

ECE 3750: EKG Sensor Final Project Report

Team High Impedance

December 10th, 2017

Team Members Responsibilities:

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On our honor, we have not given or received unauthorized aid on this assignment.

Signed: *Cesar Roucco, Jackson DuBro, Louis Gunning, Saad Khan*

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1 Background

1.1 Motivation and Overall Approach

Electricity is as essential to humans as it is to electronics. The human body produces very low voltage electrical signals when your heart beats, when your body exercises, when your brain thinks, and when many other daily activities occur that allow for cells to communicate and perform basic biological functions. Because electricity through the body is so essential, it is important to monitor these electrical impulses, like the ones in charge of making your heart contract. A device called electrocardiogram (EKG or ECG) sensor is responsible for monitoring these signals in the heart that would otherwise be very hard to see.

In order to conclude the term and combine the topics learned in class throughout the semester, our final project consists of designing an EKG sensor. This sensor takes 3 signals as inputs, two different signals from the wrists and a third one as reference from either the ankle or elbow. The sensor takes the 2 signals through an instrumentation amplifier and amplifies the voltage difference between the two while isolating the desire signal from the heart. However, because other unwanted frequency signals will be present, we use a 4th order Butterworth filter to eliminate high frequencies interfering with the desired signal.

1.2 Expected Signals and Requirements for Gain

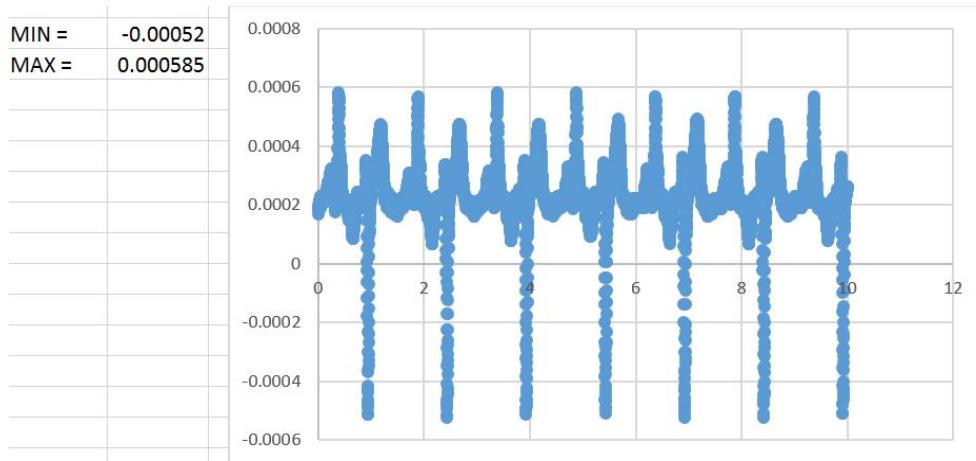


Figure 1. Expected signal LVM file

The input signals to the sensor were expected to be very low voltage signals in the range of hundreds of μV . These cannot be easily read using an oscilloscope, so we needed to amplify the difference between the two input signals to approximately the 1 V - 3.3V range in order to actually see a heartbeat. If the expected maximum

voltage input is 0.000585 V and the minimum voltage input is -0.00052 V, that gives us a range of 0.001105 V. In order to scale it up to 3.3 V we would need a gain of $\frac{3.3}{0.001105} = 2986.425$. However, the AD623 datasheet shows that the component has a max gain of 1000. The equation for gain is given in the datasheet:

$$Gain = 1 + \frac{100,000}{R_g}$$

The gain resistor, R_g , determines the gain for the instrumentation amplifier. Since the max gain of 1000 can get our signal in the 1 V range and that's large enough to be seen by an oscilloscope, we choose this gain and find an R_g value of 100Ω .

1.3 Filter Requirements

A number of filters are necessary to recover this small signal. A difference amplifier, used to provide the gain of the system, is needed to filter out noise that is common in both input signals. Additionally, an anti-aliasing filter is needed before sampling. With the sampling frequency at 5000 Hz, the Nyquist rate was 2500 Hz. Thus, the anti-aliasing filter needed to severely attenuate the signal at 2500 Hz, preferably greater than -80 dB of the original signal.

2 Schematics

This section outlines every subsystem in the circuit along with a multisim schematic of each and explains their purpose.

