Electrocardiogram Project

May 11th, 2022

On my honor, I have neither given nor received unauthorized aid on this assignment.

Team Members

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Max McCullough	[mdm6ua]
Bruce Bui	[bb6dv]

Responsibilities

Leonardo

Assisted in the layout of the project board and calculated the component values for the gain resistor, V_{Mid} network, instrumentation amplifier, and isolator. Wrote the test plan for the instrumentation amplifier and helped test every section of the board for every class period of testing. Helped with identifying proper component values, continuity testing, and re-calculating component values when necessary. Responsible for gathering pictures, screenshots, writing filtering code, and data outputs from each section of the board. Formatted the final paper and wrote Section 1 and the conclusion.

Max

Created the layout of the final board to be used in the project. Calculated component values for the antialiasing filter and ran each AC sweep and transient simulation for the overall board. Wrote the test plan for the antialiasing filter and helped test every section of the board for every class period of testing. Helped with identifying proper component values, continuity testing, and re-calculating component values when necessary. Responsible for soldering, de-soldering, writing filter code, and making connections on the board for testing each input and output. Wrote Section 2 of the final paper and helped with formatting.

Bruce

Responsible for helping with the first day of testing and writing the test plan for the power supply and the isolator.

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Section 1

Background

Approach

Our general approach was to focus on one block at a time. We knew the order in which the signal would reach each block (power supply, instrumentation amplifier, antialiasing filter, and isolator), so we could begin in order. The bypass capacitors were all set to $0.1\ \mu F$ as a standard, so we continued on to calculating our block component values.

Signal and Gain Outputs

The initial gain resistor was calculated to be $100\ \Omega$, though it was left off the board since we were unsure exactly what gain we wanted to achieve when testing the board. We also knew that V_{Mid} from the instrumentation amplifier had to be around $1.65\ V$ (half of the supply voltage), so we calculated our voltage divider and capacitor network accordingly. We also had a $3\ dB$ breakpoint on the RC inputs of the I-Amp of $0.05\ Hz$ to $0.1\ Hz$, so we calculated those components accordingly. Lastly, the isolator was to have no gain, so the output of the isolator should look almost identical to the input.

Filtering Requirements

The antialiasing filter had a strict requirement of -72 dB at 500 Hz. We were required to create a 4th order Butterworth filter to achieve a maximally flat passband and a sharp attenuation at the corner frequency.

Schematics

Top-Level Schematic

The top-level circuit schematic is provided below in **Figure 1**.

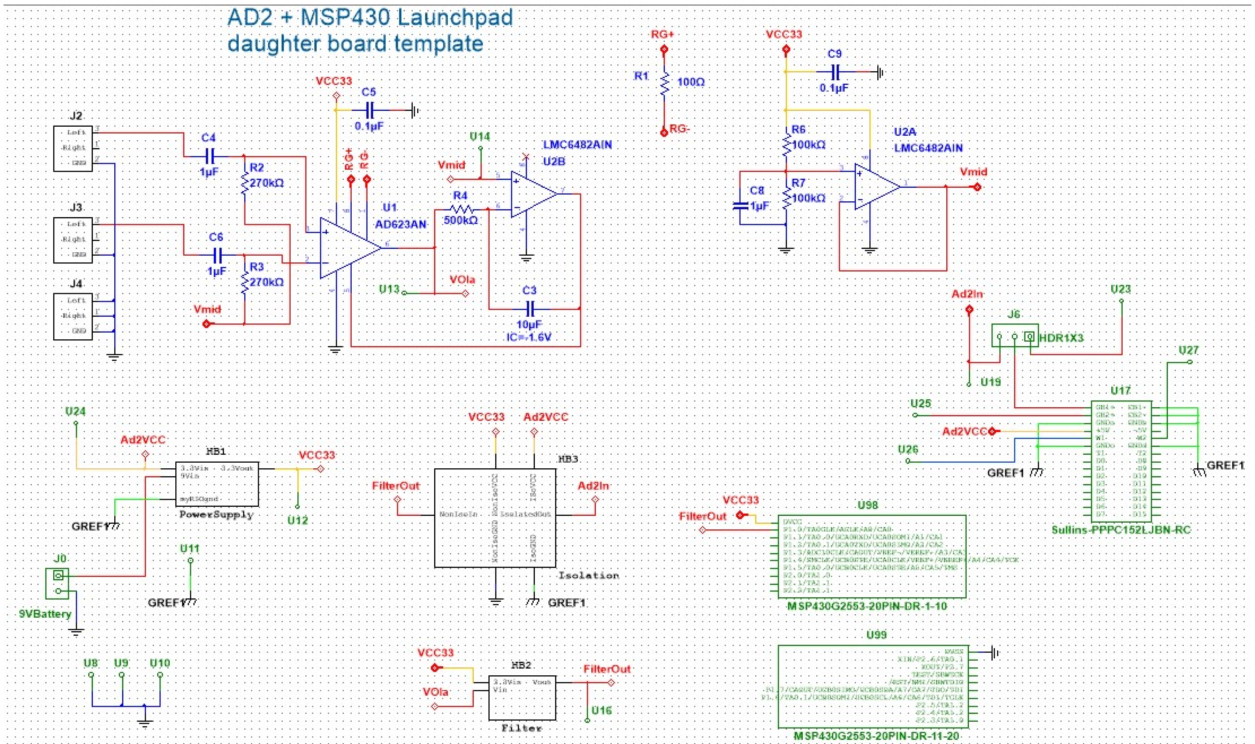

Figure 1: Top-Level Circuit Schematic

Above is the schematic for our overall circuit design. Each component will be explained in detail in the upcoming sections. We also want to mention that the bottom sets of blocks involve connections to the MSP430 and the AD2.

Power Supply

The circuit schematic for the power supply is provided below in **Figure 2**.

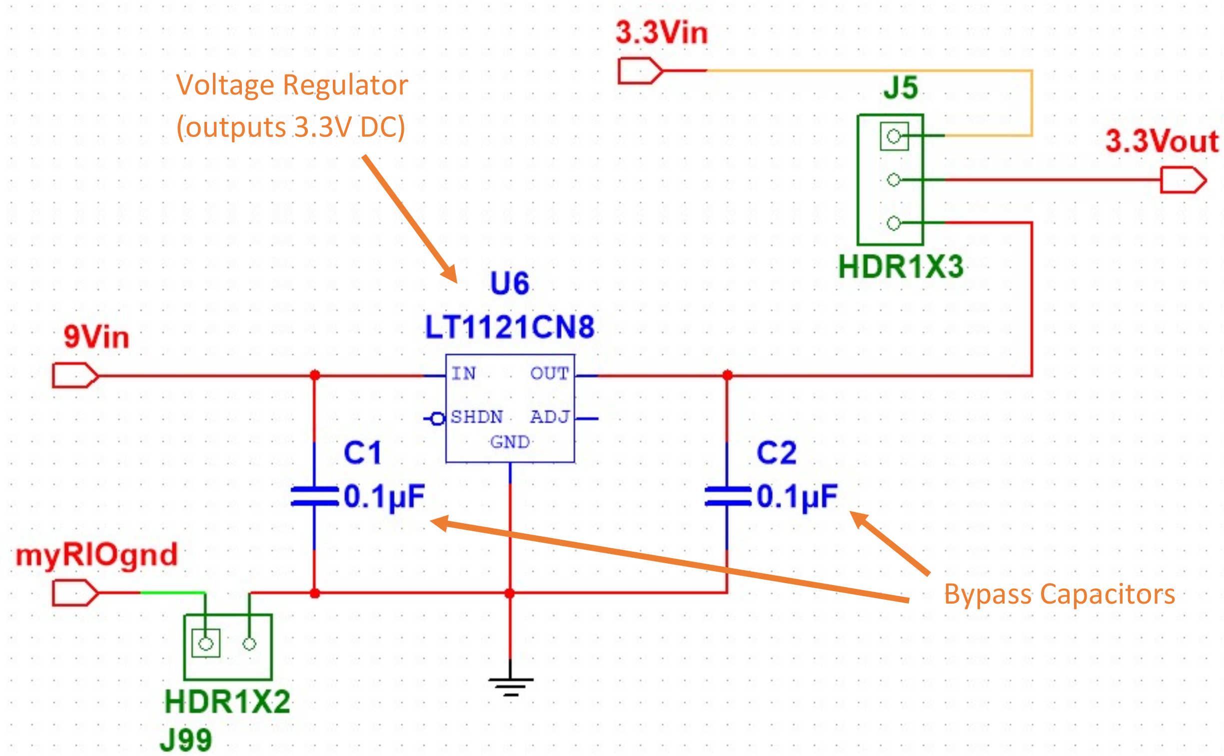

Figure 2: Power Supply Circuit Schematic

The power supply's main function is to provide power to each system in the EKG from a 9V battery. It also involves a voltage regulator that outputs 3.3 V DC. Two bypass capacitors are placed on the input and output of the regulator (C_1 and C_2) to capture DC noise.

Instrumentation Amplifier

The circuit schematic for the instrumentation amplifier is provided below in **Figure 3**.

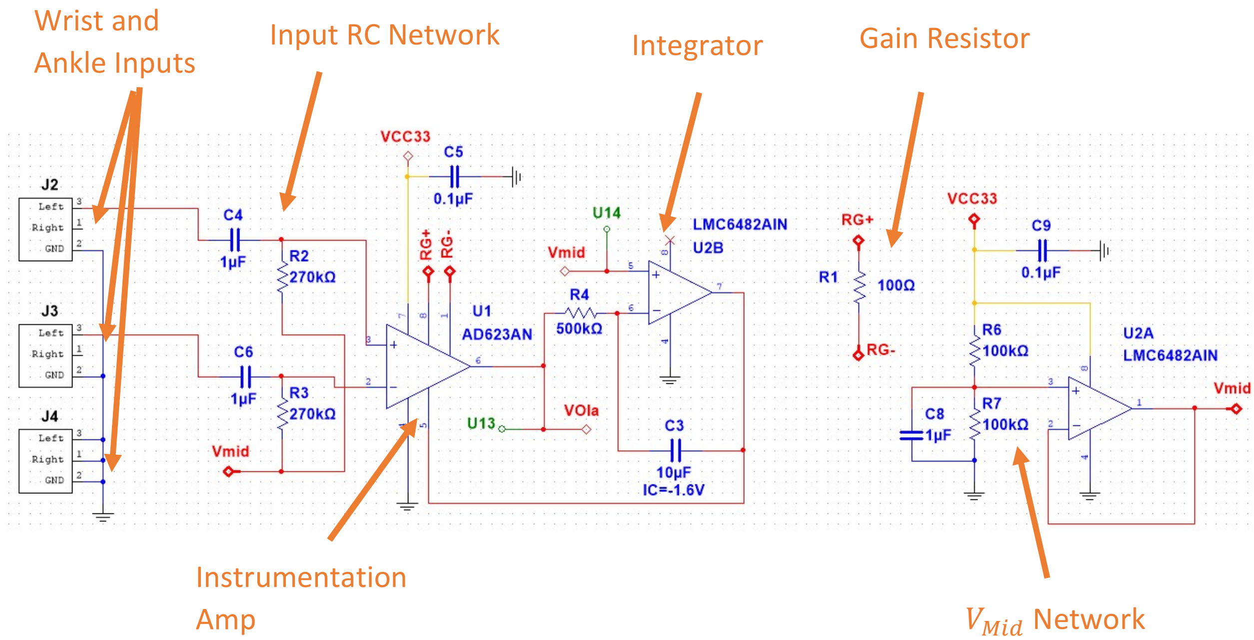

Figure 3: Instrumentation Amplifier Circuit Schematic

The purpose of the instrumentation amplifier is to measure and output the difference between the heartbeat signal coming from the two wrists of the subject. The node at V_{Mid} as mentioned before is set to 1.65 V, meaning that the output of the I-Amp will have a +1.65 V offset. Two RC input networks feed the I-Amp and exist to attenuate very small signals (up to 0.1 Hz). The I-Amp then feeds into an integrator. The purpose of the integrator is to produce a steadily changing output voltage for a constant input. Shown above are the RC input networks (R_2, R_3, C_4, and C_6), the integrator (R_4 and C_3), the gain resistor (R_1), the V_{Mid} network (R_6, R_7, and C_8), and the bypass capacitors (C_5 and C_9).

