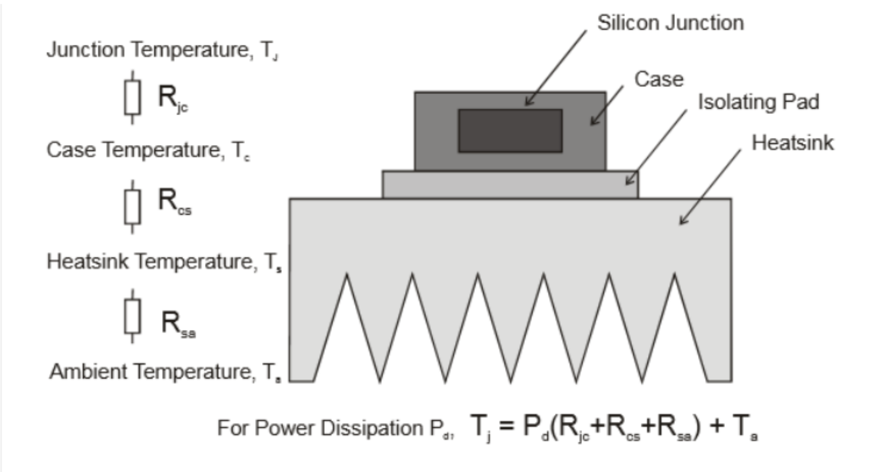



Figure 4: The above image represents the various components of a heat sink.

$$P_D = \frac{\Delta T}{\theta_{total}}$$

PD = Power dissipated by the semiconductor (W)

□□□□□□□□□□□ T = temperature differential

$\theta$total = sum of the thermal resistance

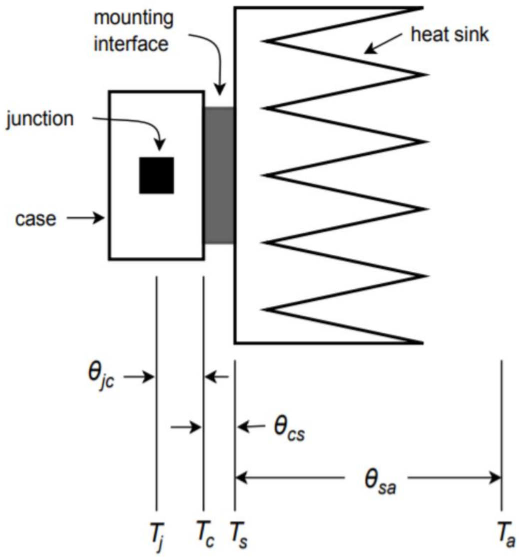



Figure 5: The above figure shows the power dissipated based on the specific features of the semiconductor.

$$P_D = \frac{T_j - T_a}{\theta_{jc} + \theta_{cs} + \theta_{sa}}$$

$\theta$jc = junction and ambient temperature
$\theta$cs = thermal resistance (function of case style and insulation material)
$\theta$sa = thermal resistance of the heat sink

## 3.8 Load Regulation:

Load regulation refers to the ability of the power supply to maintain a steady consistent output. Ideally, the load regulation would be 0 meaning the output voltage is completely independent from temporary surges occurring within the circuit. By measuring the maximum load, minimum load, and nominal load the output stability can be determined.

*%load regulation = V (full load) - V(minimum load) / V (nominal load) * 100%*

## 3.9 Meter Accuracy:

Meter Accuracy is the accuracy of the provided current and voltage values based on the programmable input given by the user. For the power supply, the meter inaccuracy of the voltage supply should be less than 0.1 V, while the current inaccuracy should be less than 1 mA.

*OVA (%) = (Vout - Vnom)/ Vnom * 100*

*Vnom - nominal voltage*

*Vout - output voltage*

OVA - Output voltage accuracy

## 3.10 Serial Interface:

Standard Commands for Programmable Instruments (SCPI) is supported in our design and it will meet IEEE 488.2 requirements. This allows the power supply to communicate via serial with any number of SCPI compatible programs, such as NI-VISA and PyVISA for C and Python respectively. For example, the following command syntax and commands, from [8], will be supported:

| | |
|---|---|
| `INST?` | *Check currently selected output* |
| `1` | |
| `INST CH2` | *Select channel two as current channel* |
| `VOLT 10` | *Set output voltage* |
| `CURR` | *Set output current* |
| `CURR:PROT:STAT?` | *Check OCP status* |
| `0` | |
| `CURR:PROT:STAT 1` | *Enable OCP* |
| `CURR:PROT:DEL 100ms` | *Set OCP delay* |
| `OUTP 1` | *Enable output* |
| `MEAS?` | *Measure output voltage* |
| `10.00` | |
| `MEAS:CURR?` | *Measure output current* |
| `0.00` | *Current is zero since no load is connected* |

## 3.11 Analog to Digital Converters (ADC):

To measure voltage across the outputs, we are using the MSP430’s built-in 12-bit ADCs. To obtain our desired voltage accuracy of 0.1 V, we will need to determine the resolution required of our ADCs. This can be determined by taking the maximum voltage divided by the total number of ‘steps’ in the ADC, in our case 2^12 - 1 or 4095. The result of this calculation determines that the maximum resolution that can be achieved by our MCUs is 2.9mV. The value produced by the 12-bit ADC can be converted to Volts with the following ratio:

$$\frac{2^n - 1}{V_{max}} = \frac{ADC\ Output}{V_{ADCinput}},$$

where n is 12, because it is a 12-bit ADC, and Vmax is 12 Volts.