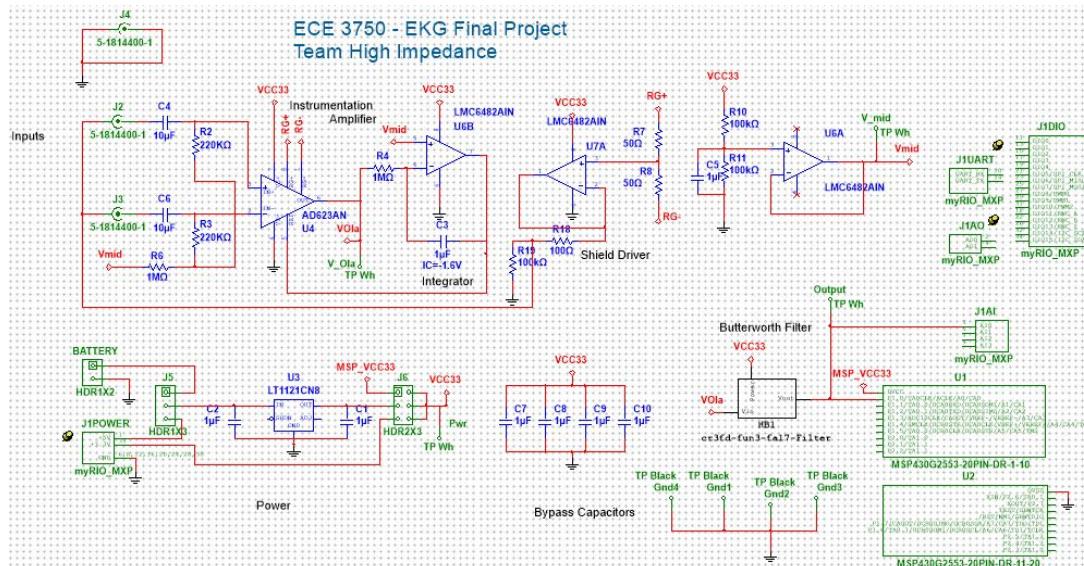


Figure 2. Multisim schematic of the entire circuit

2.1 Subsystem 1: Power

The first subsystem to our project is power. This is the most important subsystem and therefore the first one dealt with. The circuit board is powered with 3.3 V that can be supplied from three different sources. The first source is a 9V battery that is regulated to 3.3 V using a linear voltage regulator. The second source is the power supply of the MSP430 that outputs 3.3 V and does not go through the voltage regulator. The third source is the MyRIO board that outputs two different voltages: a 3.3 V supply that directly powers the board and a 5 V supply that is regulated to 3.3 V using the same voltage regulator. As shown in Figure 3, these are chosen by appropriately putting jumpers on J5 and J6 to connect the pins and choose the desired power supply.

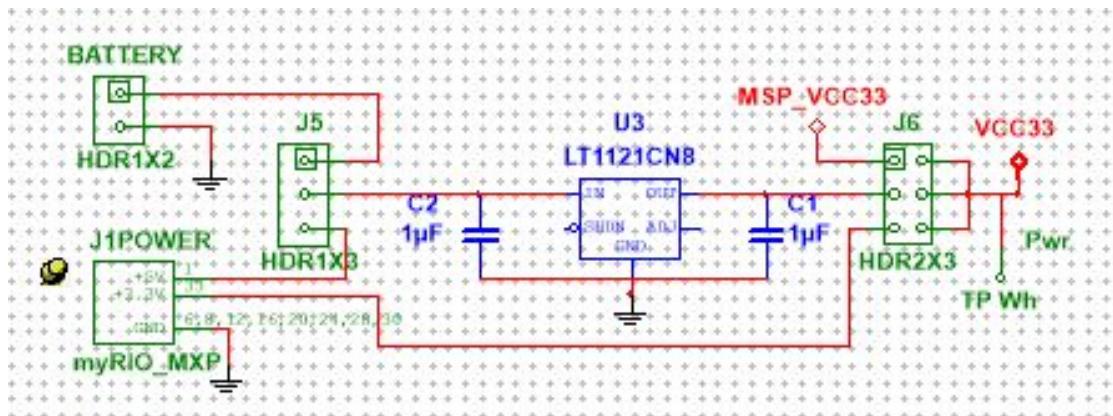


Figure 3. Schematic of the power subsystem

The bypass capacitors served a very specific function to the circuit, they protected from any sudden change in the power supply and allowed for the chips to get a consistent voltage and prevent saturation. These are attached close to the chip they feed so that it takes less time for the capacitor to discharge and be of better use to the circuit.

