Isolated Current Sensor

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Abstract

This report discusses our solution to accurately sensing high current signals. This is exactly what our system does, and it is able to do it accurately in real time. Our system utilizes a Hall-Effect sensor, an analog to digital converter, a microcontroller, linear regulators to provide power, and an LCD display to view the results. This is a universal device that can test any circuit up to 10A with an accuracy of +/- 1%.

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1. Introduction

1.1 Problem

In power electronics research, we often need to equip microcontrollers with the ability to accurately sense a high current signal. Accurately sensing the current through a circuit allows the user to gain knowledge about the circuit and be more informed with regards to the safety precautions that may need to be in place. For example, if we are looking at situations with high current, we need to be careful with which materials we use and how we use them, as we could fry the parts and/or cause injuries to ourselves. Secondly, situations such as motor-control feedback, power-supply, or even high-side sensing require accurate measurements. The result of not having such a current sensing circuit is an inefficient use of time and effort, as this would require creating a new circuit that will manually test the current for every use case. The ability to maximize the time of the user is the main attractive feature of this product.

1.2 Solution

There are three main options in terms of how to approach creating a fully isolated current sensor: (1) the current transformer, (2) the Rogowski coil, and (3) some sort of Hall-effect device. We have decided to go with a Hall-effect current sensor over the other options for a few main reasons. The Hall-effect sensors are accurate and are able to be used on a wide range of currents. The other options offer more complications as well as restrictions in terms of how we can design our circuit.

As shown below, there are a few subsystems we have to take into consideration. First, there will have to be power supplied to all the parts. We are planning on using a battery to power each component, as the power requirements are not too high. Second, we need to feed the current we want to calculate into the hall effect current sensor. This will then output a voltage that will be fed into the analog to digital convertor. From here, we will feed the digital outputs to the microcontroller, which will then calculate a current value to be displayed on an LCD screen.

1.3 Visual Aid

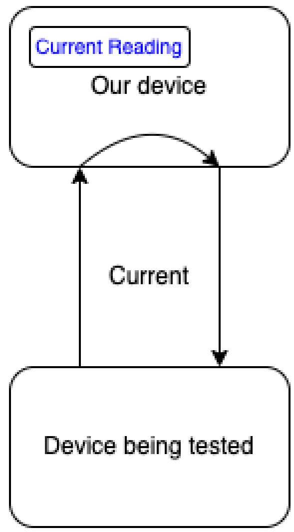

Figure 1. Simple Visual Aid

1.4 High-Level Requirements

1. This product should have a reading accuracy of +/- 1% with 3 concurrent current inputs.
2. This product should have the ability to handle up to 50 KHz in bandwidth.
3. This product should have the ability to handle up to 10 Amps of current.