# 4. Detailed Design (Level-2)

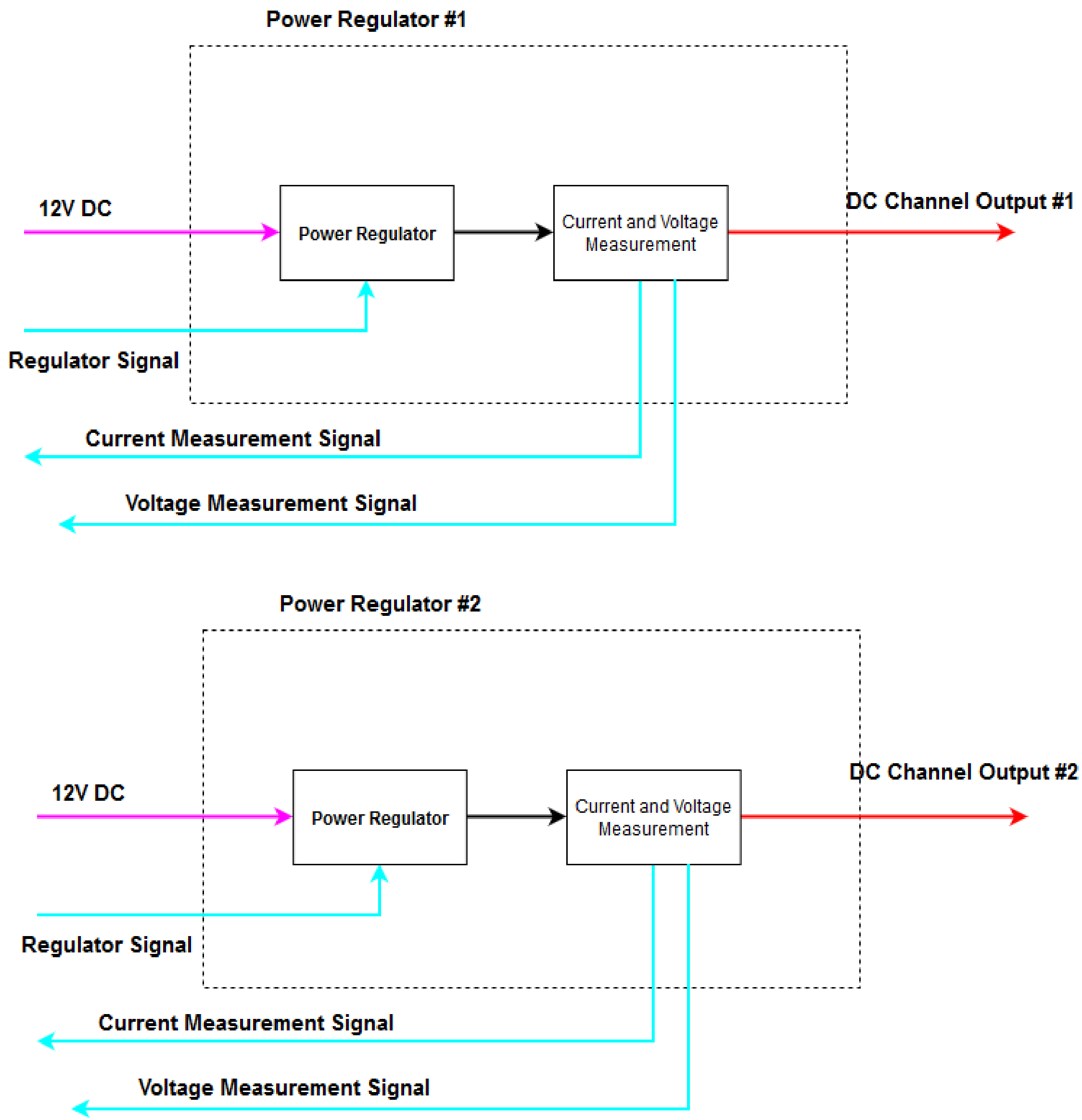



***Figure 4. Power Regulators Level-2***

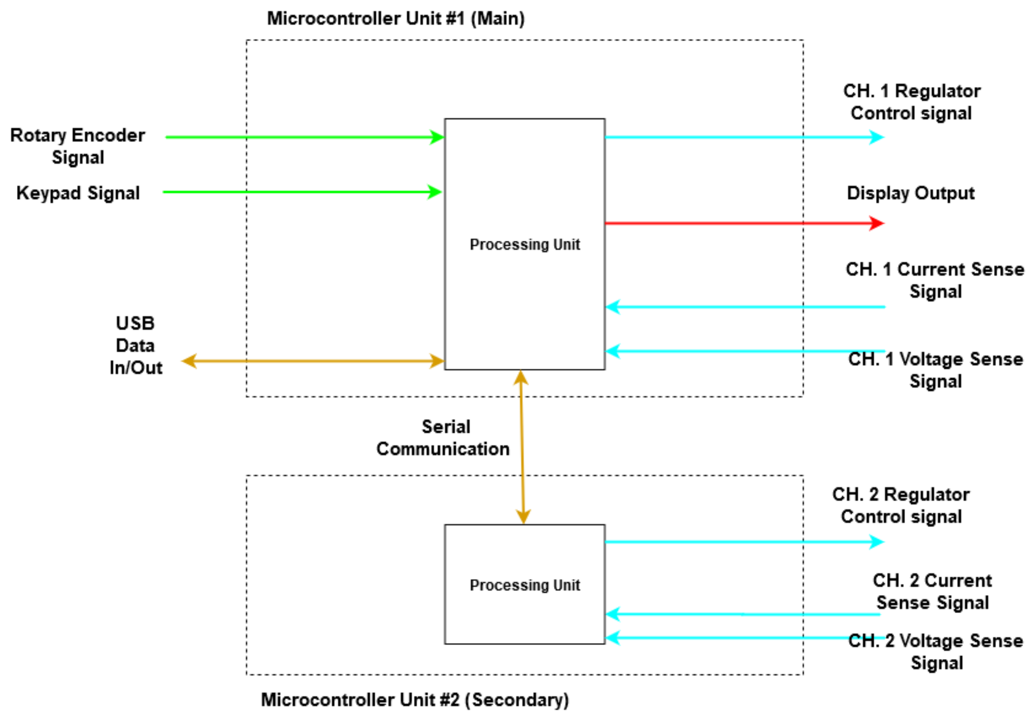



*Figure 5. Processing Units Level-2*

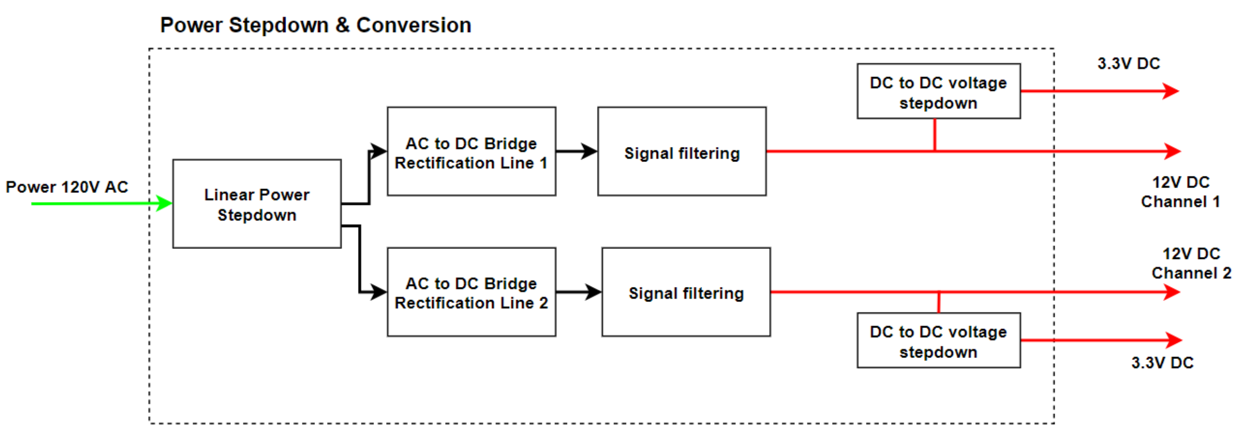



*Figure 6. Power Step Down & Conversion Level-2*