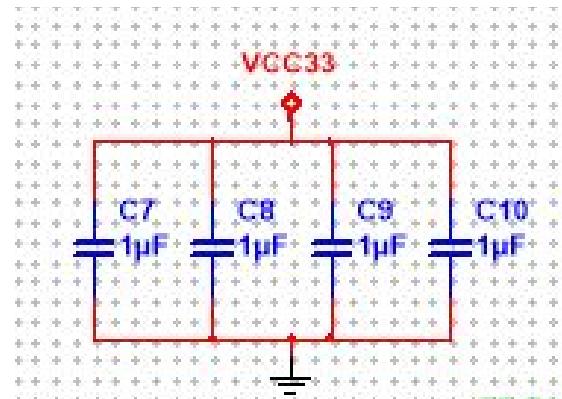
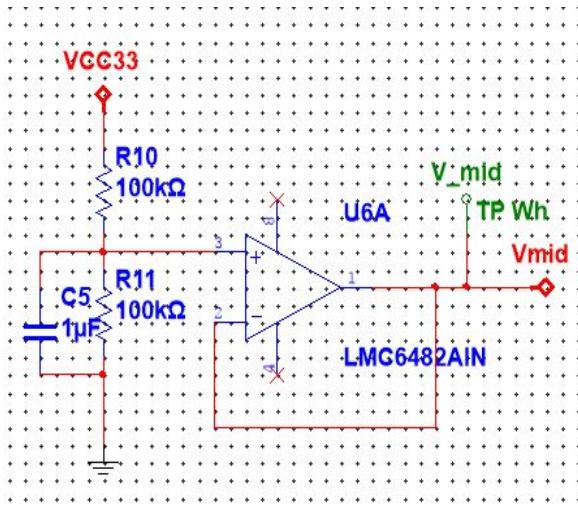


Figure 4. Bypass capacitors



The next part of the power subsystem is V_{mid} . We use a voltage divider to half the 3.3 V power source, as well as a voltage follower and a bypass capacitor that will help maintain a steady voltage which is expected to be about $\frac{3.3}{2} = 1.65$ V. Tolerances associated with the resistors are 5% for each resistor, at worst case rendering our voltage divider $R_{10} = 95\text{k}$ and $R_{11} = 105\text{k}$, or vice versa. This would result in a V_{mid} of 1.5675V or 1.7325, which is 0.0825V more or less than expected.

Figure 5. V_{mid}

2.2 Subsystem 2: Butterworth Filter

The next subsystem is the Butterworth Filter, which is shown in the schematic it is shown as a hierarchical block. This represents a subcircuit that has two inputs and one output. It takes the signal to be filtered and the power supply for the chip as inputs, and it outputs the filtered input signal. In this case, the signal to be filtered is the output of the instrumentation amplifier.

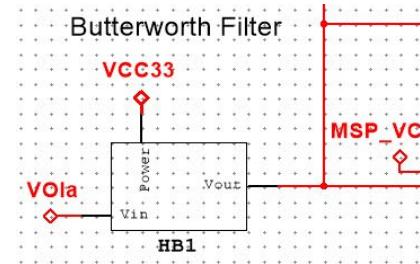


Figure 6. BW Filter subcircuit

The Butterworth filter will be used as an anti-aliasing filter to get rid of high frequency noise while leaving the desired signal unaffected. Using a Sallen-Key configuration, we first calculated the values. As we are sampling at 5 kHz, Nyquist's Theorem states the highest frequency we can sample is 2500 Hz. Since the Butterworth filter is an anti-aliasing filter we expect essentially no signal at 2500 Hz. With a 4th order system, we expect -80 dB of attenuation per decade. Thus we chose a cutoff frequency 1 decade below 2500 Hz, and approximated $-80 \text{ dB} = 0$ signal. Thus $f_c = \sim 250 \text{ Hz}$, 1 decade lower than 2500 Hz. For a 4th order Butterworth with an overall Q of 0.707, the SLOA document outlines that we need the first 2nd order to have a Q of 0.5412 and the second to have a Q of 1.3065.