Antialiasing Filter

The circuit schematic for the antialiasing filter is provided below in **Figure 4**.

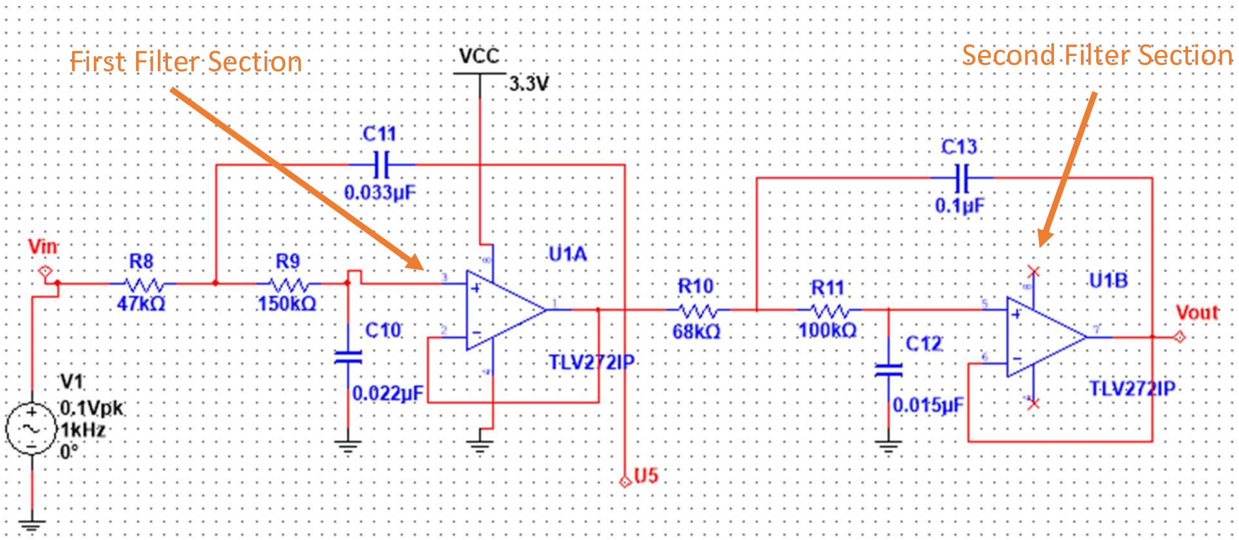

Figure 4: Antialiasing Filter Circuit Schematic

The purpose of the antialiasing filter is to filter out any unwanted frequencies from the filter. Although the instrumental amplifier has taken the signal mostly out of the 60Hz signal any other signals that are too high will be filtered out. This will help remove the aliasing when the signal is processed digitally. The antialiasing filter is a fourth order Butterworth filter. This is made up of two 2^{nd} order filters which Q values product is 0.707. The capacitors and resistor values were found by taking the parameters of the transfer function of the filter and running them through code to find the best values.

The procedure for finding our filter values was as follows:

- $-72dB\ at\ 500Hz$
- $Lowest\ Q\ filter\ must\ be\ first\ in\ the\ sequence$
- Minimum resistance value $= 47K\Omega$

4^{th} order has -80dB/decade roll off:

$$10^{\frac{A_{dB}}{20}} = \frac{1}{1+\left(\frac{f}{\frac{\omega_0}{2\pi}}\right)^4} = 10^{\frac{-72d}{20}} = \frac{1}{1+\left(\frac{500Hz}{\frac{\omega_0}{2\pi}}\right)^4}$$

$$\omega_0 = 452.47\frac{rad}{s}$$

Simplification (Gain = 1):

$R_8 = Rm,\ R_9 = R, C_{10} = C,\ C_{11} = nC$, and $K = 1$ results in $f_0 = \frac{1}{2\pi RC\sqrt{mn}},\ Q = \frac{\sqrt{mn}}{m+1}$

$$Q_1 = 0.541,\ Q_2 = 1.31,\ Q_1 * Q_2 = Q_{total} = 0.707$$

Filter 1:

1. $R_8 = Rm$
2. $R_9 = R$
3. $C_{10} = C$
4. $C_{11} = nC$
5. $K_1 = 1$
6. $\omega_0 = 452.47\frac{rad}{s} = \frac{1}{2\pi R_9 C_{10}\sqrt{mn}}$
7. $Q_1 = 0.541 = \frac{\sqrt{m_1 n_1}}{m_1+1}$

$$f_0 = 452,\quad Q_1 = 0.539,\quad K_1 = 1$$

$$R_8 = 47\ k\Omega,\ R_9 = 150\ k\Omega$$

$$C_{10} = 22\ nF,\ C_{11} = 33\ nF$$

Filter 2:

1. $R_{10} = Rm$
2. $R_{11} = R$
3. $C_{12} = C$
4. $C_{13} = nC$
5. $K_2 = 1$
6. $f_0 = 452.47\frac{rad}{s} = \frac{1}{2\pi R_{11} C_{12}\sqrt{mn}}$
7. $Q_1 = 0.541 = \frac{\sqrt{m_2 n_2}}{m_2+1}$

$$\omega_0 = 454,\quad Q_2 = 1.291,\quad K_2 = 1$$

$$R_{10} = 68\ k\Omega,\ R_{11} = 100\ k\Omega$$

$$C_{12} = 15\ nF,\quad C_{13} = 0.1\ \mu F$$

Isolator

The circuit schematic for the isolator is provided below in **Figure 5**.

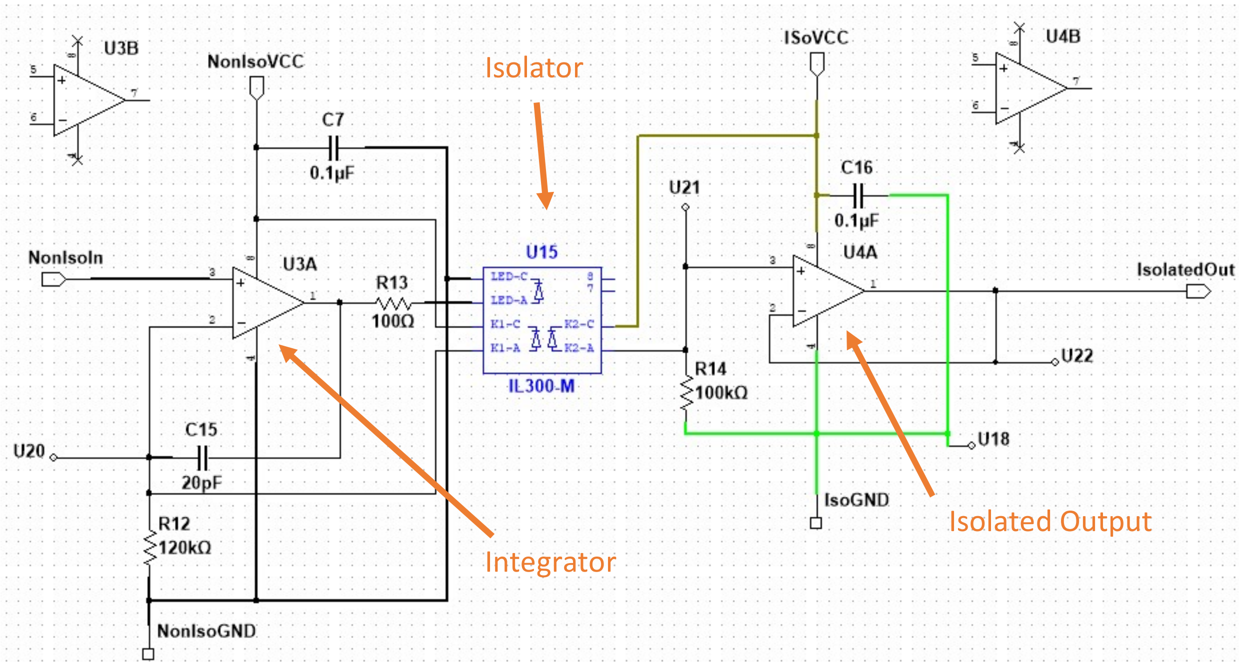

Figure 5: Isolator Circuit Schematic

The purpose of the isolator is to produce an identical signal separate from the overall circuit. This is because if we are measuring someone's heart rate and need to simultaneously defibrillate them, we do not want the signal from the defibrillator to travel into the circuit and destroy it. Therefore, we need to isolate the signal read from the heartbeat and create a copy. In the schematic we have our standardized values for isolator input (C_{15} and R_{13}), bypass capacitors (C_7 and C_{16}), and gain resistor values (R_{12} and R_{14}) to match the required isolator bin (bin H).

Simulations

The simulation of the overall circuit is provided below in **Figure 6**.

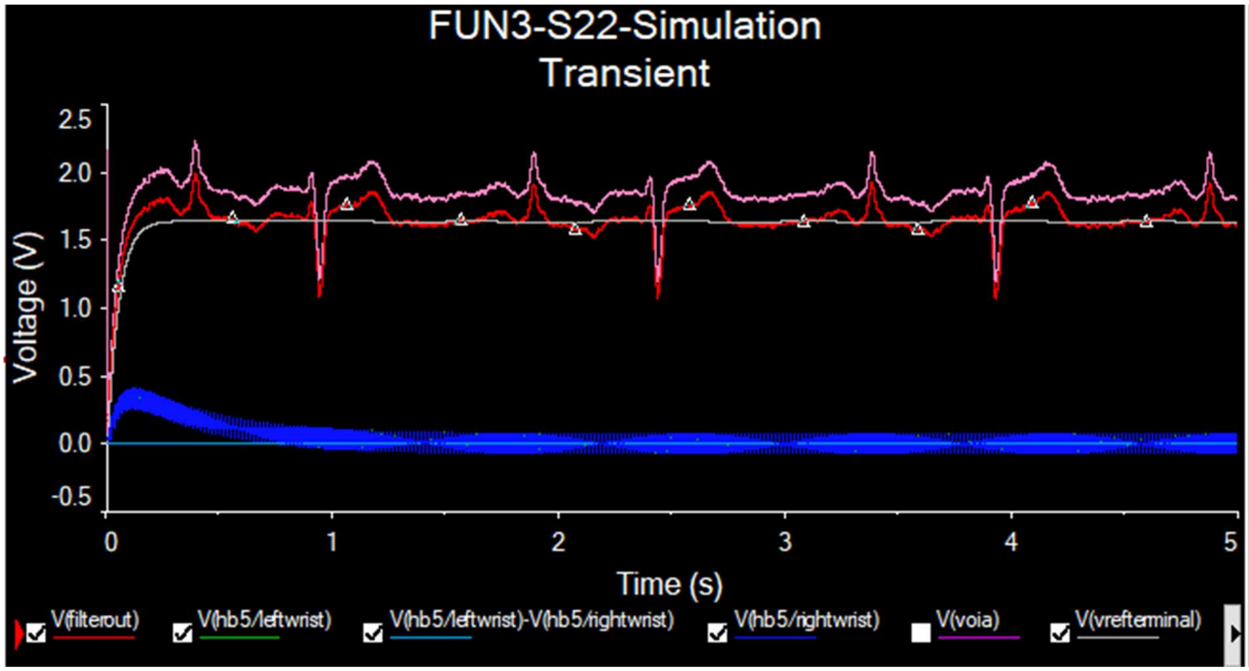

Figure 6: Transient Analysis of EKG Over 5 Seconds

We notice from the simulation that the output signal is shifted by about 1.65 V above the input signal, as expected. It also looks very similar to the input since it is being reconstructed from analog to digital, then back to analog. We may have some slight amplification from the isolator which isn't ideal, but in the end it will not greatly affect our results.