2. Design

2.1 Block Diagrams and Schematic

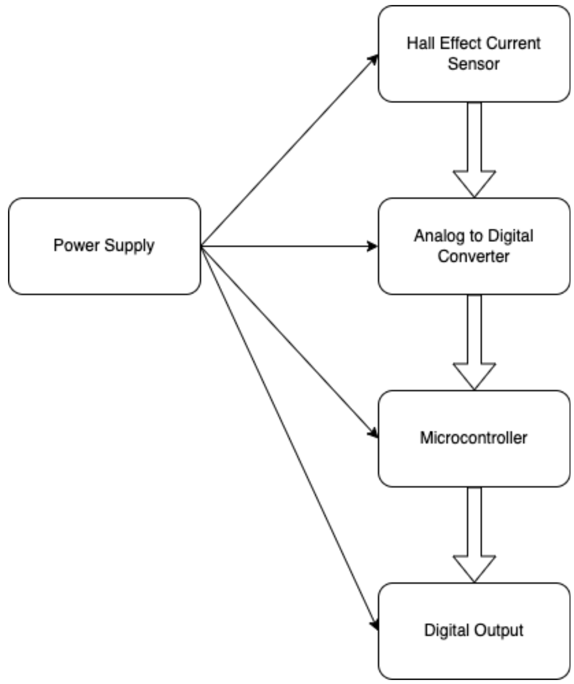

Figure 2. Simple Block Diagram

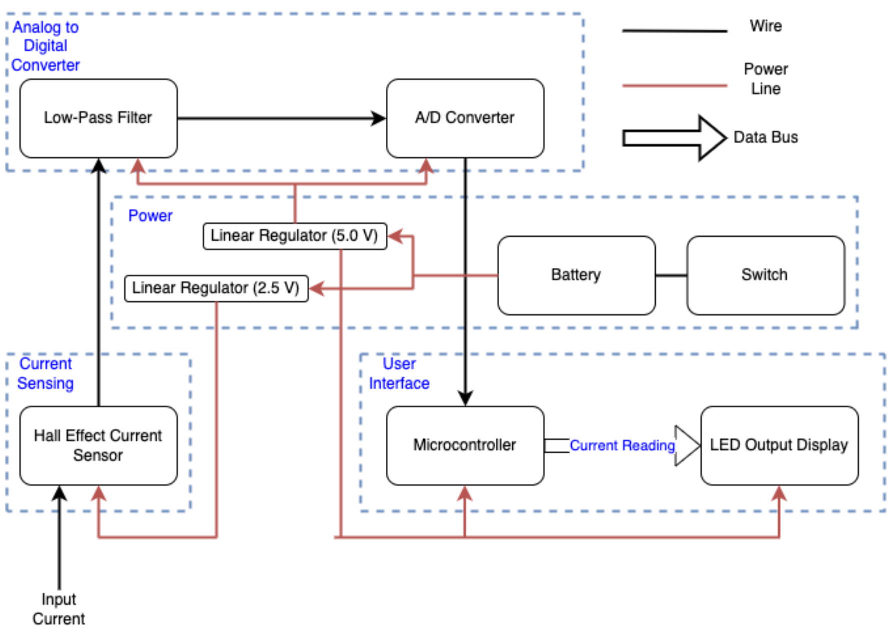

Figure 3. Detailed Block Diagram

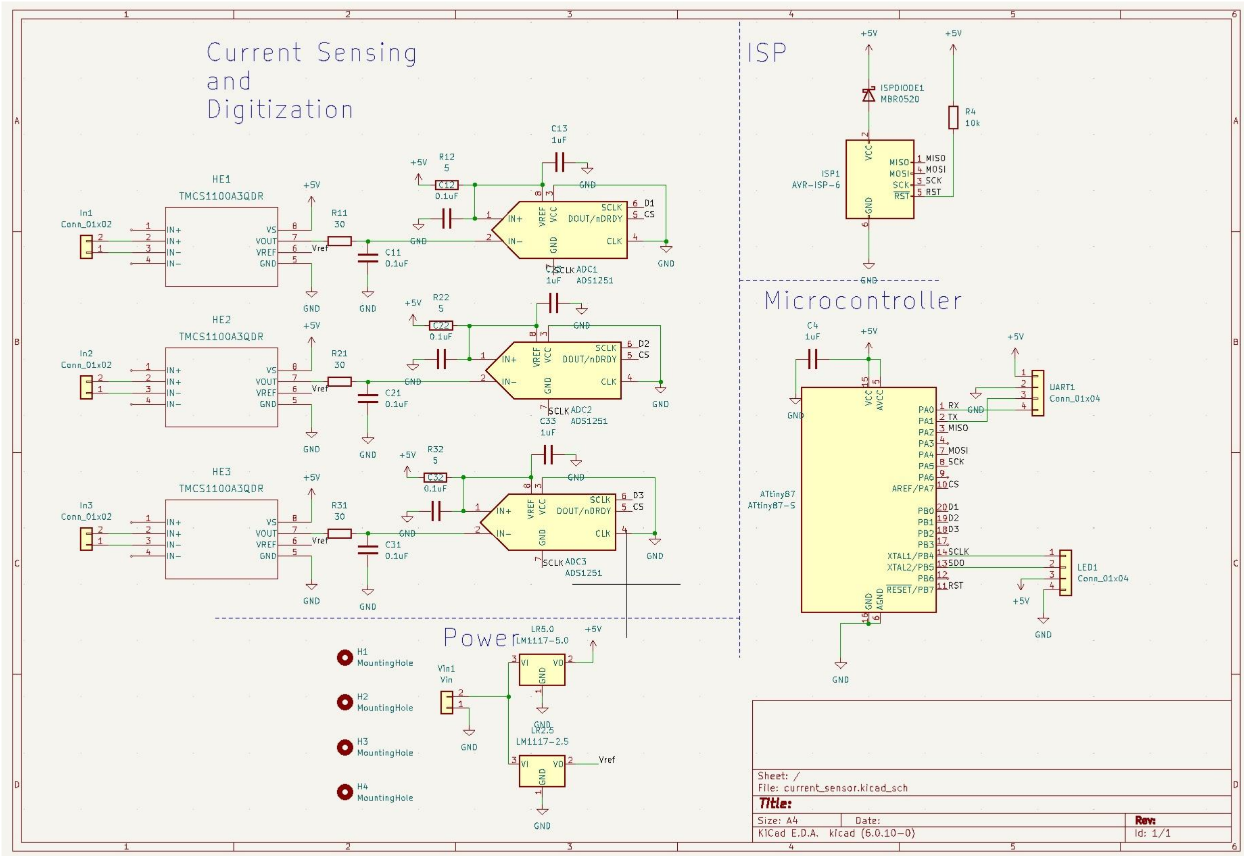

Figure 4. KiCAD Schematic

2.2 Subsystem Components

2.2.1 Hall-Effect Current Sensor

We will utilize the Texas Instruments TMCS1100, a galvanically isolated Hall-effect current sensing IC, to accurately measure current through a system. This chip will receive the current that we want to read and output voltage to the analog to digital converter subsystem. The specific chip that will be used has a sensitivity of 200 mV/A [1], meaning the max voltage output will be 2 Volts . The sensor will require between 3 and 5 Volts for the power supply and 2.5 volts for the reference voltage[1]. The Vref input pin provides a variable zero-current output voltage, enabling bidirectional or unidirectional current sensing[1]. This current detector should function between +/- 10A, however this sensor will be able to handle up to +/- 11.3 A to provide a buffer.

As mentioned above we knew the Hall-Effect Current sensor was able to handle up to +/- 11.3 A, which is higher than our required 10 Amps. However, we never specifically tested that high due to safety concerns in our laboratory. We tested up to two amps and this proved the success of this subsystem.

2.2.2 Analog to Digital Converter

The next subsystem is the analog to digital converter. This takes the resulting analog voltage signal from the previous system, the Hall-Effect sensor, and converts it into a digital signal. First, the output voltage from the Hall-Effect sensor will be passed through a low pass filter to ensure there is not aliasing. Next, the resulting signal will be sent to the ADC. The ADC will be sampling at a rate of over 100 kHz to ensure no aliasing, as we want to be able to handle a bandwidth of 50 kHz. Additionally, this ADC will be a twelve bit ADC using a reference voltage of five Volts. This means that the step voltage will be $5/4096 = 1.221 * 10^{-3} V$. This is low enough to achieve an error rate of no greater than 1%. The new digital signal will be connected to the microcontroller for further calculations.