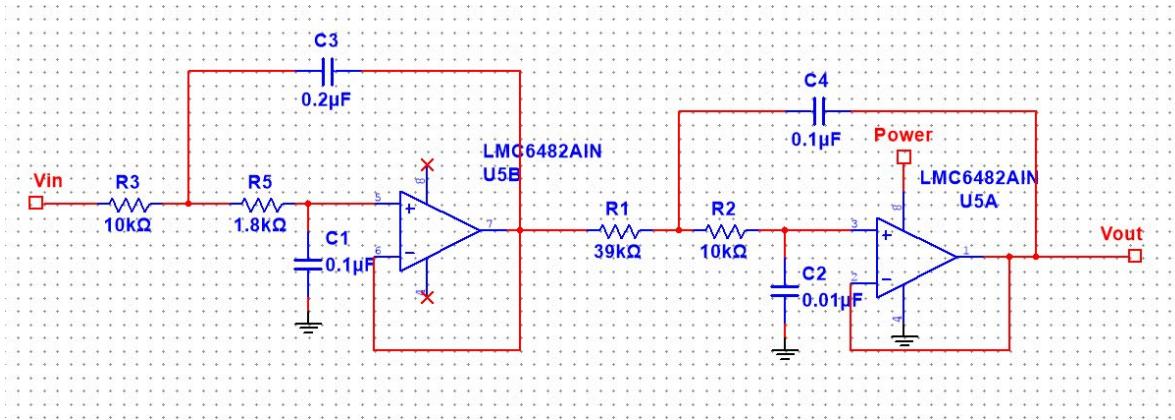


Figure 7. 4th order Butterworth Filter

For the first Sallen-Key, with an ideal Q of 0.542, we chose $C_1 = 0.1\mu F$, $C_3 = 0.2\mu F$, $R_3 = 10k\Omega$ and $R_5 = 1.8 k\Omega$. For the second Sallen-Key, we chose $C_2 = 0.01\mu F$, $C_4 = 0.1\mu F$, $R_1 = 39k\Omega$, and $R_2 = 10k\Omega$. A picture of the hand calculations can be found in the Appendix.

2.3 Subsystem 3: Instrumentation Amplifier

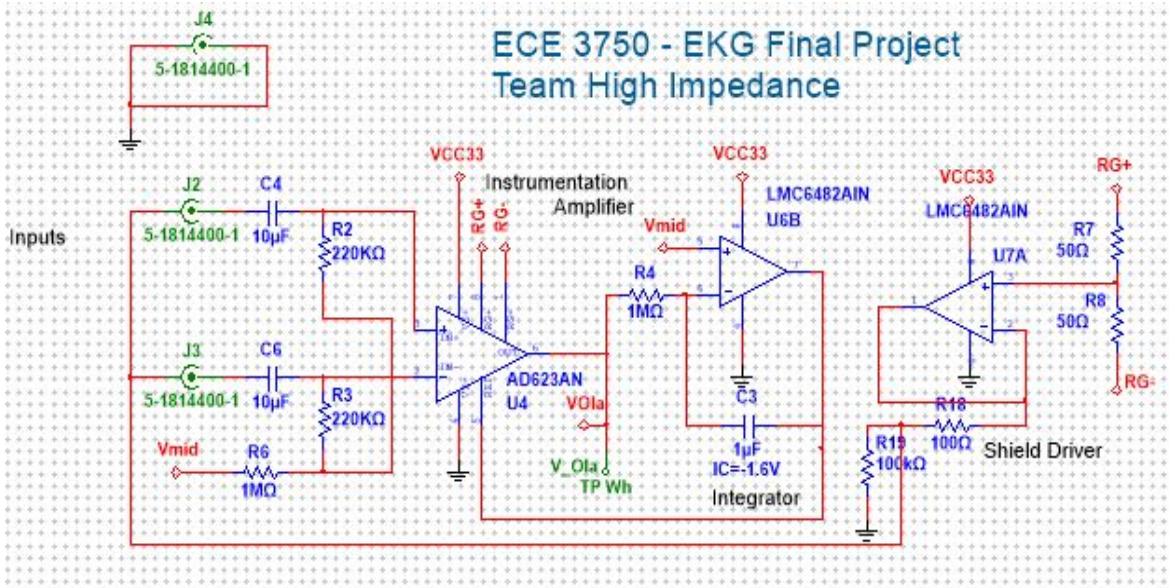


Figure 8. Instrumentation Amplifier subsystem

The instrumentation amplifier subsystem was divided in a couple of parts. First, the inputs J2 and J3 pass through a high pass filter that gets rid of any DC signal from the input before going into the instrumentation amplifier. The input J4 is directly connected to ground because it serves as our reference. After the high pass filter, the signal passes through the instrumentation amplifier that amplifies it 1000

times. This gain is set by the gain-setting resistors R7 and R8. As explained in the requirements for gain section, these resistors should add up to a resistance of 100 Ω in order to achieve a gain of 1000, so we chose two 50 Ω resistors in series. Then, the difference of the amplified output of the instrumentation amplifier and V-mid went through the integrator to take any remaining DC signal in the output, this was then fed back into the reference pin of the instrumentation amplifier and keep the signal centered at V-mid.