Below we next provide an AC sweep for the integrator section of the I-Amp, as shown in **Figure 7**.

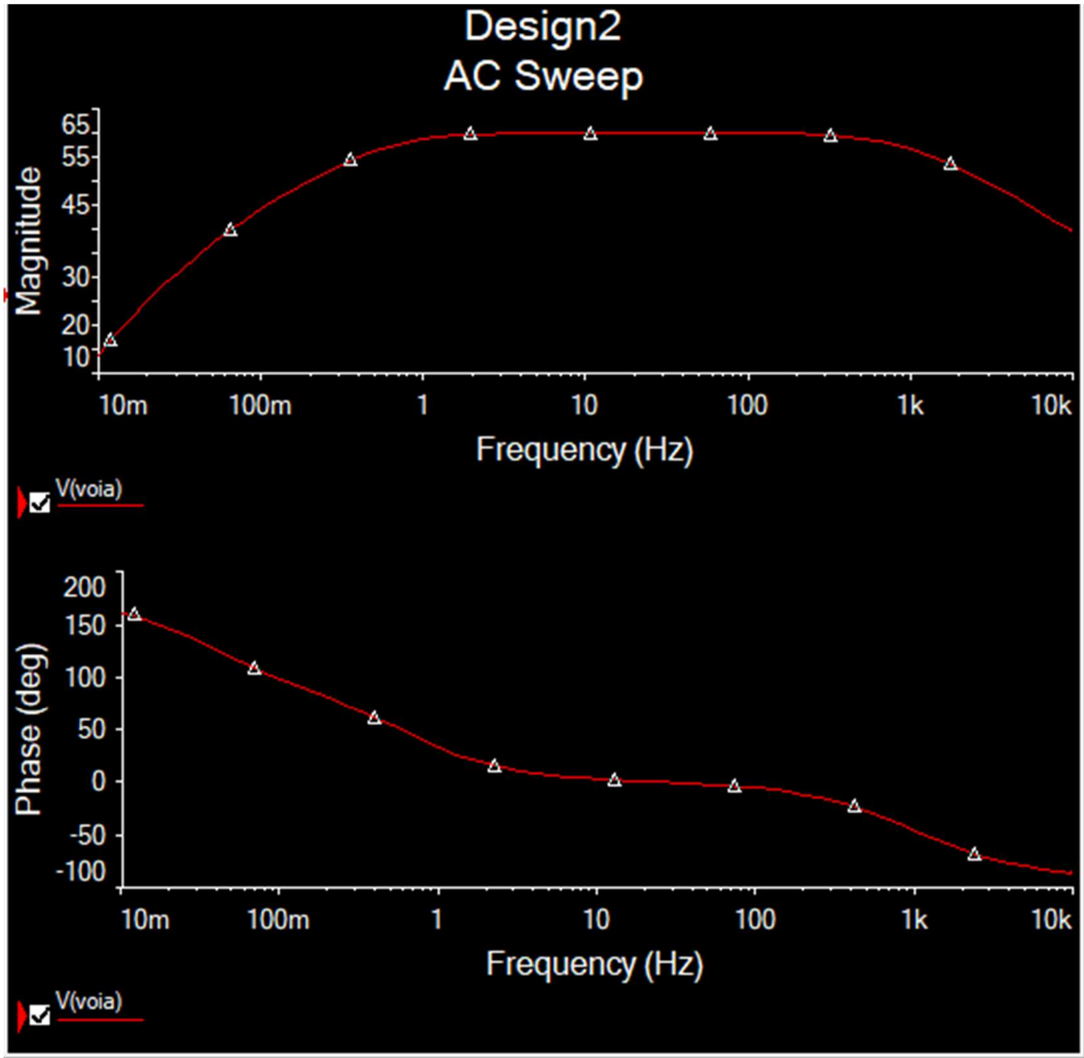

Figure 7: Integrator AC Sweep

We notice that the integrator has a high-pass attenuation from the input RC network. We also see a low-pass attenuation from the V_{Mid} network. This forms a band-pass filter.

We next provide an AC sweep of the V_{Mid} network below in **Figure 8**.

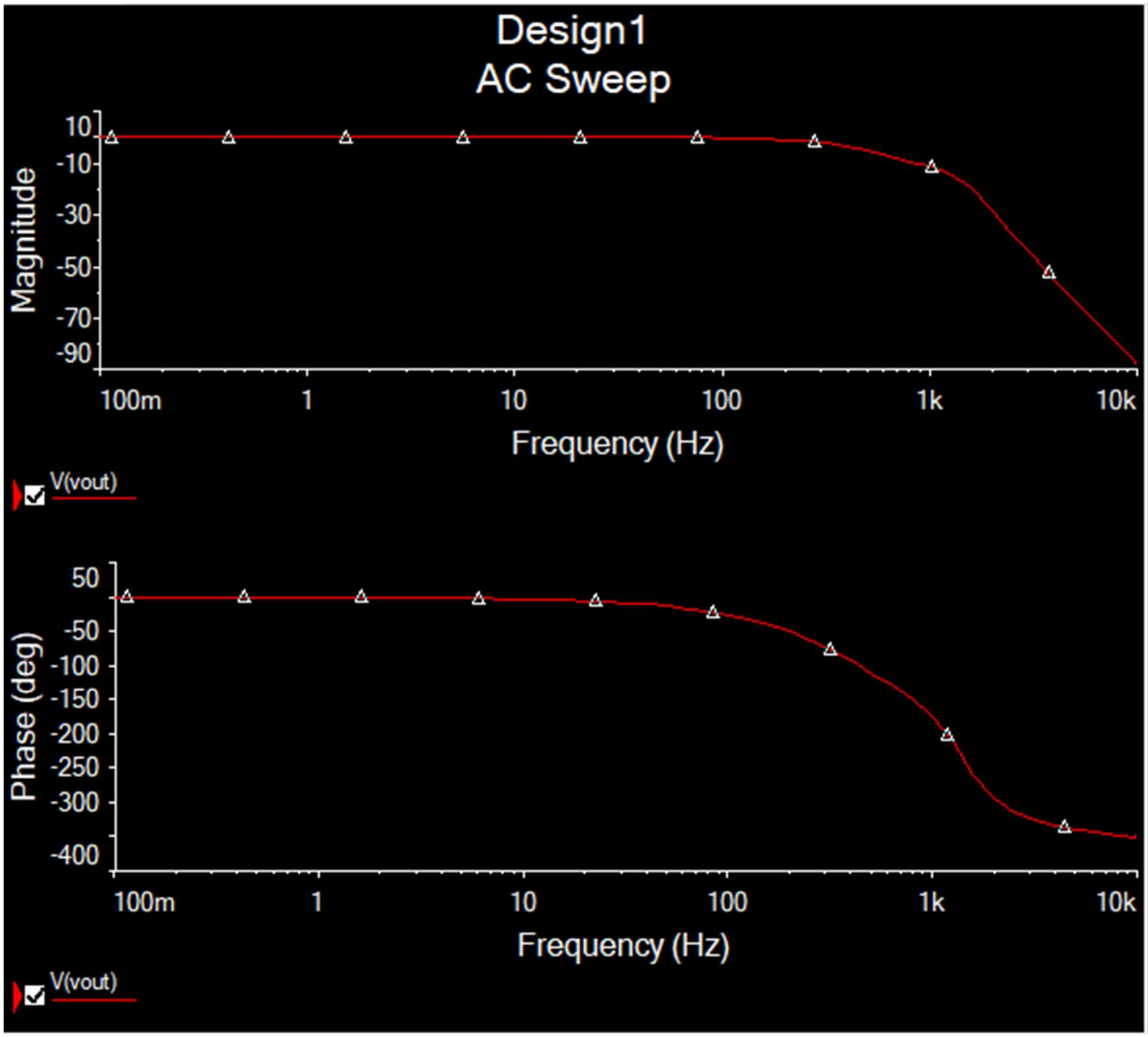

Figure 8: V_{Mid} AC Sweep

We again see the low-pass attenuation at around 1kHz from the V_{Mid} network.

We lastly provide the Bode plot for the antialiasing filter below in **Figure 9**.

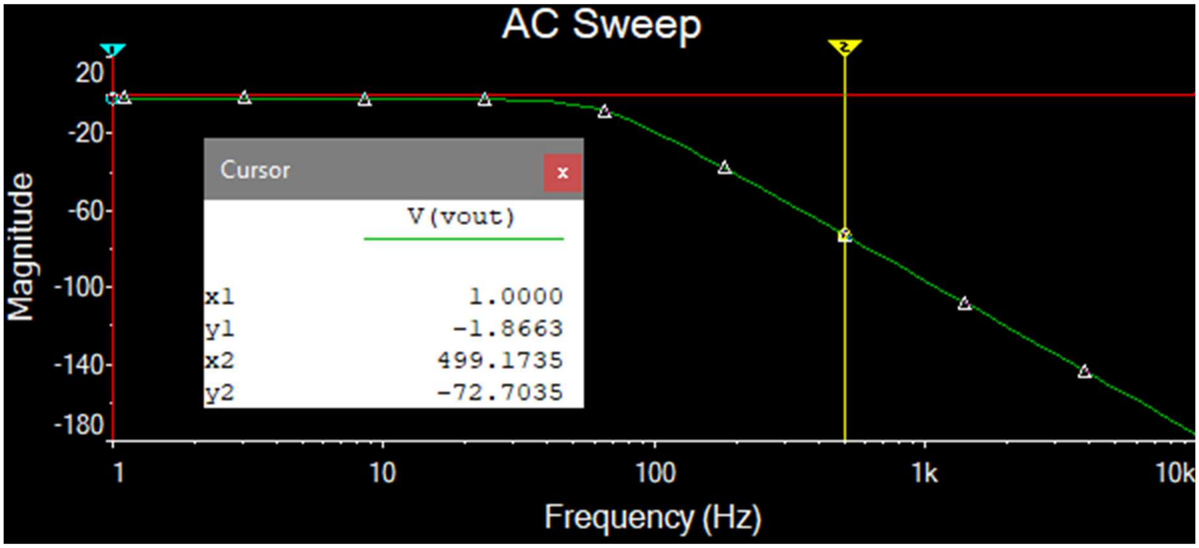

Figure 9: Antialiasing Filter Simulation Bode Plot

We see that in our filter simulation, the -72 dB mark is hit almost exactly at 500 Hz.