# 5. System models

## 5.1 State Diagram:

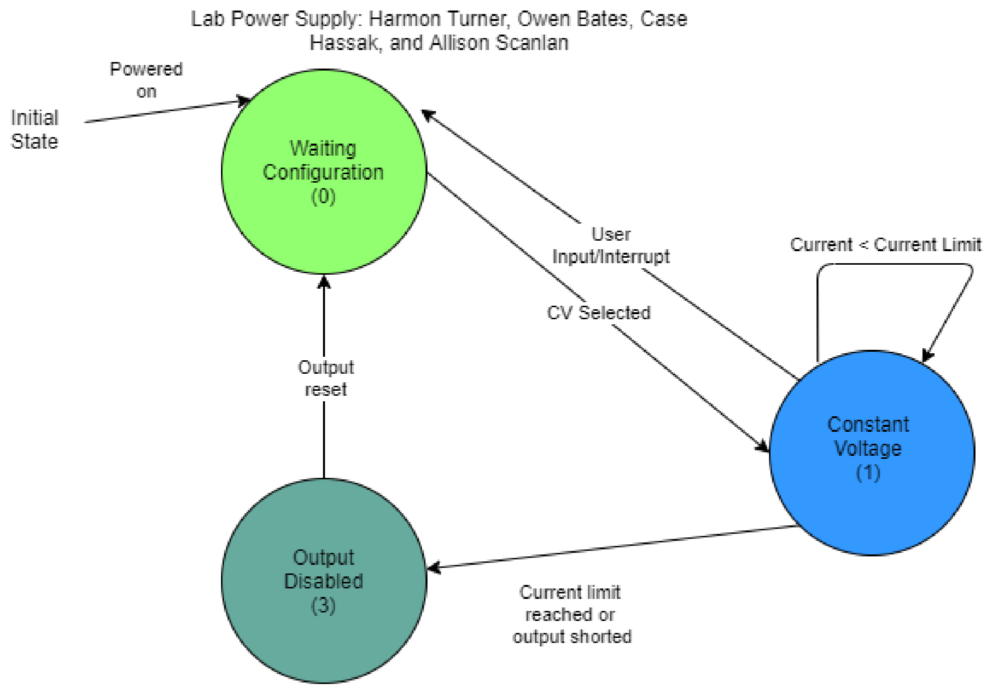



***Figure 7. Internal State Diagram***

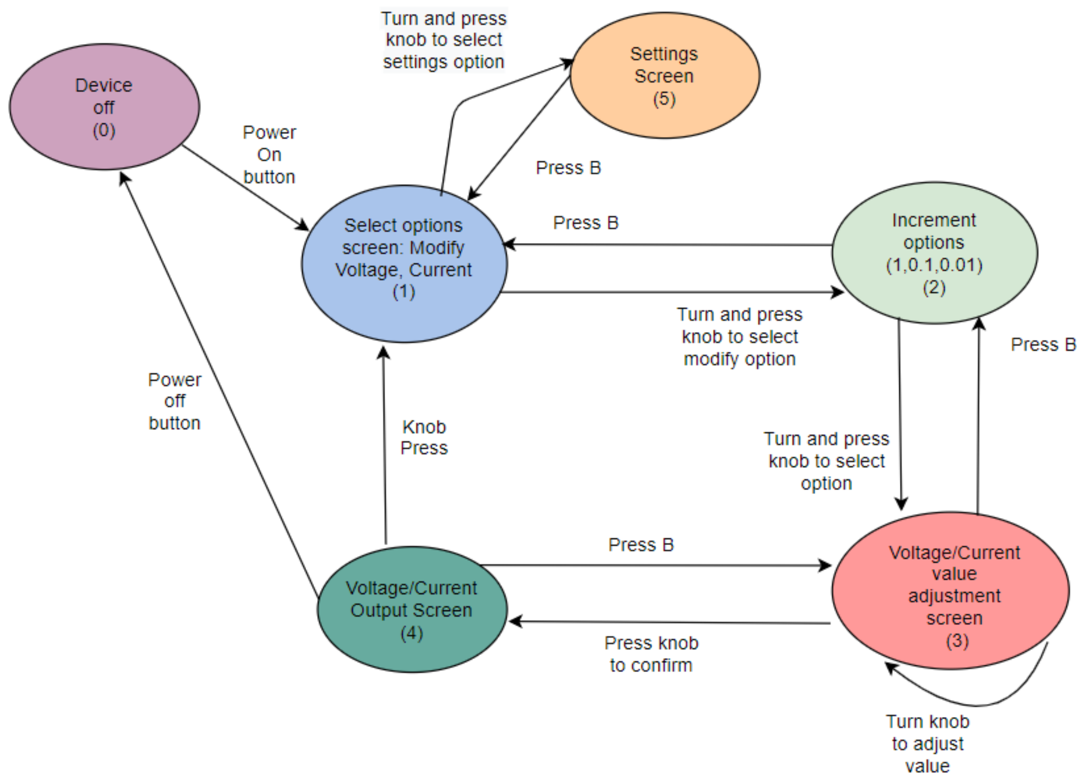
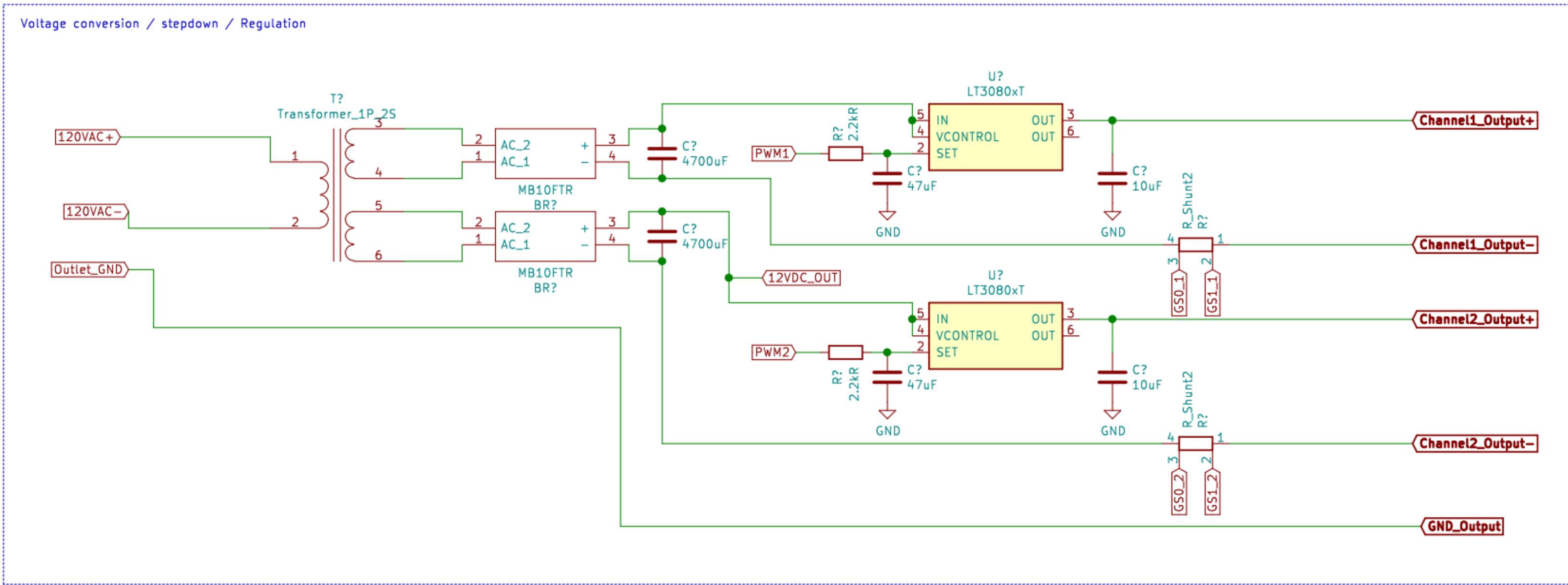
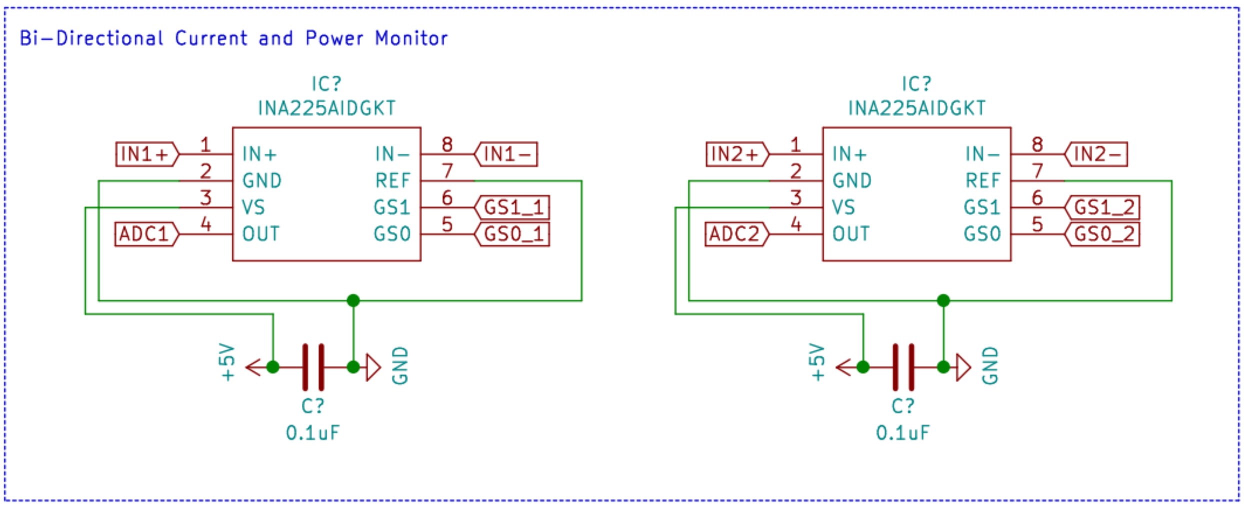