Testing the requirements of the ADC proved more challenging than the Hall-Effect Sensor. We were able to learn about the different machines we have in our lab and use a waveform generator to help verify that our low pass signals do in fact attenuate frequencies above 50 kHz. We passed a 10 volt sinusoidal wave at 50 kHz into our low pass filter. Next, we used an oscilloscope to measure the signal after it had passed through the filter. We saw that the resulting signal had an amplitude of 7 - 7.1 volts, which is right around the theoretical value of 7.07 volts. The reason this proves the efficacy of our low pass filter is because the largest frequency that should be allowed to pass through corresponds to the three dB value of the input signal. The three dB value is 0.707 of the amplitude of the input signal. In our case, that would be 7.07 volts.

2.2.3 Microcontroller/User Interface

The final subsystem is the human interface, which will display the current reading from our device. Our system will have an ATtiny85-20SU microcontroller that takes the digital signal from the ADC and should be able to calculate the current passing through. The microcontroller will be programmed to understand the readings of the ADC. For example, if the ADC outputs a value of 2048, the microcontroller will convert that to Amps in the following way. First, it is established that the reference voltage will be 5 volts. This means that a reading of 2048 from the microcontroller will evaluate to 3072/4096 *5 = 3.75 volts. Next, to convert voltage to Amperes, the microcontroller will divide the voltage by the sensitivity, which is 200 mV in this case. Therefore, we will have (3.75 - 2.5) Volts/0.2 V/A = 6.25 A. This value will be outputted to the seven segment display and will have a display value of 6.25 A. This reading should be accurate up to the hundredths decimal place, and be capable of displaying the information received from the microcontroller in real time.