Layout

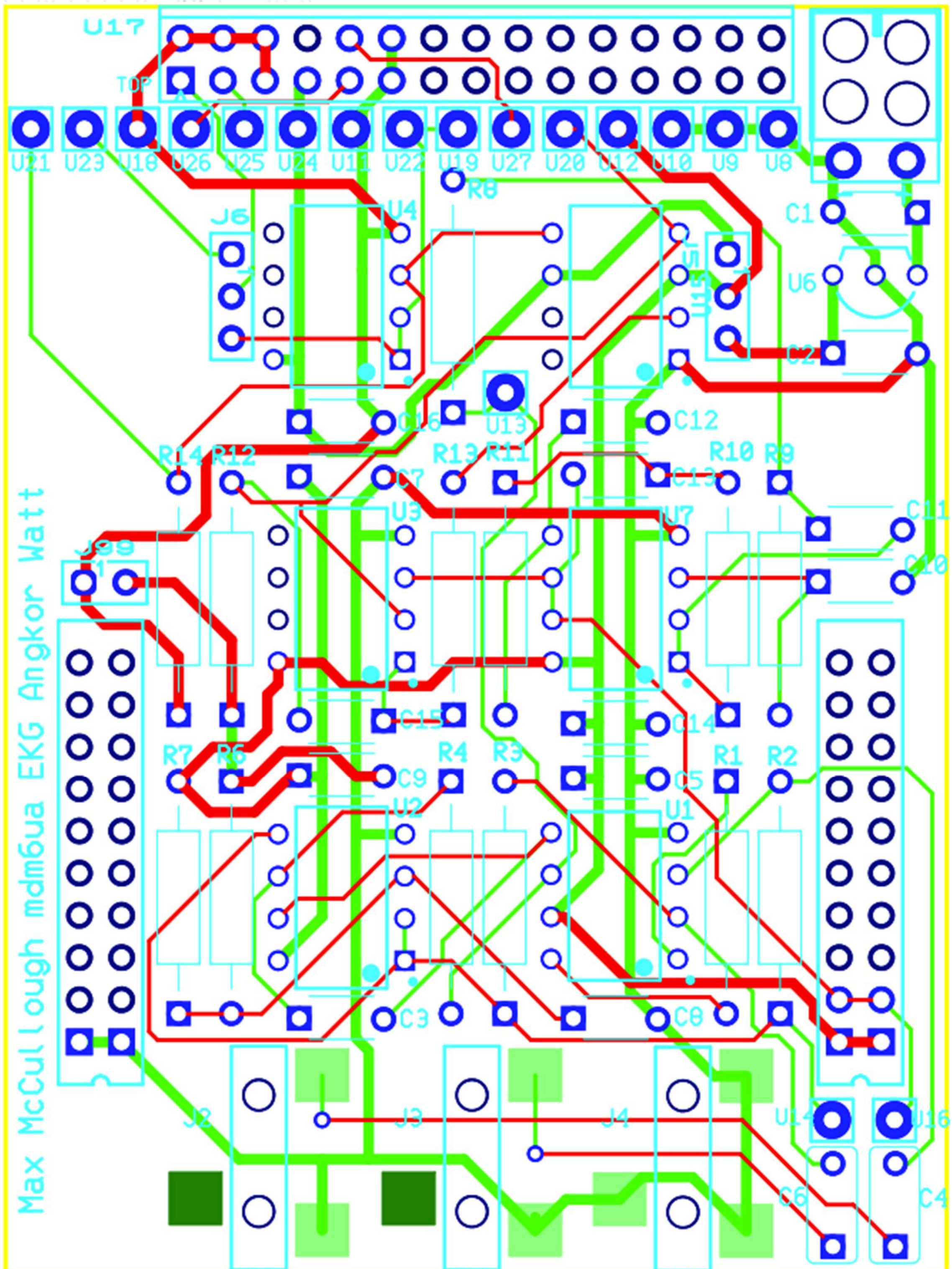

Figure 10: PCB Layout Silkscreen (Cyan), Copper Top (Green), and Copper Bottom (Red)

When designing the board the main goal was to make it as simple and organized as possible. The board is centered around the 6 main chips. From there to keep things neat there is two power traces going up the center of each column of chips so that all chips have power while using as little of the board as possible. From there each section of the board has its corresponding resistors and capacitors as close as possible to it. Ensuring that bypass capacitors are especially close to each chip. To limit the number of vias on the board all traces going vertically and/or up and to the right are on the copper top. All traces going horizontally and/or up and to the left are on the copper bottom. This rule is not strictly met but it is the general case for most traces. Almost all of the test pins are at the top of the board for ease of access and special concerns. As for the labels all of them are directly above of the component and if that was not possible, they are to the right of the component.

After the PCB was designed it had to be turned into a CAM file so that it could be manufactured. Initially the FreeDFM check failed with many potential showstoppers, but this was just due to an outdated CAM converter. After the new one was installed, there was only one issue. This was just a missing connection so fixing it was straight forward ad then the final CAM file was verified.

Section 2

Assembly and Testing

Initial Tests

Our initial tests involve verification of correct component values and ensuring we have no continuity issues on our board. When cross referencing our resistor values with the Ultiboard layout, we noticed that our resistors R_{11} and R_{13} were swapped, so we quickly de-soldered them and switched them to their proper positions. After confirming that all other component values were correct, we then performed a continuity test as shown below in **Figure 11**.

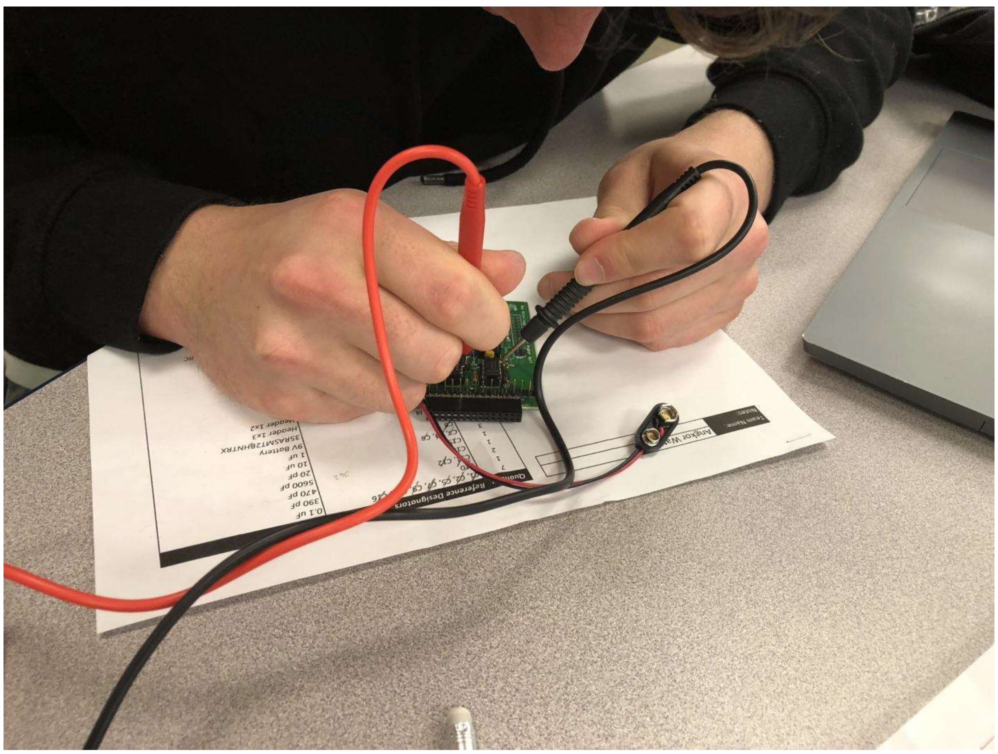

Figure 11: Continuity Testing

No continuity errors were found on our board, so we were ready to proceed to testing the power supply.

Power Supply

In the power supply block, we should expect a 3.3 V DC output at U_{12} (the output of the voltage regulator). We should also expect a 3.3 V DC output at U_{24} (the connection to VCC on the AD2). We first connected the AD2 to the battery input terminals on the board, as shown below in **Figure 12**.

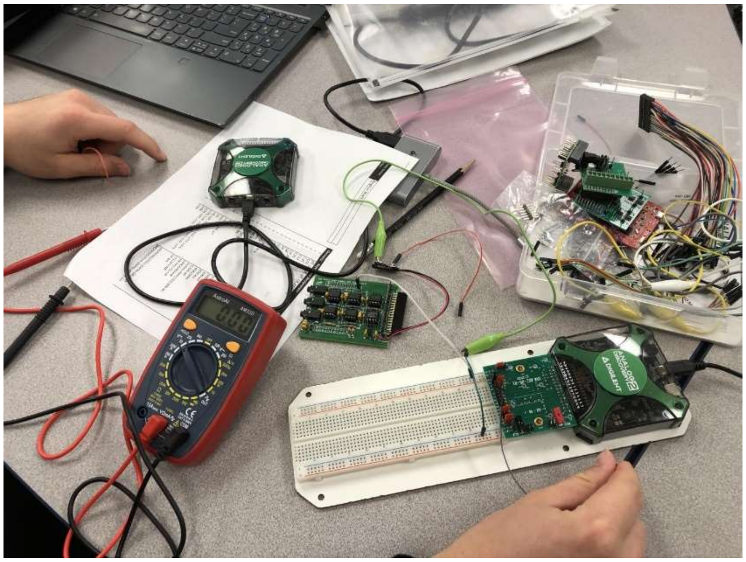

Figure 12: Using the AD2 as a Power Supply

Once connected, we were able to measure 9V across the battery input terminals and were now ready to measure the output of the regulator as shown in **Figure 13**. The output of the regulator was measured to be 3.3V, so we successfully verified the power supply block.

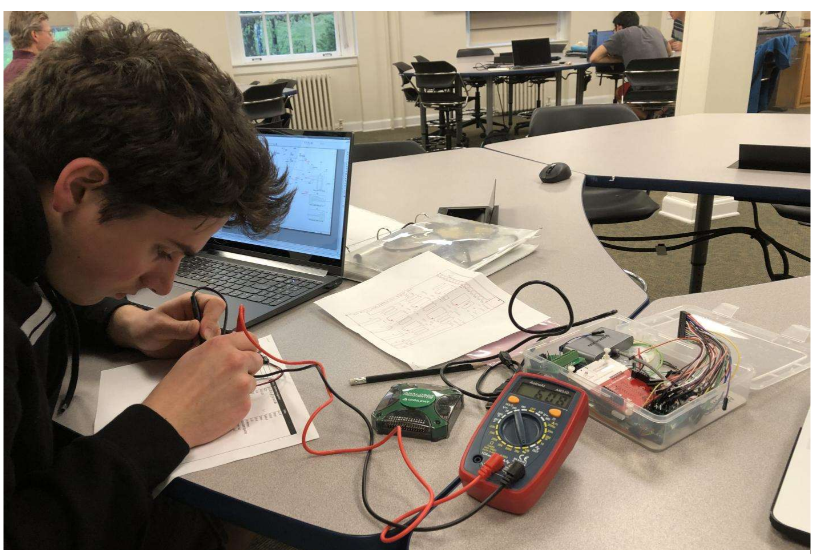

Figure 13: Measuring Regulator Output

Instrumentation Amplifier

Our first expectation of the I-Amp block is that the V_{Mid} node (or U_{14}) is at a steady 1.65 V, or half of the voltage supplied to the amplifier. Running a simulation on this block, we receive the output as shown in **Figure 14**.

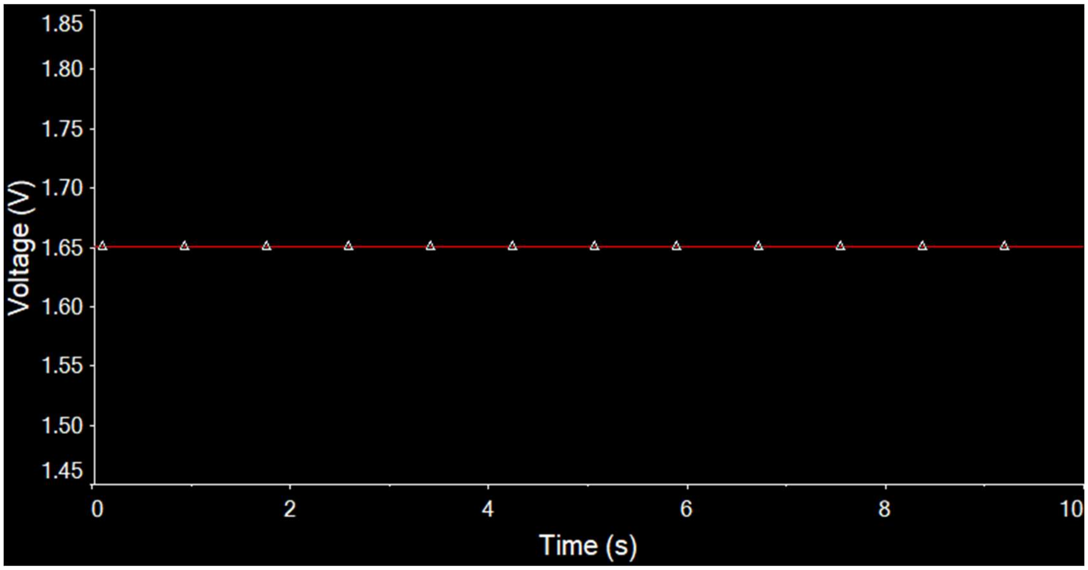

Figure 14: V_{Mid} Simulated Output

We see that the V_{Mid} node is at a steady 1.65 V in the simulation, so now we can continue to test it on the board. The setup and confirmation of V_{Mid} is provided below in **Figure 15**.