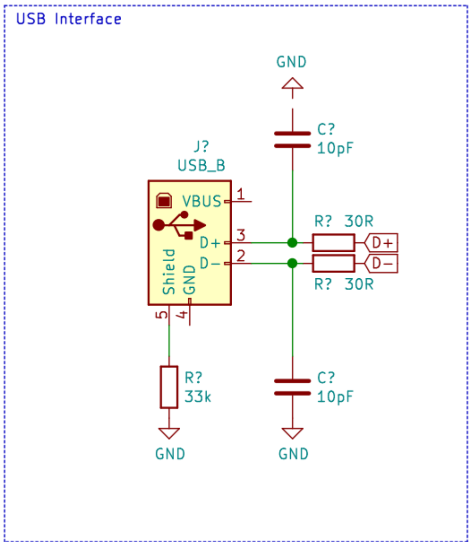

*Figure 8: User Interface State Diagram*

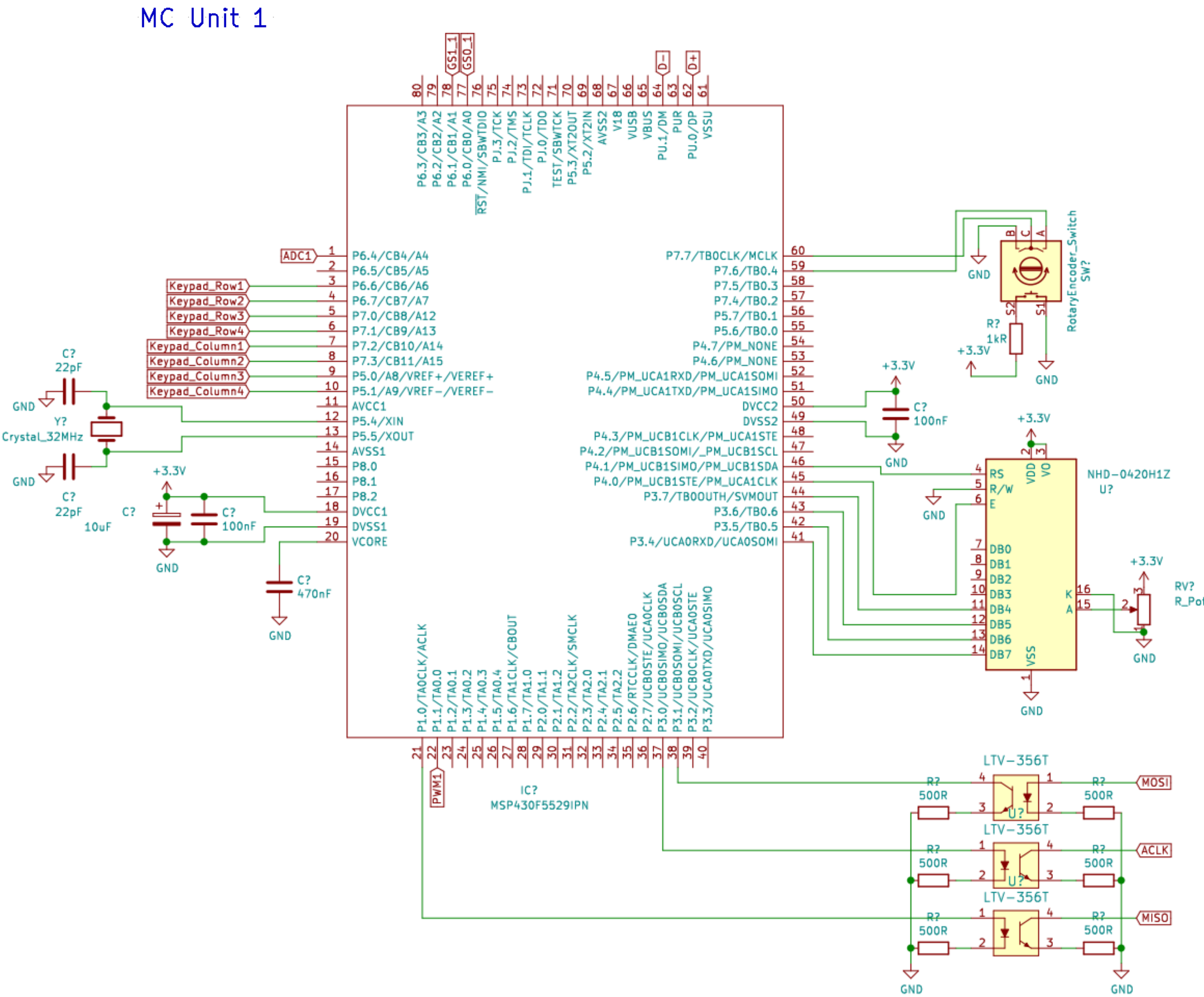
# 6. Schematics and Parts Selection

## 6.1 Schematics:

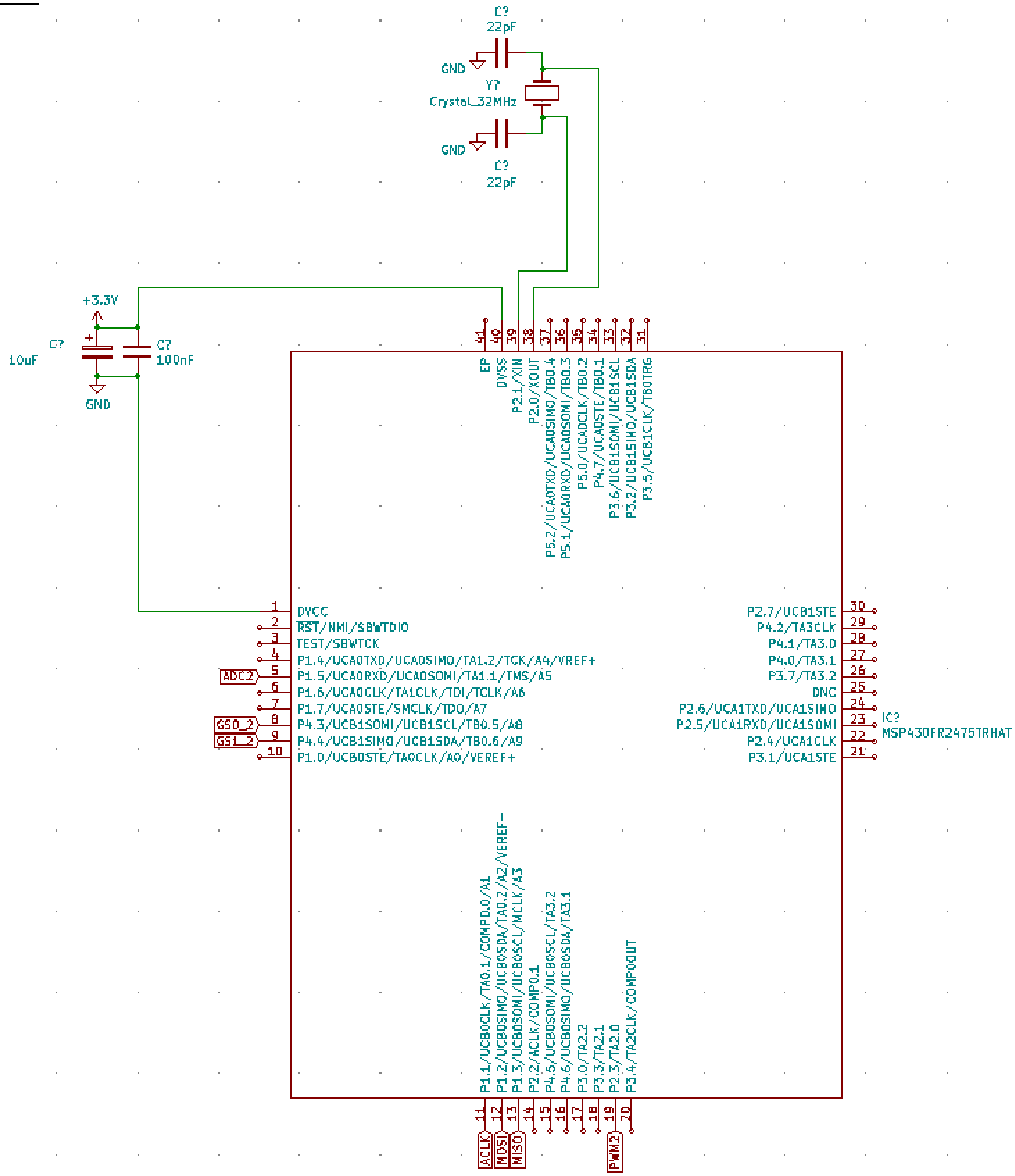

Voltage conversion / stepdown / Regulation
T?
Transformer_1P_2S
120VAC+
120VAC−
Outlet_GND
AC_2
AC_1
MB10FTR
BR?
C?
4700uF
U?
LT3080xT
IN
VCONTROL
SET
OUT
PWM1
PWM2
R?
2.2kR
47uF
10uF
GND
12VDC_OUT
R_Shunt2
GS0_1
GS1_1
GS0_2
GS1_2
Channel1_Output+
Channel1_Output−
Channel2_Output+
Channel2_Output−
GND_Output


Bi−Directional Current and Power Monitor
IC?
INA225AIDGKT
IN1+
IN1−
ADC1
GS1_1
GS0_1
IN2+
IN2−
ADC2
GS1_2
GS0_2
IN+
GND
VS
OUT
IN−
REF
GS1
GS0
+5V
GND
C?
0.1uF


USB Interface
GND
C?
10pF
J?
USB_B
VBUS
D+
D−
Shield
GND
R? 30R
R?
33k


MC Unit 1
IC?
MSP430F5529IPN
Keypad_Row1
Keypad_Row2
Keypad_Row3
Keypad_Row4
Keypad_Column1
Keypad_Column2
Keypad_Column3
Keypad_Column4
ADC1
GS1_1
GS0_1
D−
D+
PWM1
Y?
Crystal_32MHz
C?
22pF
10uF
100nF
470nF
+3.3V
GND
RotaryEncoder_Switch
SW?
R?
1kR
NHD−0420H1Z
U?
RV?
R_Pot
LTV−356T
500R
MOSI
ACLK
MISO

# MC Unit 2


C?
22pF
GND
Y?
Crystal_32MHz
GND
C?
22pF
+3.3V
C?
10uF
C?
100nF
GND
DVCC
RST/NMI/SBWTDIO
TEST/SBWTCK
P1.4/UCA0TXD/UCA0SIMO/TA1.2/TCK/A4/VREF+
P1.5/UCA0RXD/UCA0SOMI/TA1.1/TMS/A5
P1.6/UCA0CLK/TA1CLK/TDI/TCLK/A6
P1.7/UCA0STE/SMCLK/TDO/A7
P4.3/UCB1SOMI/UCB1SCL/TB0.5/A8
P4.4/UCB1SIMO/UCB1SDA/TB0.6/A9
P1.0/UCB0STE/TA0CLK/A0/VEREF+
ADC2
GS0_2
GS1_2
P2.7/UCB1STE
P4.2/TA3CLK
P4.1/TA3.0
P4.0/TA3.1
P3.7/TA3.2
DNC
P2.6/UCA1TXD/UCA1SIMO
P2.5/UCA1RXD/UCA1SOMI
P2.4/UCA1CLK
P3.1/UCA1STE
IC?
MSP430FR2475TRHAT
EP
DVSS
P2.1/XIN
P2.0/XOUT
P5.2/UCA0TXD/UCA0SIMO/TB0.4
P5.1/UCA0RXD/UCA0SOMI/TB0.3
P5.0/UCA0CLK/TB0.2
P4.7/UCA0STE/TB0.1
P3.6/UCB1SOMI/UCB1SCL
P3.2/UCB1SIMO/UCB1SDA
P3.5/UCB1CLK/TB0TRG
P1.1/UCB0CLK/TA0.1/COMP0.0/A1
P1.2/UCB0SIMO/UCB0SDA/TA0.2/A2/VEREF-
P1.3/UCB0SOMI/UCB0SCL/MCLK/A3
P2.2/ACLK/COMP0.1
P4.5/UCB0SOMI/UCB0SCL/TA3.2
P4.6/UCB0SIMO/UCB0SDA/TA3.1
P3.0/TA2.2
P3.3/TA2.1
P2.3/TA2.0
P3.4/TA2CLK/COMP0OUT
ACLK
MOSI
MISO
PWM2

## 6.2 Parts Selection:

We plan to use two of the LT3080 linear voltage regulators to control the output voltages through each channel. For the microcontrollers a MSP430F5529 will be used as the main microcontroller. This microcontroller is able to be controlled by USB. The secondary microcontroller will be a MSP4302475TRHAT. Two bridge rectifiers will be used and they are the MB10FTR. Also, a rotary encoder with a push button will be used as the knob for the power supply, as well as, a keypad for additional control options. The display screen will be a 16x4 LCD Character Display with a backlight.