3 Simulations

3.1 Time Domain

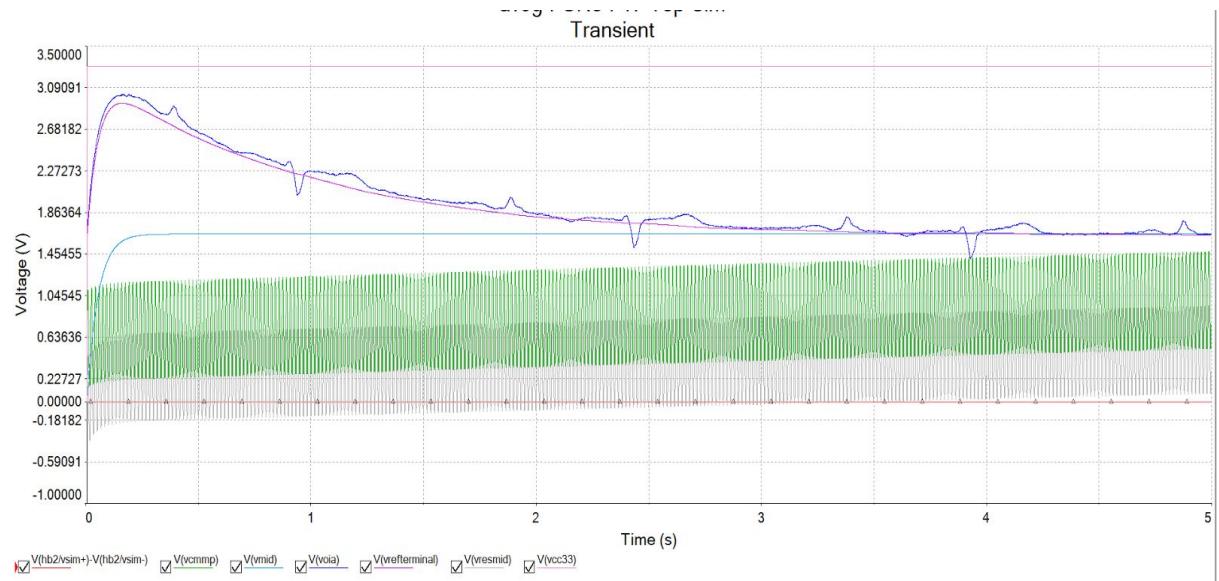


Figure 9. Transient Analysis simulation using LVM files

The initial simulation is shown in Figure 9. In blue we can see the expected output of the instrumentation amplifier which is eventually settling at V-mid. This is the signal that then goes through the Butterworth filter in order to get rid of noise in the signal.