~1.65 V measured at V_{Mid} node

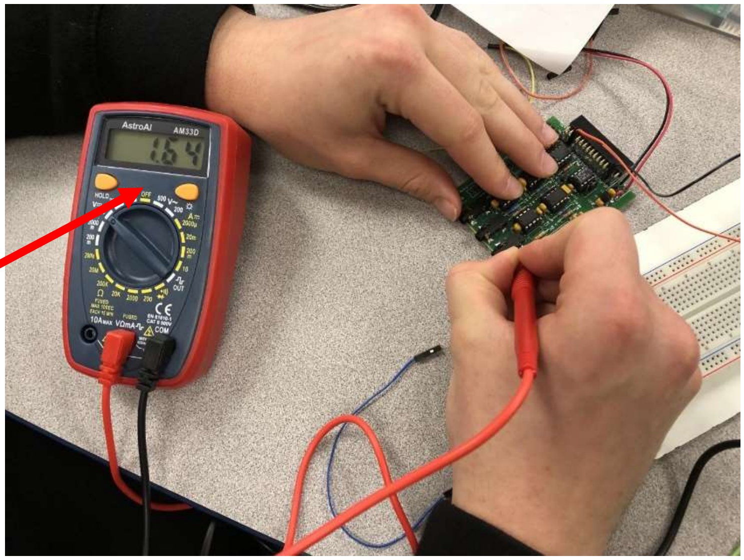

Figure 15: Measuring V_{Mid}

We have confirmed that the V_{Mid} node is 1.65 V when the output of the regulator is 3.3 V. We now want to measure the output of the I-Amp (U_{13}) given several variations of input waves. The setup for measuring the input and output of the I-Amp is provided below in **Figure 16**.

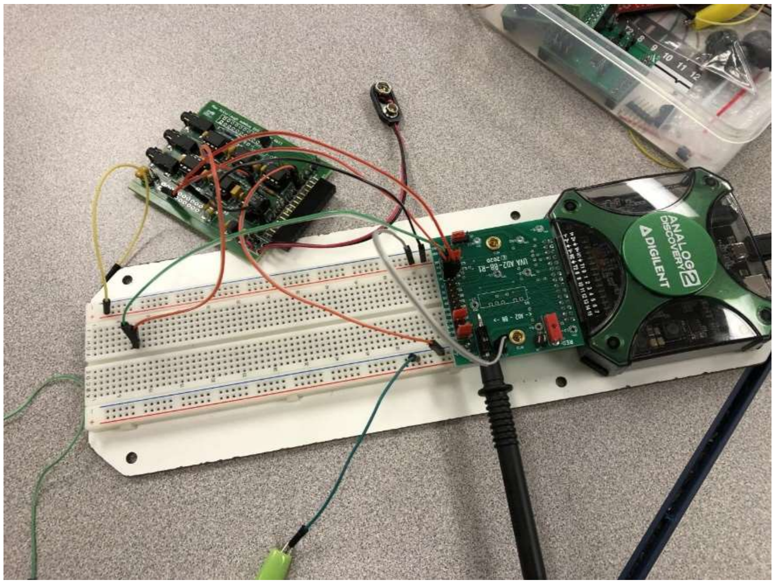

Figure 16: Instrumentation Amplifier Setup

The first test with the I-Amp involved inputting two of the same waveforms into the system. We should see a single DC output since there is no difference between the two input waves. We should also see the 1.65V offset. The output of the I-Amp from two of the same waveforms is provided in **Figure 17** below.

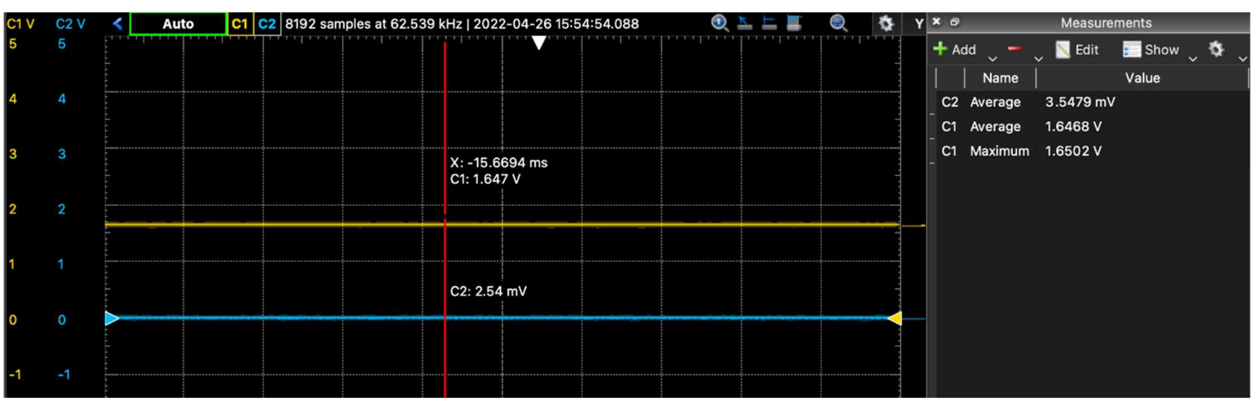

Figure 17: I-Amp Output from Two of the Same Input Waves

We see that the output (yellow) of the I-Amp is a single DC source at approximately a 1.65V offset. This has verified that our I-Amp functions for two of the same input waves. The next step is then to input two different waves, which we will do by simply offsetting the second wave by a 180° phase difference, as shown below in **Figure 18**.

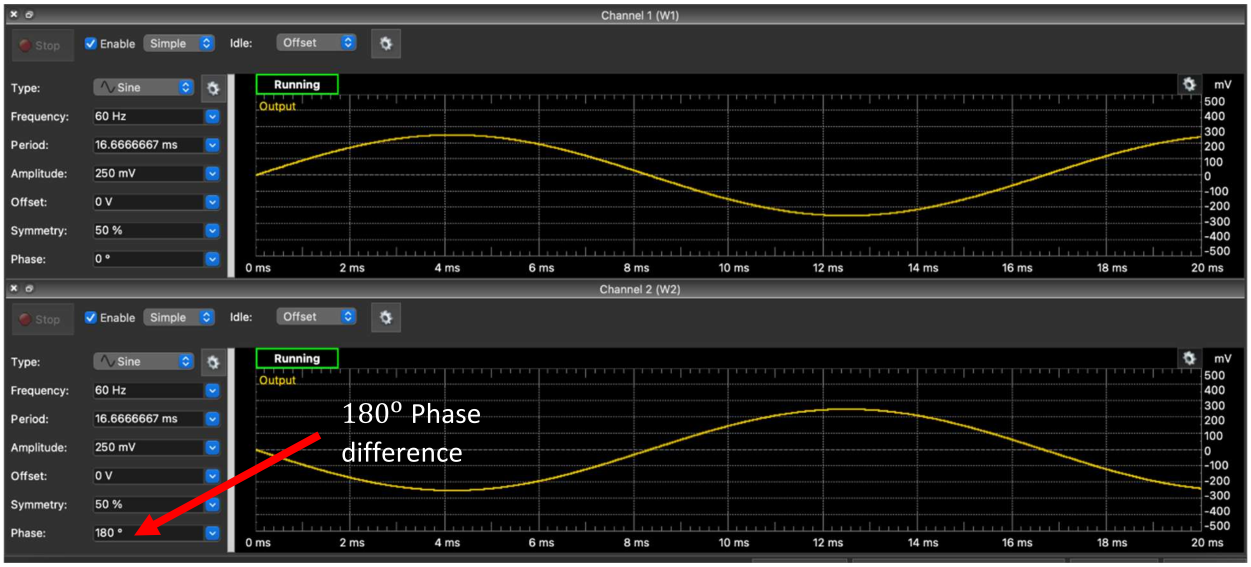

Figure 18: Two Input Waves with 180^{o} Phase Difference

The corresponding output should then be a 60Hz waveform at a 1.65V offset. The output is shown below in **Figure 19**.

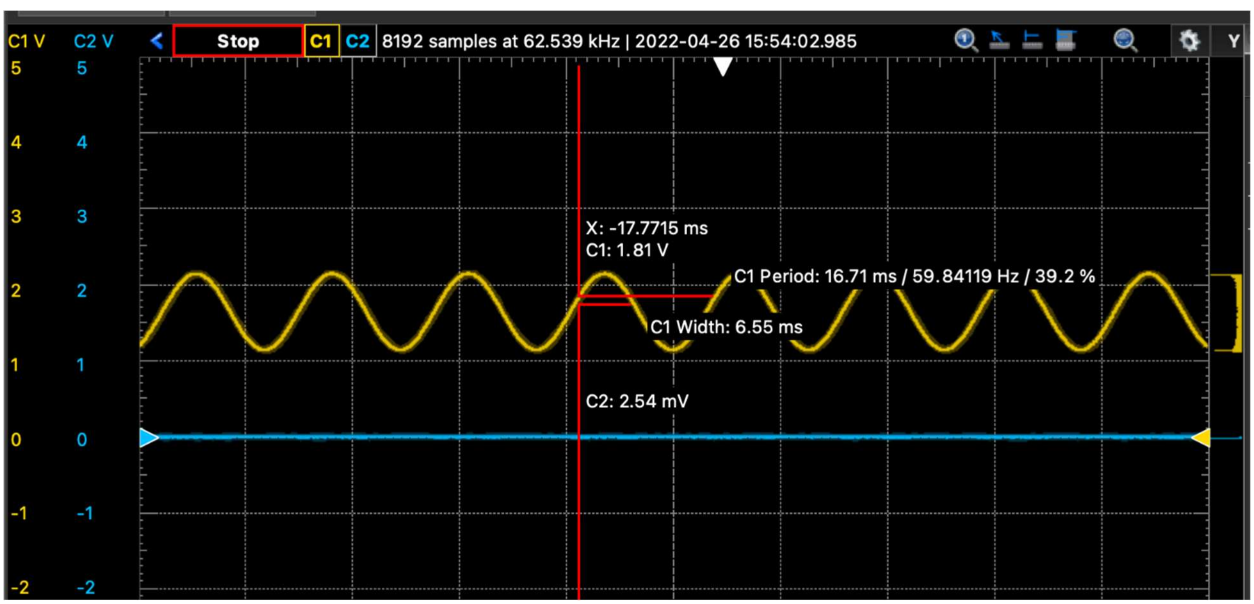

Figure 19: Two Offset Waves I-Amp Output

We see that as calculated, the output of the I-Amp shows a single waveform at ~60Hz at an offset of ~1.65V. This means that our I-Amp is properly outputting the difference between two waves with no noise or gain, as we had expected.

Antialiasing Filter

Having verified the I-Amp, we now move to the antialiasing filter. We first want to confirm that test point U_5 (the output of the first filter sequence) is that of a 2nd order Butterworth filter. We should expect a corner frequency if about 72 Hz with an overdamped Q value of around 0.54. The simulated output of the first stage in the filter is provided below in **Figure 20**.