# 7. Prototyping Activities and Progress Discussion

## 7.1 Prototyping Activities:

We have ordered many parts to assist with prototyping including: a TI Launchpad, LT3080 regulators, 16-character by 4-row LCD displays, 4x4 keypads, as well as various resistors, capacitors and diodes.

The Launchpad we ordered, (part # MSP-EXP430F5529LP), has helped us begin software development with the main microcontroller. We have tested the basic USB serial functionality, SPI functionality for inter microcontroller communications, although this stage has not been tested with the specifically chosen second microcontroller yet. Along with this testing on the MSP430, we have also tested basic PWM outputs and ADC interfaces of the MCU.

The LT3080 was used to prototype how the core regulator functionality will operate. It was specifically used to test if specific inputs produced specific outputs. This was also performed with the capacitor values in the above schematics, as to test expected output from the information provided on the LT3080's datasheet. For this stage of prototyping with the regulators, we have not yet used an AC power source to produce the 12VDC input that the LT3080 is expected to have in our final design. We have instead used a discrete DC power source to substitute in its place until we have the final transformer module.

We have also begun physical design prototyping. The case we have selected measures 7.3" long, 6.3" wide, and 2.75" high. This allows for a front panel that has 6"x2.5" of usable space. Our chosen display is 2.7" wide and 1.4" tall, our keypad, which may need to be sized smaller in the final prototype, is 2.4" wide and 2.3" tall, this leaves just enough space for the rotary encoder with a built-in button, and five terminals, two pairs of which are spaced appropriately for standard ¾" banana plugs to fit, as well as an ground terminal. We have drawn this up, see section 2.3, printed out 1:1 representations on paper, so we can get a better feel for the design before we begin cutting holes in our case, and adjusted for aesthetics and usability.