The microcontroller handles all the code of our project. The code was responsible for taking in digital values, representing voltage, from the ADC and converting them to a value representing current. This was done by several mathematical operations as well as a linear regression model. There were some offsets and errors associated with each of the chips, but we were able to secure a final output with an error of less than one percent using the linear regression model, which accounted for the errors along the way. We tested this by creating circuits on a breadboard and feeding in power at a certain current. The power supply displayed the actual current value and we compared this to the output on the I2C display. We were consistently under the one percent error benchmark. This also verified that the microcontroller was able to handle mathematical operations and printing the correct values to the I2C.

2.2.4 Power

Our device will use a 9V battery to power each of the components. The battery will be connected to two linear regulators that will output two different voltages. As for power supply, there are only two values we need: 2.5 Volts and 5 Volts. All of our components need 5 volts, whereas the Hall-Effect Sensor and the ADC both need a reference voltage of 2.5 volts. This battery will be turned on and off by a switch and should be able to feed into the linear regulators at 9 +/- 0.1V continuously. The sole purpose of the switch is to make sure we are able to shut off power to the other components. When the switch is in the off position, no power will be going to the devices.

We were able to show that our product consistently supplied the appropriate power to each of our components using a microcontroller. The ADC power supply, ADC reference voltage, the microcontroller, the Hall-Effect power supply, and the I2C display all required 4.8 - 5 V, while the reference voltage for the Hall-Effect sensor required 2.4 - 2.5. We verified that all the pins that needed 4.8- 5 V all received between 4.98- 5 V, while the reference voltage for the Hall-Effect sensor received 2.48 - 5 V. These were all within the acceptable ranges. Additionally, using the voltmeter as well, we were able to verify that the power supply was in fact 12 Volts.

2.3 Tolerance Analysis

Of all of the subsystems, the analog to digital converter posed the most risk to the completion of our project. It is the most complicated of the subsystems as it involves programming the filters onto the chip and it feeds the output needed into the microcontroller. The project also deals with three simultaneous current inputs, so the choice of ADC chip is crucial to ensure that all the requirements are being met.

The most crucial part to the design is the Analog to Digital Converter and ensuring it is able to output voltages within reasonable parameters, allowing the final output reading to be within 1%

of the input current. Current will be inputted into a Hall-Effect Current sensor with a typical error of .4%. However, the extreme cases are vital here, so the maximum error, which is .9%, is the important number to analyze. The output voltage from the Hall-Effect Current Sensor, will be fed into a low pass filter to be bandlimited. Then, this will flow to the ADC and finally the microcontroller. The ADC needs to have enough bits and a high enough sampling rate so that we do not lose any data and report accurate results.

Here is the analysis of the Hall-Effect Current sensor with the ADC, to ensure that the results will be within +/- 1% of the true current. Our input current can go up to 10 Amps, which means that the Vout can go up to 2 Volts +/- .9%. Since, the max voltage of Vout is 2.018 Volts, the reference voltage should be around that value or slightly higher, in this case 2.5 Volts. This means that the number of bits the ADC outputs will be very important in the accuracy of the circuit. Twelve bits seems to be the optimal number as it gives us the cheapest ADC that still has enough bits +/- 1%. This can be proven with some analysis. With a twelve bit ADC, each increment in value is given by our reference voltage divided by 2^{12}. This would be $5/4096 = 1.221 * 10^{-3} V$. Now, when the percent error is being calculated the biggest difference between the actual voltage and the expected voltage is the step voltage divided by two, which gives us $6.103 * 10^{-4}$. Now, we want the percent error to be less than or equal to 1%, so we divide this value by 0.01 and then convert it back to Amps by dividing by 0.2. This results in .304 Amps. The only time the percent error could be greater than 1% is if the current is less than .304 Amps.