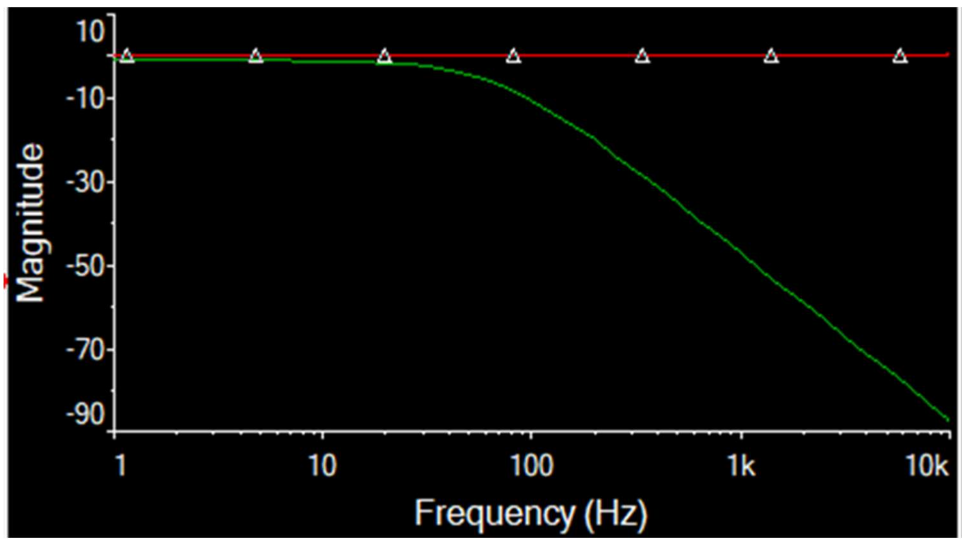

Figure 20: Simulated Frequency Response of First Filter Stage

We next want to check the output of the entire antialiasing filter (test point U_{16}). The response should be critically damped and show an attenuation of about 80 $dB/decade$, or a 4th order Butterworth response. We want to also obtain -72 dB of gain at around 500 Hz, while the corner frequency should again be about 72 Hz. The simulated output of the overall filter is provided in below.

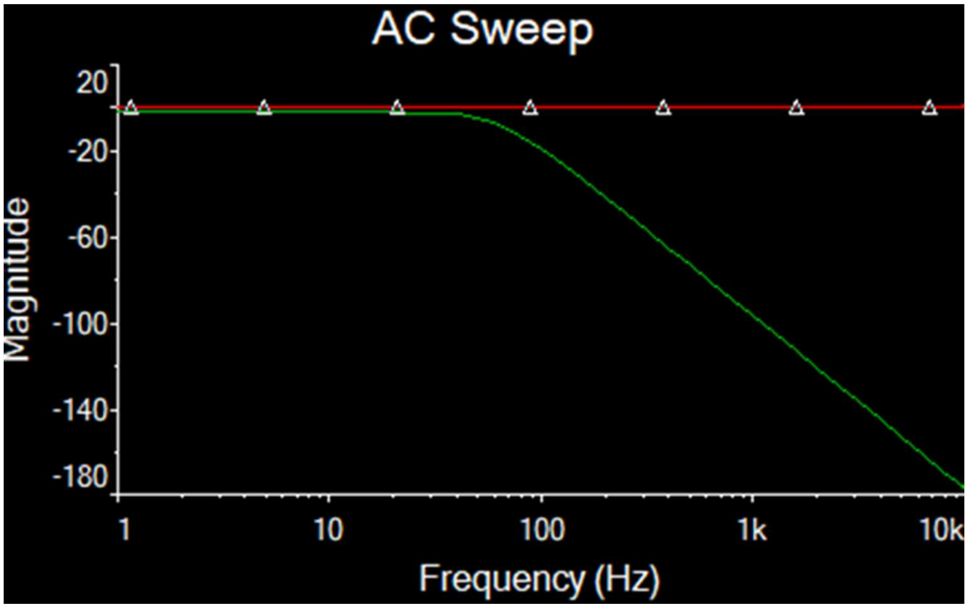

Figure 21: Simulated Frequency Response of Overall Filter

Now that we have confirmed our simulations, we can test the board. We had known that the components previously soldered onto the board would not provide us with the right output, so we simply de-soldered the components and put on our new components. Before soldering on our new components, we created a prototype on the AD2 breadboard and ran a spectrum analysis to find the Bode plot output. The prototype output is provided below in **Figure 22**.

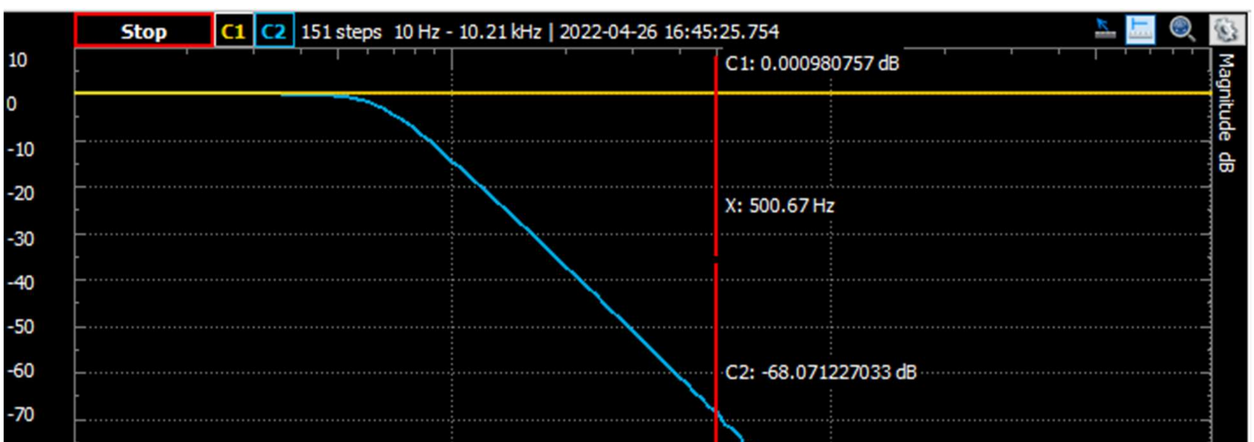

Figure 22: Antialiasing Filter Prototype Bode Plot

We see that at 500 Hz, the magnitude reaches approximately -68dB. Although we had hoped for $-72\ dB$, we are within tolerance of the predicted output. We then soldered the new components onto the board, as shown in **Figure 23** below.

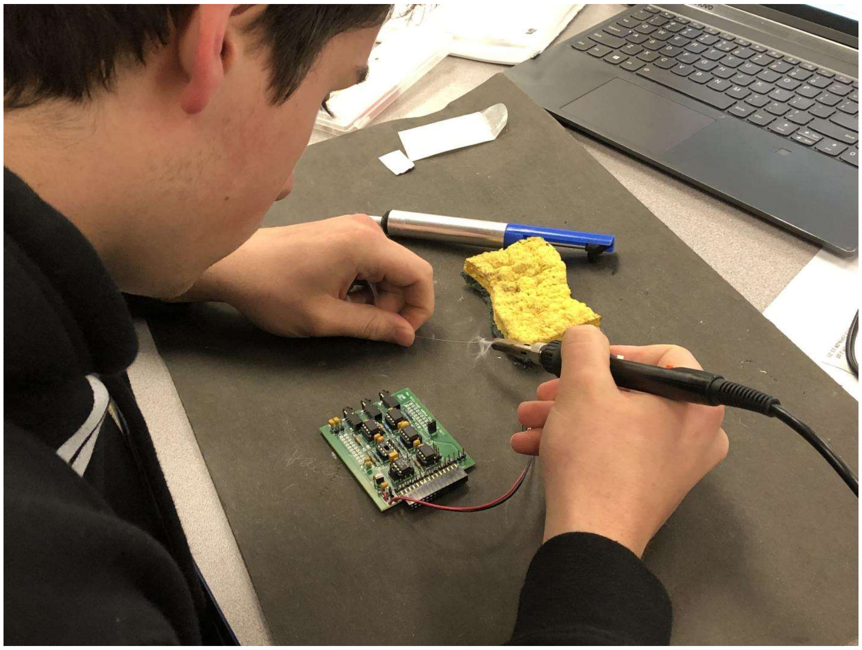

Figure 23: Soldering New Components onto the Filter

We then once again tested and confirmed the output of the filter on the board once more, obtaining the output shown in **Figure 24** below.

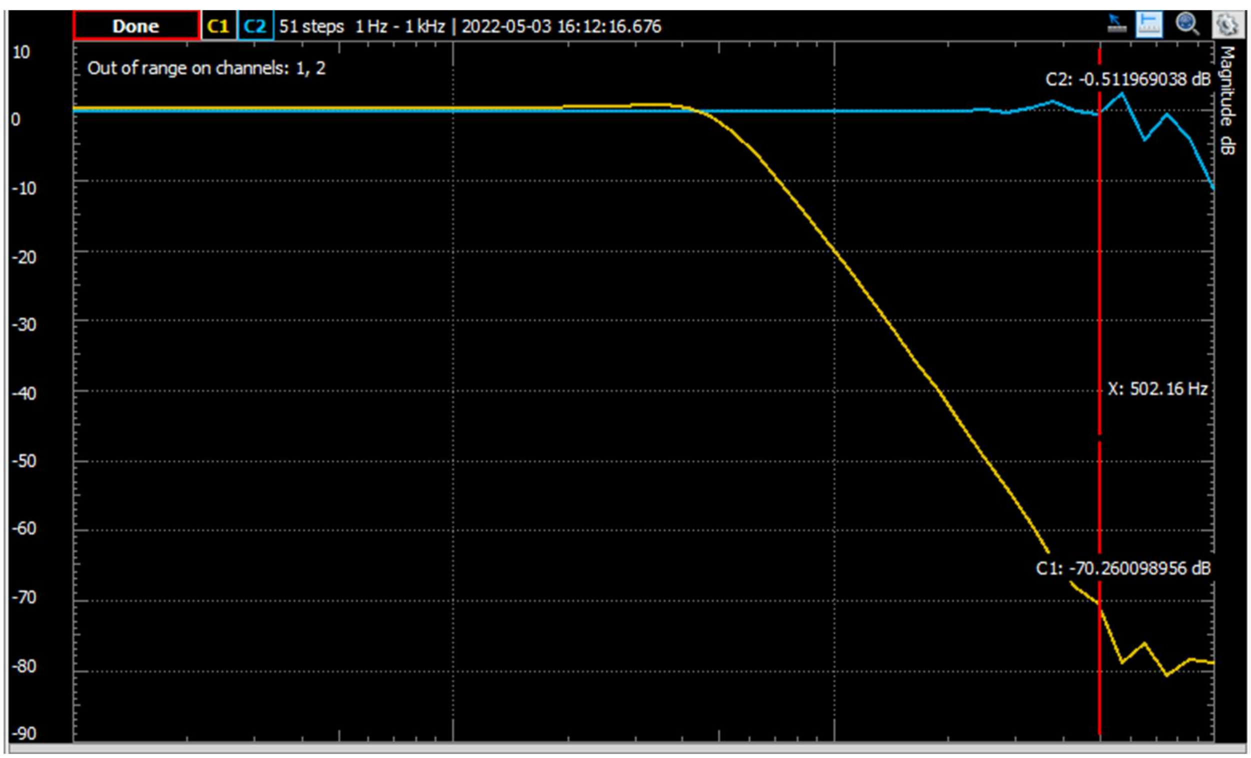

Figure 24: Frequency Response of Overall Filter on the Project Board

Isolator

Now that all other blocks have been tested and verified, we move onto the isolator. We had some problems obtaining an output of the isolator for several reasons. As mentioned previously, two resistors had been mistakenly swapped, so we could not get any signal input into the isolator. Also, we had not been told until later that the bin we had calculated for the isolator (bin C) was not in fact the bin we ended up purchasing (bin H), so we had to recalculate our resistor values. The only test point we want the output of for the isolator is test point U_{22}, which is the isolator's output. We should see that the input and output waves are almost identical with no gain since the point of the isolator is to only separate signals. The output of the isolator is provided in **Figure 25** below.