## 7.2 Progress Discussion:

We have created many level diagrams that go into the specifics of how the project functions have been created. We have also created and revised schematics for the design of the power supply. The team has selected our initial prototype parts for the design and begun prototyping as described in section 7.1. Many development parts have also been ordered to assist in prototyping efforts. These parts include a TI Launchpad, LT3080 regulators, 16-character by 4-row LCD displays, 4x4 keypads, as well as various resistors, capacitors and diodes.

## 7.3 Plan For Next Semester:

1/20: We will continue ordering parts as needed. We expect this step to be worked on largely during Winter Break.

1/31: At this stage we hope to have most parts we could need ordered, especially the main components. We also plan on having the beginnings of the final codebase at this stage. The regulator circuit should be working at this time, but we are expecting to continue to fine tune values.

2/15: By this time we expect to have basic code written that can control the output of the channels via at least one of the given input methods.

2/28: By this time we expect to be working with a prototype PCB.

3/10: We are hoping to have all inputs working at a basic level to control the outputs of each channel at this time.

3/15: At this time we expect to have the project assembled on the PCB and will begin fine tuning and troubleshooting.

3/15-4/15: Throughout this time period we will be testing the assembled supply and troubleshooting any problems that arise.

4/15: By this date we expect to have the project complete, and inside of housing. If any remaining adjustments to be taken care of, we will address them here.

5/1: Here we will have all bugs and issues worked out and the power supply will be completely finalized.

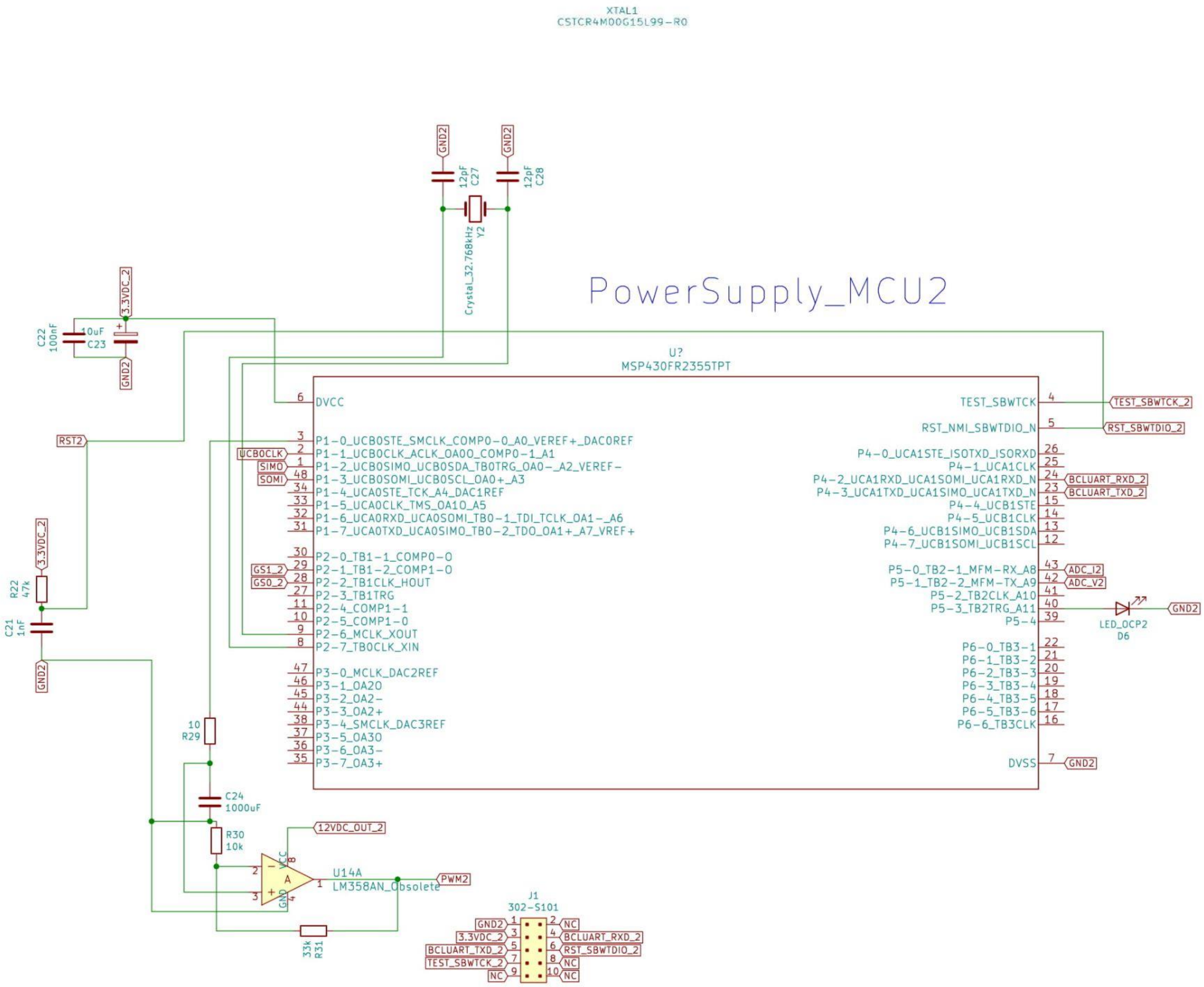
## 8. Encountered Problems

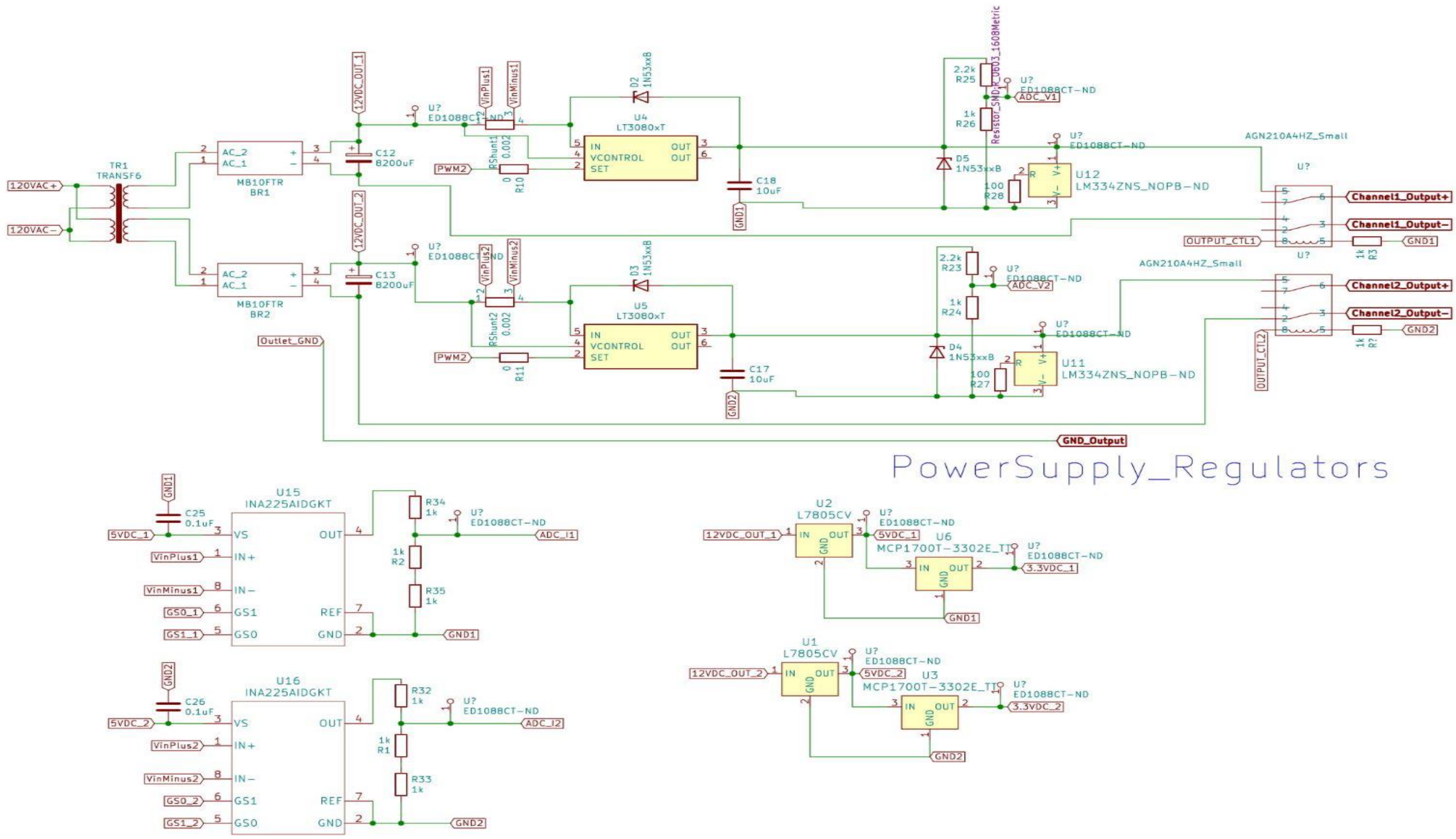
One problem discovered by the team was that each component chosen for this project has many options of parts that can do the job. This made the team have to evaluate many parts to select the most cost effective one that fits the desired parameters. Our team also has found that making a product that is completely user friendly creates challenges in design and general layout of various physical components. Another discovered challenge has been figuring out the best way to layout our regulators to produce the lowest noise possible but still be cost effective in the overall design.