Additionally, the error from the current sensor would not affect the accuracy of the circuit excpt at very low amperage discussed here, it would not change the output of the ADC. Similarly, at higher amperes closer to 10 A, it still would not affect the output because the difference in the reading and the error value would be too low to push the total error to above 1%.

2.1.3 Proof of Concept

Table 1. Proof of Concept Mathematical Reasoning

Mathematical Step	Reasoning
$5/4096 = 1.221 * 10^{-3} V$	This represents the step voltage of the ADC.
Input Voltage - Digital Output < $1.221 * 10^{-3}/2$	This is the largest value that difference can have.
|Input Voltage - Digital Output| /0.2 = .00304 = Current Reading	Converts the voltage to Amps
(|Input Current - Current Reading| /Input Current) <0.01	Percent Error Formula
Input Current = .00304/.01 = .304 Amps Therefore, as long as we are above .304 Amps, we are guaranteed to have an output current that is $\pm$ 1% of the actual value.	Using Substitution from Above

Hall-Effect Current Sensor:

$Vout = (Input\ Current) \times (0.2\ V) \pm 0.9\%$ (Eq. 1)

ADC:

$Digital\ Output = (2^{N(bits)} * Vout)/Vref$ (Eq. 2)

$Voltage\ Reading = (Digital\ Output/2^{N(bits)}) * Vref\ (Eq.\ 3)$

Final Answer Percent Error:

$|(Input\ Current - (Digital\ Output/0.2))/Input\ Current)| \leq 0.01\ (Eq.\ 4)$

3. Schedule and Cost Analysis

3.1 Schedule

Table 2. Weekly Schedule

Week	Goals	Person
Week 1-3 (1/16 - 2/6)	Creation of group and formation of idea	Everyone
Week 4-6 (2/13-2/20)	Create initial design of project	Everyone
Week 7 (2/27)	Finalize component choices, begin designing PCB schematic	Everyone
Week 8 (3/6)	Complete PCB design, choose device enclosure and talk with machine shop	Sean
	Purchase components	Akshat, Rohan
Week 9 (3/13 - Spring Break)	Review and improve PCB design, select new components if necessary	Everyone
Week 10 (3/20)	Implement low-pass filter	Akshat
	Develop first prototype - assemble components	Everyone
	Begin programming	Rohan, Sean
Week 11 (3/27)	1. Test Hall-effect Current Sensor 2. Begin Programming Microcontroller 3. Display information on I2C	Rohan
	1. Talk to machine shop about box/switch 2. Begin Programming Microcontroller	Sean

	3. Display information on I2C	
	1. Test ADCs 2. Create/Test LPF 3. Test Linear Regulators	Akshat
Week 12 (4/3)	Assemble final prototype	Rohan, Sean
	Complete programming microcontroller	Rohan, Sean
	Miscellaneous Testing	Akshat
Week 13 (4/10)	Problem Solving Week: Bugs will arise, so we set aside this week to solve any unforeseen issues	Everyone
Week 14 (4/17)	Additional Time for any bugs Give mock demo to TA, practice for final demo	Everyone
Week 15 (4/24)	Complete final demo, practice for and give mock presentation, begin putting together final papers, practice final presentation	Everyone
Week 16 (5/1)	Practice for and give final presentation, complete final papers	Everyone

3.2 Cost Analysis

To calculate labor costs for our project, we took the average salaries of computer and electrical engineers from the University of Illinois for the 2020-2021 academic year[2] in order to find an hourly rate that we would earn while creating this project. This came out to an average of $92,824, and assuming 50 working weeks with five eight-hour days, this gives us an hourly rate of $46.41. Assuming that the three of us dedicate 8 hours each per week for the next nine weeks, we come to the final figure of $10,024.56 for our labor. The labor required from the machine shop will be quite minimal, including helping us to order our enclosure and then drilling several holes in the enclosure. In our first conversation they said that this would not be very difficult at all, and we estimated that it would take no more than two hours for them to assist in ordering and modifying the enclosure. Assuming a $75/hour rate for the machine shop worker, this adds $150 to our costs. As seen below in table 3, the combined cost for the parts we plan to order adds up to $136.91. With an additional 5% for shipping and 10% sales tax, this comes out to $158.13. Thus our total cost comes out to be $10192.69