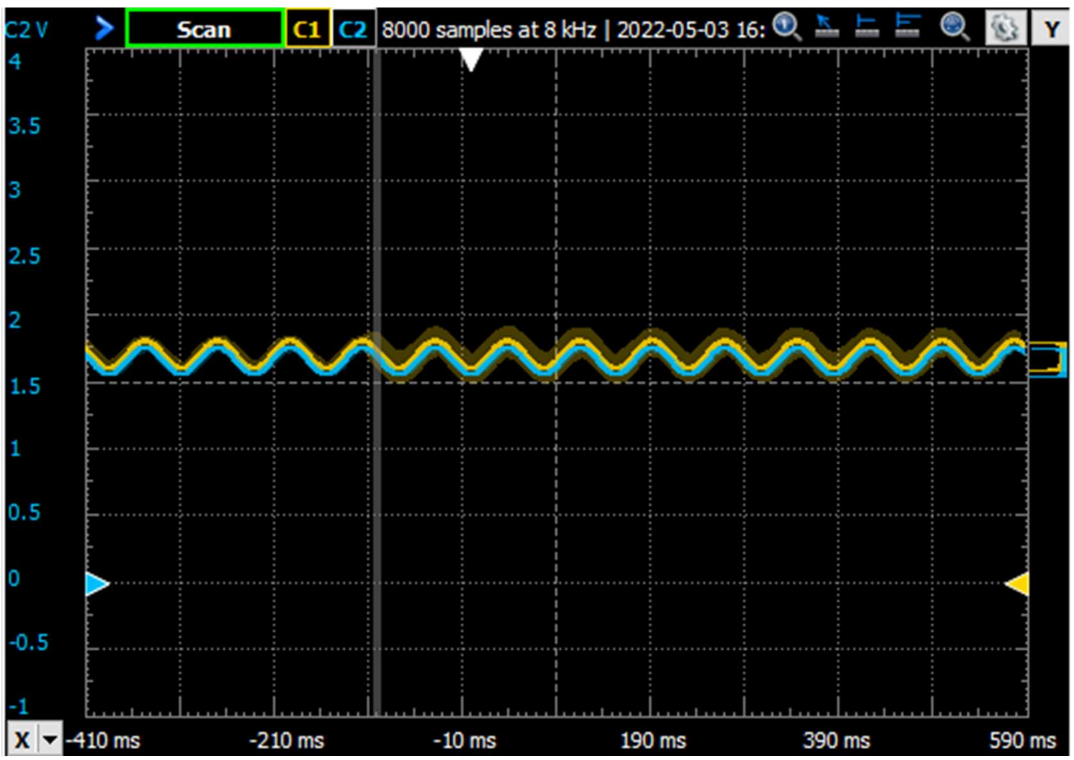

Figure 25: Isolator Signal Input (Blue) and Signal Output (Yellow)

We notice that the input and output of the isolator are almost identical, so we have successfully verified the final block on our board. We may now begin the overall board tests.

Overall Tests

Now that all of our components had been verified, we tested the output signal of the board given the ECG data input waveform. We want to see that the output waveform is similar to the input waveform, but with less noise. This is because the input is being transformed from analog to digital, then reconstructed back to analog. The output of the test ECG waveform is provided below in **Figure 26**.

Figure 26: ECG Input Waveform (Blue) and Board Output (Yellow)

We notice that the input and output are mostly identical, with the biggest difference being the phase shift. We see that the output waveform is also smoothed out and has overall less noise than the blue waveform.

Images

Board

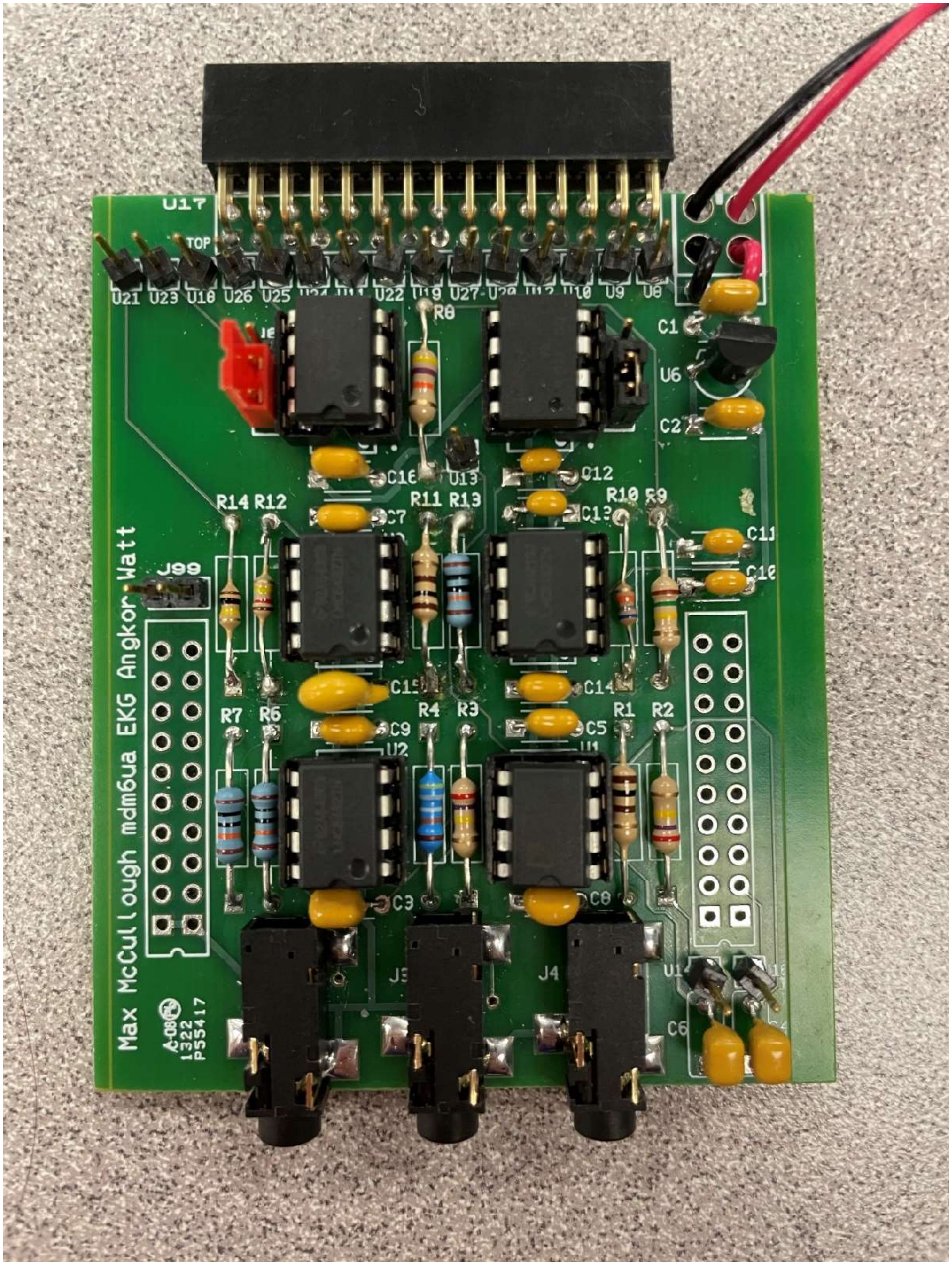

Figure 27: Front of EKG Board

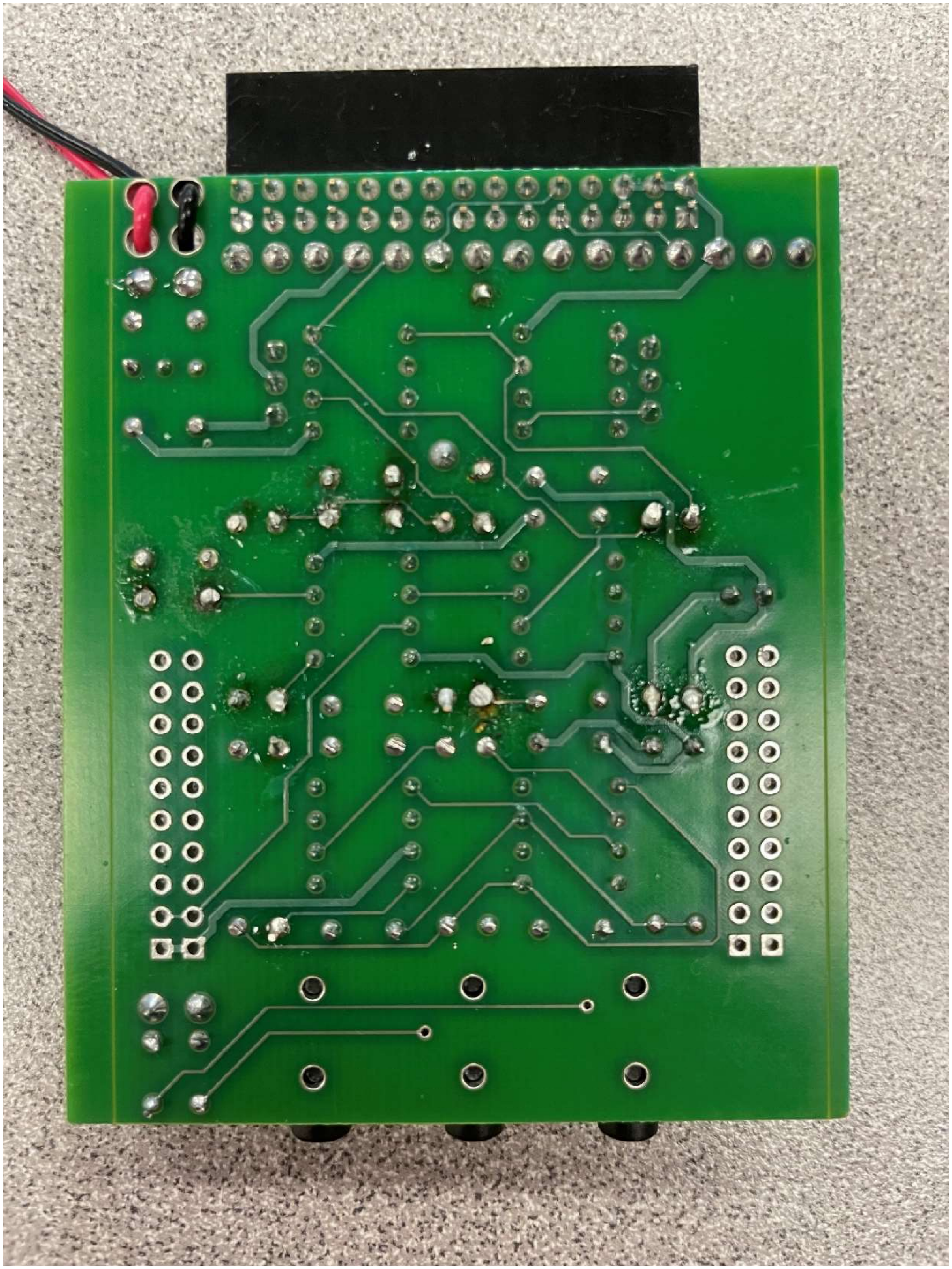

Figure 28: Back of EKG Board

Measuring Heart Rate

Figure 29: Heart Rate Measurement

Waveforms Output

After connecting our board, the outputs of our heart rate are seen as below in **Figure 30** and **Figure 31**.