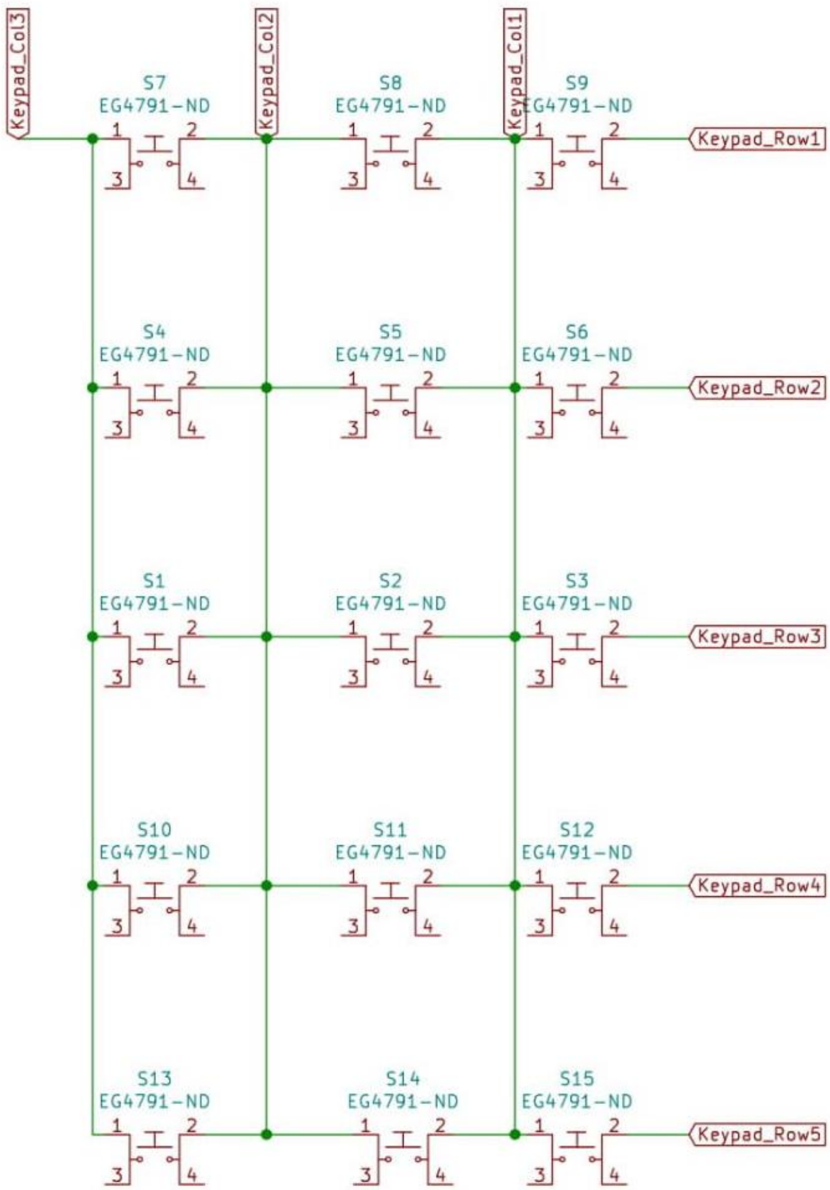
# References

[1]. https://www.electronics-tutorials.ws/transformer/transformer-basics.html
[2]. https://www.electronics-tutorials.ws/diode/diode_6.html
[3]. https://www.analog.com/media/en/technical-documentation/data-sheets/3080fc.pdf
[4]. https://www.re-innovation.co.uk/docs/heatsink-calculations/
[5]. https://eng.libretexts.org/Bookshelves/Electrical_Engineering/Electronics/Map%3A_Operational_Amplifiers_and_Linear_Integrated_Circuits_-_Theory_and_Application_(Fiore)/08%3A_Voltage_Regulation/8.05%3A_Heat_Sink_Usage
[6]. https://www.ivifoundation.org/docs/scpi-99.pdf
[7]. https://www.ti.com/lit/ds/symlink/msp430f5528.pdf?ts=1607379358830&ref_url=https%253A%252F%252Fwww.google.com%252F#%5B%7B%22num%22%3A369%2C%22gen%22%3A0%7D%2C%7B%22name%22%3A%22XYZ%22%7D%2Cnull%2C472.40875%2Cnull%5D
[8]. https://www.envox.hr/eez/bench-power-supply/psu-scpi-reference-manual/psu-scpi-programming-examples.html

# Appendix C: Schematics




PowerSupply_Regulators



Keypad_Col3
Keypad_Col2
Keypad_Col1
S7
EG4791-ND
S8
EG4791-ND
S9
EG4791-ND
Keypad_Row1
S4
EG4791-ND
S5
EG4791-ND
S6
EG4791-ND
Keypad_Row2
S1
EG4791-ND
S2
EG4791-ND
S3
EG4791-ND
Keypad_Row3
S10
EG4791-ND
S11
EG4791-ND
S12
EG4791-ND
Keypad_Row4
S13
EG4791-ND
S14
EG4791-ND
S15
EG4791-ND
Keypad_Row5