Table 3. Component List

Component	Description	Manufacturer	Part #	Quantity	Cost
Hall Effect Sensor	Utilizes galvanic isolation to detect current and output a proportional voltage	Texas Instruments	TMCS1100	9	$33.80
Microcontroller	An MCU unit that will calculate the current, and send it to the LEDs to be displayed	Microchip Technology	ATtiny87	4	$8.88
ADC	Digitizes the voltage output from hall effect sensor	Texas Instruments	ADS7816	8	$45.55
9V Battery	Supply power and reference voltages to circuit	Toshiba	6F22KG	4	$7.05
I2C 20x4 LCD Display	Displays the output of the circuit	Weewooday	157119	1	$12.59
Resistors	Used for the Low Pass Filter and	Digikey Electronics	Various	28	$4.62

	ADC				
Capacitors	Used for the Low Pass Filter and ADC	Digikey Electronics	Various	30	$0.64
Linear Regulator	Transform 12V from battery to proper voltage required for each device	Texas Instruments	LM-117/5.0 / LM-117/2.5	8	$8.64
Switch	Toggle the device on and off	E-Switch	RA1113112R	3	$1.29
Connectors	Needed to connect the PCB board to various input and Output sources	Various	Various	17	$4.85
ISP Adapter	Needed for the connection to the ISP	Adafruit	1465	2	$1.90
Shottky Diode	Needed for the USB adapter connection	Mouser Electronics	833-MBR0520-TP	2	$0.60
Jumper Wires	To connect various voltage and current sources from the breadboard to the PCB	Digikey Electronics	1471-1230-ND	2	$5.68

4. Conclusions

4.1 Accomplishments

One major component of ours that did not work was our microcontroller, the ATTINY 87.We realized too late into the project that we had not set our programming pins to the default setting that was recommended. As a result we had to use the arduino microcontroller(ATmega328P) as a substitute. Despite having to make this last minute fix, we were able to deliver some kind of functionality,and we managed to get the correct outputs of 3 concurrent currents on our LED screen.

Figure 5. Resulting Output of the Isolated Current Sensor Circuit

4.2 Functionality of the subsystems and uncertainty

The biggest success we had in terms of our subsystems was with our Hall Effect Sensor. Given that we knew the sensitivity beforehand (200 mV/A) and we had set the reference voltage to 2.5 V, we were able to verify that it closely followed the values expected based off the theoretical calculation and the pattern of behavior found in the datasheet[1].The readings of the Hall Effect Sensor also confirmed to us that the currents being inputted into the circuit were being read and processed correctly. There were some challenges while testing when we had to solder wires onto the sensor to test it on the breadboard as we noticed extra voltage being added on to the expected output, but it worked as well as it could have when interacting with the surface mount components.

The Power unit also worked as well as it needed to. Because we were using 2 linear regulators (one for 5V and one for 2.5V) there was always the risk of the different voltages being supplied in the wrong places. But we were able to verify that the necessary voltages went to the right places.

The ADC subsystem was a bit of a mixed bag. It was definitely the most difficult of the components to test initially, since we hadn't put in the filter initially and didn't fully understand how the ADC chip we decided to use had worked. We were able to figure out that we needed to average a bunch of results instead of taking each result given by the ADC, and started to see signs that we were getting the necessary digital signal needed to show the functioning of the circuit. But even after we had implemented the filter, the results we were getting were far from what we expected. When we gave in no current, the output would show as -4A or -5A. And when we looked deeper into the digital signals we were getting, we found that the average had been consistently weighed down by noise values (like 0, 50, 200 etc). Even though we were warned that maintaining accuracy with a 50 KhZ bandwidth would be very difficult, we didn't truly realize the extent to which the noise would still be prevalent even after placing the filter. We learned across the testing and demo phases that the high bandwidth could cause more noise to pass through, and we certainly think that's what happened. We needed to account for this, and were able to do so by setting a certain value threshold and if any digital signal was found to be below that value, it would be ignored in the average.

```
for (int i = 0; i < 1000; i++) {
  tmp1 = (readADS7817(D1)/4096.0)*5;
  tmp2 = (readADS7817(D2)/4096.0)*5;
  tmp3 = (readADS7817(D3)/4096.0)*5;
  if (tmp1 > 2) {
    a = a + tmp1;
    c1++;
  }
  if (tmp2 > 2) {
    b = b + tmp2;
    c2++;
  }
  if (tmp3 > 2) {
    c = c + tmp3;
    c3++;
  }
}
```