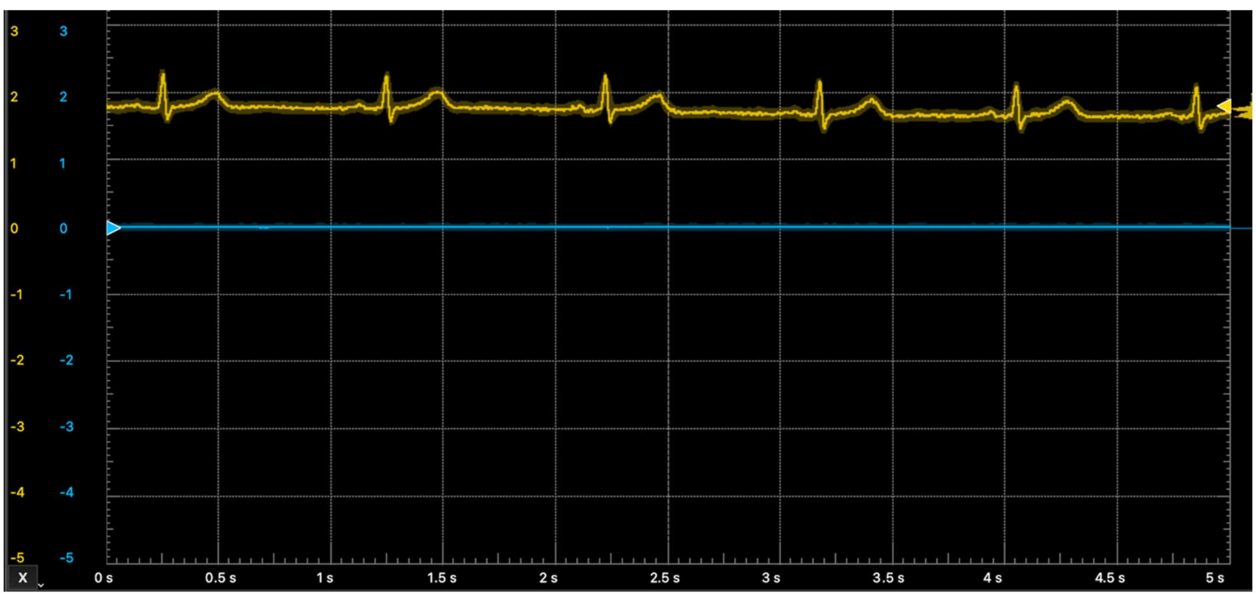

Figure 30: Leonardo's Heart Rate Reading

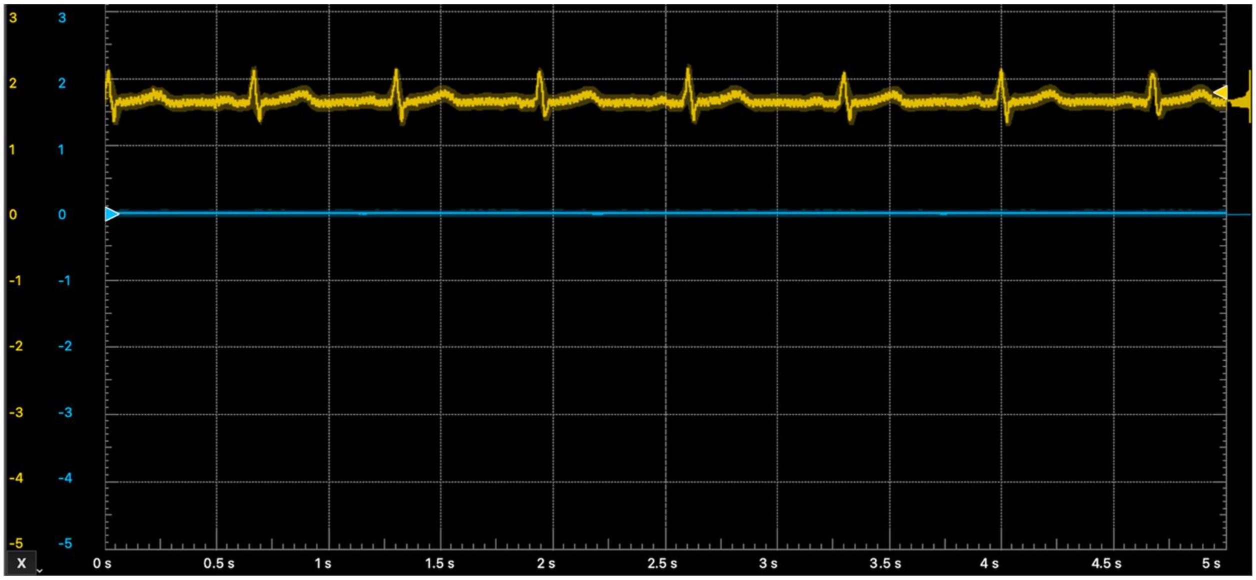

Figure 31: Max's Heart Rate Reading

We notice that Max seems to pick up more 60 Hz than Leonardo does by the way his heartbeat waveform is “jittery”.

Data Capture

The code for filtering the heartbeat signal is provided below in **Figure 32**.

```
import csv
import matplotlib.pyplot as plt
import numpy as np

data = open("Data.csv")
reader = csv.reader(data)

rows = []
for row in reader:
    rows.append(row)

values = []
for n in range(len(rows)):
  if n > 0:
    values.append(float(rows[n][1]))

def H(m):
    func = numpy.linspace(1/m, 1/m, m)
    return func

filter1 = np.convolve(values, H(27), mode = 'full')
filter2 = np.convolve(values, H(28), mode = 'full')

filter3 = []
for k in range(len(filter1)):
    filter3.append((filter1[k] + filter2[k]) / 2)

time = []
for k in range(len(values)):
    time.append(k / 1638)

timeFilter = []
for k in range(len(filter3)):
    timeFilter.append(k / 1638)

plt.xlabel("Time (s)")
plt.ylabel("Voltage (V)")
plt.title("Time (s) vs. Voltage (s)")
plt.plot(time, values)
plt.plot(timeFilter, filter3)
plt.show()
```

Figure 32: Python Code Used to Filter Signal

After filtering Leonardo’s and Max’s heartbeats, the outputs are found to be as shown in **Figure 34** and **Figure 33**, respectively.

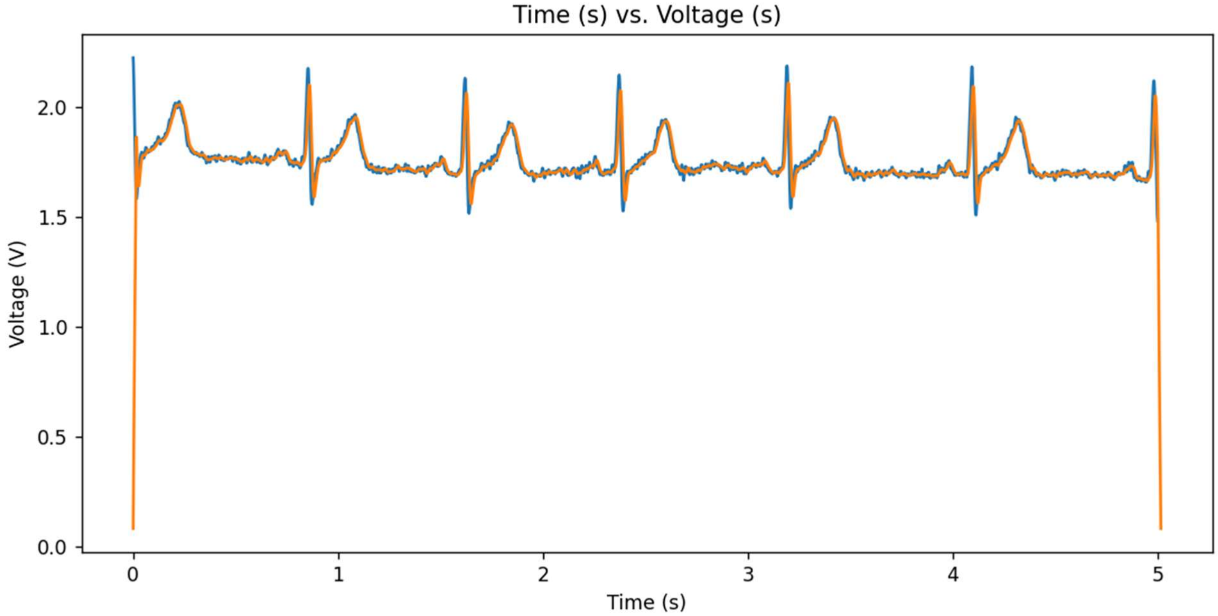

Figure 34: Leonardo's Filtered Heartbeat

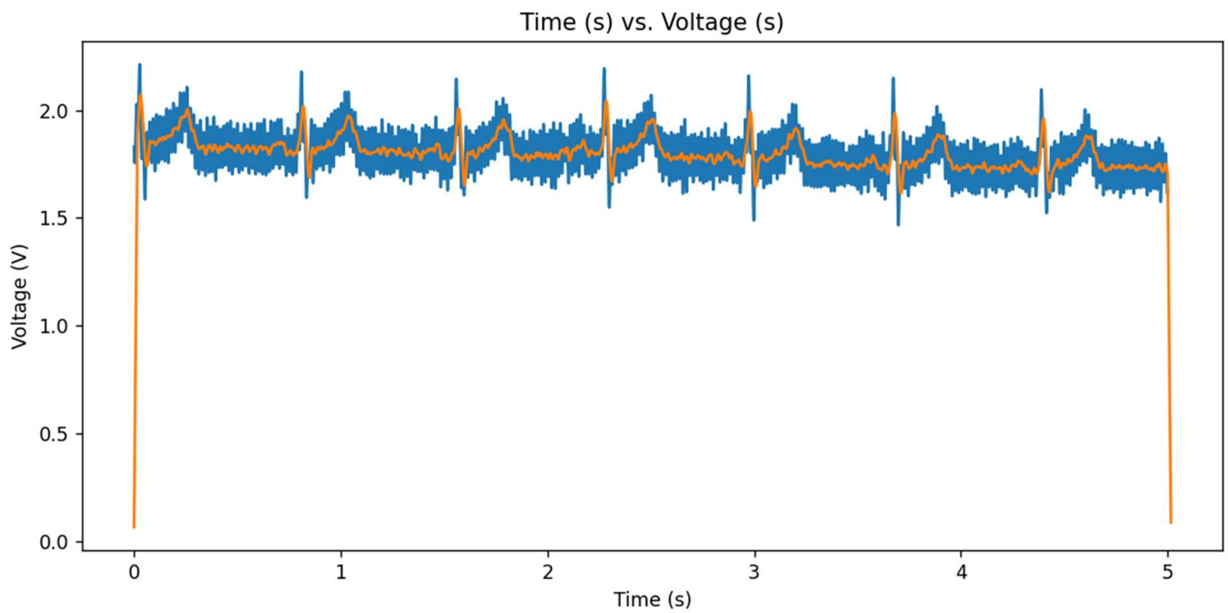

Figure 33: Max's Filtered Heartbeat

We note that Max’s heartbeat was measured while holding a laptop charger (a transformer) to produce a noisy heartbeat signal. Leonardo’s heartbeat was measured with no extra interference. We can show the effectiveness of our code by viewing the measured wave (blue) and the filtered wave (orange).

Conclusions

Summary

In this project we built a functioning EKG. We first decided how the PCB would be designed using Ultiboard, then we downloaded the Gerber files, submitted them to FreeDFM, and got the board confirmed to be physically built. Our next step was to calculate component values to be placed on the board. We went through the process in the order in which signal would travel through the board. We started by calculating component values for the power supply, then the instrumentation amplifier, the antialiasing filter, and finally the isolator. The power supply's purpose is to not only supply power to the board, but to regulate output voltage to 3.3 V using a regulator. The instrumentation amplifier measured and output the difference between the readings on the subject's two wrists with some offset. The antialiasing filter prevented overlap in the reconstruction process when transferring from analog to digital and back to analog. Finally, the isolator transferred and isolated the signal from the rest of the board to prevent a circuit breakdown in the case of an emergency. The board was then tested and confirmed to be working through the same order of blocks as described previously. We then connected the board to multiple subjects, gathered their heart rate signals, and used an averaging filter to clean up the signals. Overall, the project was a success.

Future Improvements

In the future, it would be nice to have a more even spread of work throughout the semester. It felt as if we were rushing to get the entire project completed for the last few weeks of class, and it wasn't conducive to learning how the board works. Perhaps having us calculate the values for each block when we learn about that block would be better. For example, when we finish going over instrumentation amplifiers in class, we should have an assignment where we calculate and simulate the values for the I-Amp in the project. The same should be done for the rest of the components, so by the end we aren't rushing to turn everything in and we can focus more on the test plan.