# Appendix D: Bill of Materials

| Sheet | Part | Base Qty | Price/ part (1) | Price/part (>100) | Price/part (>1000) | Subtotal (1) | Subtotal (>100) | Subtotal (>1000) | Source |
|---|---|---|---|---|---|---|---|---|---|
| MCU1 | MSP430F5529IPNR | 1 | $5.51 | $4.49 | $2.99 | $5.51 | $4.49 | $2.99 | TI.com |
| MCU1 | AMC1604CR-B-B6WTDW | 1 | $10.87 | $8.40 | $8.40 | $10.87 | $8.40 | $8.40 | digikey.com |
| MCU1/MCU2 | LM358BIDGKR | 2 | $0.15 | $0.09 | $0.05 | $0.29 | $0.19 | $0.09 | TI.com |
| MCU1 | 22pF Capacitor | 2 | $0.34 | $0.14 | $0.09 | $0.68 | $0.29 | $0.18 | mouser.com |
| MCU1/Regulators/MCU2 | 100nF Capacitor | 6 | $0.10 | $0.01 | $0.01 | $0.60 | $0.08 | $0.05 | mouser.com |
| MCU1 | 10pF Capacitor | 2 | $0.37 | $0.16 | $0.10 | $0.74 | $0.31 | $0.20 | digikey.com |
| MCU1/Regulators/MCU2 | 10uF Capacitor | 4 | $0.24 | $0.07 | $0.05 | $0.96 | $0.27 | $0.20 | mouser.com |
| MCU1/MCU2 | 1nF Capacitor | 2 | $0.10 | $0.01 | $0.01 | $0.20 | $0.03 | $0.02 | mouser.com |
| MCU1 | 470nF Capacitor | 1 | $0.28 | $0.11 | $0.07 | $0.28 | $0.11 | $0.07 | digikey.com |
| MCU1 | 1000uF Capacitor | 1 | $0.49 | $0.24 | $0.24 | $0.49 | $0.24 | $0.24 | digikey.com |
| MCU1 | 220nF Capacitor | 2 | $0.26 | $0.10 | $0.06 | $0.52 | $0.20 | $0.12 | digikey.com |
| MCU1 | 4.7uF Capacitor | 1 | $0.20 | $0.07 | $0.04 | $0.20 | $0.07 | $0.04 | digikey.com |
| MCU1/MCU2 | L513SRD-C LED | 2 | $0.18 | $0.09 | $0.05 | $0.36 | $0.18 | $0.09 | digikey.com |
| MCU1 | USB-B-S-RA-TSMT | 1 | $0.73 | $0.56 | $0.40 | $0.73 | $0.56 | $0.40 | digikey.com |
| MCU1/MCU2 | 33k Resistor | 3 | $0.10 | $0.03 | $0.01 | $0.30 | $0.10 | $0.04 | digikey.com |
| MCU1 | 30 Resistor | 2 | $0.10 | $0.03 | $0.01 | $0.20 | $0.06 | $0.03 | digikey.com |
| MCU1/MCU2 | 47k Resistor | 2 | $0.10 | $0.03 | $0.01 | $0.20 | $0.06 | $0.03 | digikey.com |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| MCU1/MCU 2 | 10k Resistor | 2 | $0.10 | $0.03 | $0.01 | $0.20 | $0.06 | $0.03 | digikey.com |
| MCU1/MCU 2 | 10 Resistor | 2 | $0.10 | $0.03 | $0.01 | $0.20 | $0.06 | $0.03 | digikey.com |
| MCU1 | 1.4k Resistor | 1 | $0.10 | $0.03 | $0.01 | $0.10 | $0.03 | $0.01 | digikey.com |
| MCU1/Regulators | 1k Resistor | 16 | $0.10 | $0.03 | $0.01 | $1.60 | $0.49 | $0.22 | digikey.com |
| MCU1/Regulators | 100 Resistor | 3 | $0.10 | $0.03 | $0.01 | $0.30 | $0.09 | $0.04 | digikey.com |
| MCU1 | 1M Resistor | 1 | $0.10 | $0.03 | $0.01 | $0.10 | $0.03 | $0.01 | digikey.com |
| MCU1/Regulators | 2.2k Resistor | 3 | $0.10 | $0.03 | $0.01 | $0.30 | $0.09 | $0.04 | digikey.com |
| MCU1 | Rotary Encoder | 1 | $2.27 | $1.50 | $1.43 | $2.27 | $1.50 | $1.43 | arrow.com |
| MCU1/Keypad | MJTP1234 Button | 17 | $0.30 | $0.25 | $0.18 | $5.10 | $4.28 | $3.09 | digikey.com |
| MCU1 | KB817 | 4 | $0.14 | $0.14 | $0.14 | $0.56 | $0.56 | $0.56 | digikey.com |
| MCU1 | CSTCR4M00G55B-R0 | 1 | $0.28 | $0.19 | $0.15 | $0.28 | $0.19 | $0.15 | digikey.com |
| MCU1/MCU 2 | 32kHz Crystal | 2 | $1.10 | $0.88 | $0.72 | $2.20 | $1.76 | $1.44 | digikey.com |
| Regulators | 8200uF Capacitor | 2 | $2.89 | $1.78 | $1.36 | $5.78 | $3.57 | $2.72 | digikey.com |
| MCU1/Regulators | 0 Resistor | 4 | $0.10 | $0.03 | $0.01 | $0.40 | $0.12 | $0.06 | digikey.com |
| Regulators | 0.01 Shunt Resistor | 2 | $0.46 | $0.15 | $0.08 | $0.92 | $0.30 | $0.16 | digikey.com |
| Regulators | FS24-800-C2 Transformer | 1 | $14.16 | $9.07 | $8.69 | $14.16 | $9.07 | $8.69 | mouser.com |
| Regulators | LM7805CV | 2 | $0.87 | $0.74 | $0.40 | $1.74 | $1.48 | $0.80 | TI.com |
| Regulators | MCP1700T-3302E_TT | 2 | $0.39 | $0.29 | $0.29 | $0.78 | $0.58 | $0.58 | digikey.com |
| Regulators | LT3080 | 2 | $4.83 | $3.55 | $2.57 | $9.66 | $7.10 | $5.14 | mouser.com |
| MCU2 | 12pF Capacitor | 2 | $0.37 | $0.16 | $0.10 | $0.74 | $0.31 | $0.20 | mouser.com |
| Regulators | INA225 | 2 | $1.60 | $1.41 | $0.79 | $3.21 | $2.81 | $1.59 | TI.com |

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|---|---|---|---|---|---|---|---|---|---|
| Regulators | LM334Z/NOPB | 2 | $0.65 | $0.59 | $0.26 | $1.30 | $1.18 | $0.53 | TI.com |
| Regulators | 1N5373BRLGO SCNT-ND | 4 | $0.47 | $0.26 | $0.15 | $1.88 | $1.04 | $0.59 | digikey.com |
| MCU2 | MSP430FR2355 TRSMR | 1 | $2.08 | $1.82 | $1.03 | $2.08 | $1.82 | $1.03 | TI.com |
| Regulators | PCB | 1 | $1.62 | $0.74 | $0.64 | $1.62 | $0.74 | $0.64 | JLPCB.com |
| MCU1/MCU 2/Keypad | PCB | 1 | $1.62 | $0.73 | $0.64 | $1.62 | $0.73 | $0.64 | JLPCB.com |
| All | Case | 1 | $8.49 | $6.49 | $6.49 | $8.49 | $6.49 | $6.49 | jameco.com |
| Regulators | C14 Jack w/ Fuse | 1 | $1.49 | $1.15 | $1.15 | $1.49 | $1.15 | $1.15 | jameco.com |
| Regulators | Power Switch | 1 | $1.25 | $0.95 | $0.85 | $1.25 | $0.95 | $0.85 | jameco.com |
| Regulators | Output Terminal Set +/- | 2 | $1.75 | $1.25 | $1.25 | $3.50 | $2.50 | $2.50 | jameco.com |
| Regulators | Output Terminal Earth | 1 | $2.55 | $2.37 | $2.37 | $2.55 | $2.37 | $2.37 | arrow.com |
| All | Standoffs (4-pack) | 2 | $2.95 | $2.29 | $1.75 | $5.90 | $4.58 | $3.50 | jameco.com |
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| | | | | | TOTALS: | $105.4052 | $73.6633 | $60.4782 | |