Figure 6. Code to cut out noise from the ADC

The digital signals are first converted back to the voltage value that should ideally be the output of the Hall Effect Sensor and then checks whether that value is below the threshold we set (in this case 2). We were able to reduce a lot of the noise through this, and results stabilized.

However, we still noticed that there was an offset that was preventing us from reaching the ± 1% accuracy target that we had set for ourselves in the high level requirements. We realized that the offset was not constant as we increased the current in uniform increments, and it wasn't increasing uniformly either. To try and fix this, we collected input and output data from 0 A to 1.7 A in 0.05 increments and ran a linear regression model on the data.

Input Current (A)	Output Result (A)
0	0.03
0.1	0.17
0.2	0.28
0.3	0.38
0.4	0.5
0.5	0.6
0.6	0.7
0.7	0.8
0.8	0.9
0.9	1
1	1.11
1.1	1.22
1.2	1.32
1.3	1.42
1.4	1.53
1.5	1.63
1.6	1.74
1.7	1.84

Figure 7. Input and Output Data Collected

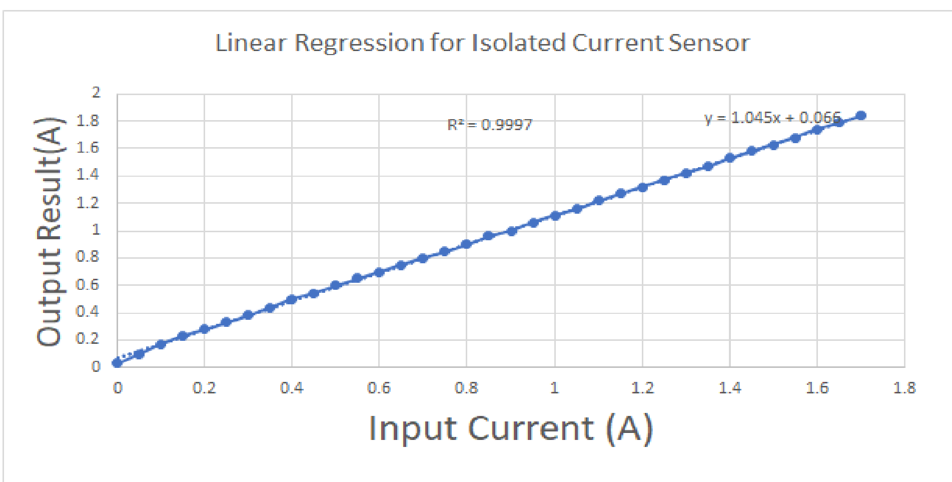

Figure 8. Result of the linear regression model ran on the data

We were able to get a formula for the regression model with a very high R^2 value of 0.997, which shows that the regression model very much fits the data set. The formula we got was y = 1.045x + 0.066, where x is the input current and y is the output result. We solved for x and used this formula in the code to obtain values that were within or close to the desired accuracy percentage for currents > 0.1A.

4.3 Future Work and Alternatives

There are a lot of improvements that could be made to the implementation that we have right now. The most obvious improvements that could be made are the implementation of a functioning microcontroller. One thing we realized late into the project is that we could have used a more simple microcontroller (like the ATTINY 85) because we only ended up using 5 pins for the respective programming and data signals.

Another major area of improvement would be around that of the filter design. There wasn't anything wrong theoretically with the design, but we didn't think about a lot of the practical factors that may have affected the filter system, and investigating those causes and trying to implement a more efficient filtering system would benefit this device greatly.

Beyond those improvements, there are many things that can be added to the device. We had planned to implement a UART connection before deciding not to prioritize it towards the end of the project, and that can certainly help with data collection. It would also be ideal to add an enclosure to the device and make it more presentable. And at the end of day, we would want to see the device being put into use by those who need it the most.

4.4 Ethical and Safety Considerations

4.4.1 Ethical Considerations

In accordance with point 5 under Article I of the IEEE code of Ethics, which states "t*o seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, to be honest and realistic in stating claims or estimates based on available data, and to credit properly the contributions of others;*"[3], we took it upon ourselves to be honest about the data collected, acknowledged the work done by various team members and gave back constructive and honest feedback to each other. We also treated each other with respect and abided by the IEEE code of ethics as dictated by Article II, which states "*To treat all persons fairly and with respect, to not engage in harassment or discrimination, and to avoid injuring others"*[3], and Article III, which states *" To strive to ensure this code is upheld by colleagues and co-workers."*[3] .

4.4.2 Safety Considerations

The main area of caution was around the use of high currents. When it comes to the designing and manufacturing of the device, the goal was to ensure that the device was able to handle currents up to ± 10 A, and issues could have arisen because of this. To reduce risk we ensured that 1) at least 2 of us were working on the project at all times, and 2) we kept insulator objects around and put other safeguards in place to ensure no one gets hurt. Pertaining to point 6 under Article I of the IEEE code of ethics, which states *"to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations; "*[3], everyone associated with the project also took the necessary electrical safety trainings that had been made available to us.

Since the hope for this project is for it to be a useful tool for many different tasks in the future, it was important that this project considered the safety concerns that may arise from the use of high isolated current for the users. Our main responsibility was to ensure that the device is as safe to use as possible, in accordance with point 1 under Article I of the IEEE code of ethics, that states *" to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment;"*[3].

References

[1] Texas Instruments, "1% High-Precision, Basic Isolation Hall-Effect Current Sensor With ±600-V Working Voltage," TMCS1100 datasheet, Sept. 2019 [Revised July 2021].

[2] Grainger Engineering Office of Marketing and Communications, "Salary averages," *Electrical & Computer Engineering | UIUC*, 2022. [Online]. Available: https://ece.illinois.edu/admissions/why-ece/salary-averages. [Accessed: 22-Feb-2023].

[3] *IEEE Code of Ethics*. (n.d.). https://www.ieee.org/about/corporate/governance/p7-8.html

Appendix A Requirements and Verification Tables

Table 4. Hall Effect Sensor R&V

Requirements	Verification
- Handle up to 10 Amps in current	- Current in measurements up to 10 Amps will be provided to the sensor with a DC power supply - We will set up a circuit with resistance and pass that to our sensor to ensure that it can handle up to 10 A

Table 5. User Interface R&V

Requirements	Verification
- LED displays provide the correct output	- The microprocessor will feed test values into the LED and will observe whether those values are showing up or not.
- Ability to compute appropriate values using simple mathematical operations	- Once the LED connection is tested, it will display the output reading of the current being read by the sensor. - Based on the value found at the ADC, the theoretical value of the current will be found and compared to the value being displayed.
- Error rate of Output is < 1%	- We will use the power supply machines in the lab to test and verify the validity of our output. - We will input a certain amount of power into a simple circuit we will build on a breadboard and create current - We will compare the actual current

	value to the output on the I2C display over a range of values.

Table 6. Analog to Digital Converter R&V

Requirements	**Verification**
- Low pass filter passes Frequencies < 50 kHz	- We will use a waveform generator to generate a sinusoidal wave and measure at what frequency we get the three dB value of the signal - The three dB value is 0.707 of the amplitude of the input signal

Table 7. Power Supply R&V

Requirements	**Verification**
- Supply voltage at 12 V	- A voltmeter will be used to test to make sure the battery is supplying the appropriate amount of voltage - The black pin of the voltmeter will be touching ground, while the red pin will be touching the power supply to measure the voltage being supplied

- Linear regulator appropriately regulates the supply voltage for the necessary values
- 5 Volts:
    - ADC power supply
    - ADC reference voltage
    - Microcontroller
    - Hall-Effect power supply
    - I2C display
- 2.5 Volts:
    - Hall-Effect Reference Voltage
	- A voltmeter will be used to test to make sure the regulator is outputting the correct values
	- The black pin of the voltmeter will be touching ground, while the red pin will be touching the power supply/Vref to measure the voltage given to that pin