3.2 Frequency Domain

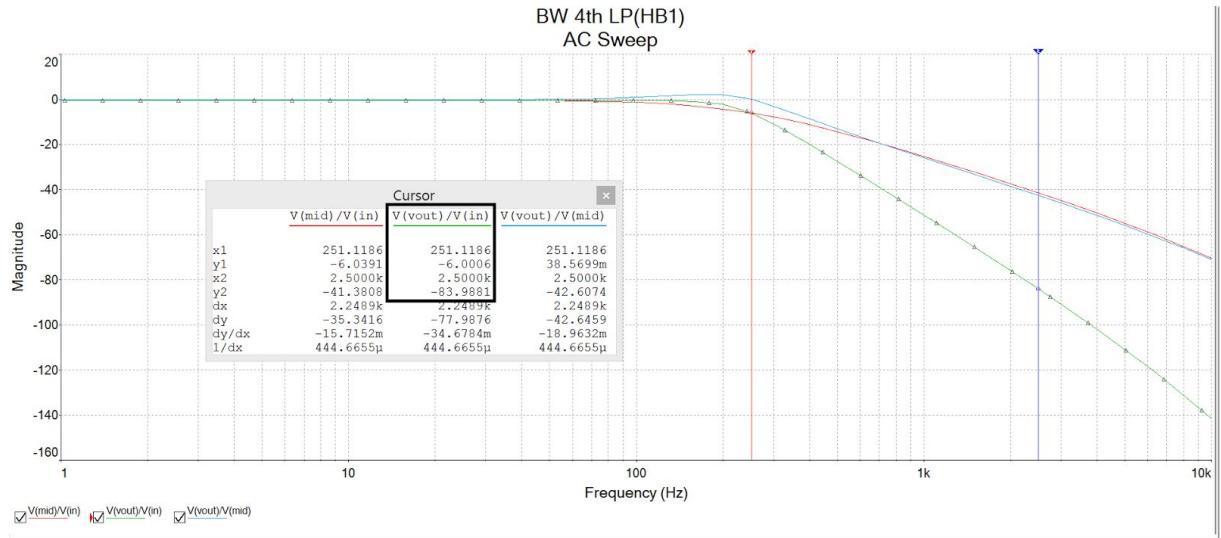


Figure 10. AC Sweep of Butterworth Filter subsystem

After simulating the instrumentation amplifier and saw that it gave us the expected result, we performed a frequency sweep simulation of the Butterworth filter. In Figure 10 we see in red the response of the first stage of the Butterworth filter, and in blue we can see the response of the second stage. These two combined gave the response shown in green and we found the -6 dB frequency (combination of two stages) to be at about 250 Hz as desired.

4 Layout

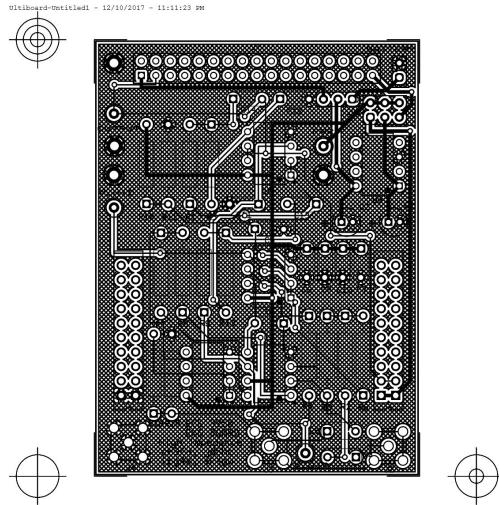


Figure 11. Final Ultiboard design layout

4.1 Silkscreen Top Layer

The components are placed on the silkscreen top layer of the board. The placing of the components were chosen to keep each subsystem as close as possible. We had to take into consideration the distance between the components in order to minimize the length of the tracings.

4.2 Copper Top and Bottom Layers

The copper top layer was where most of the tracing was done. We kept a convention of horizontal tracings in the top layer and vertical tracings in the bottom layer. The width of the tracings were increased for the power tracings.

4.3 Gerber file generation and FreeDFM Submission

When we finished the final design of the layout, we made sure that all of the components were correctly placed and that all of the tracings were correctly connected. We ran a connectivity test and a DRC test and got the results shown in Figure 12.

Connectivity check [Untitled1] - Tuesday, November 7, 2017, 4:13:28 PM
Completed; 0 error(s), 0 warning(s); Time: 0:00.06

DRC and netlist check [Untitled1] - Tuesday, November 7, 2017, 4:13:30 PM
Completed; 0 error(s), 0 warning(s), 0 filtered error(s); Time: 0:00.06

Figure 12. Connectivity and DRC check

At this point we were ready to submit to FreeDFM. We followed the procedure outlined by the instructors and submitted the necessary files and got the results back saying No Show Stoppers.

What FreeDFM found on your design

Show Stoppers

We Found None!

Problems Automatically Fixed

[Insufficient Silkscreen Line Width \(829 violations\)](#)

[1](#) [2](#) [3](#) [4](#) [5](#)

Figure 13. FreeDFM Submission

5 Assembly and Testing.

5.1 Visual Inspection and Soldering

Before the production of the PCB, the group formulated an assembly and test plan, and followed this plan. To start, the components for the power subsection were soldered on. The first step was loading in the connectors for the 5V and 3V3 power, namely J1, J5, J6, and the battery connector. We then visually inspected the power supply portion of the circuit to make sure connectors were firmly in the circuit without any detachments and that they were not damaged on their surface. Additionally, we visually checked for any connectivity issues on the board. The board being tested with the MSP430 is shown in Figure 14.

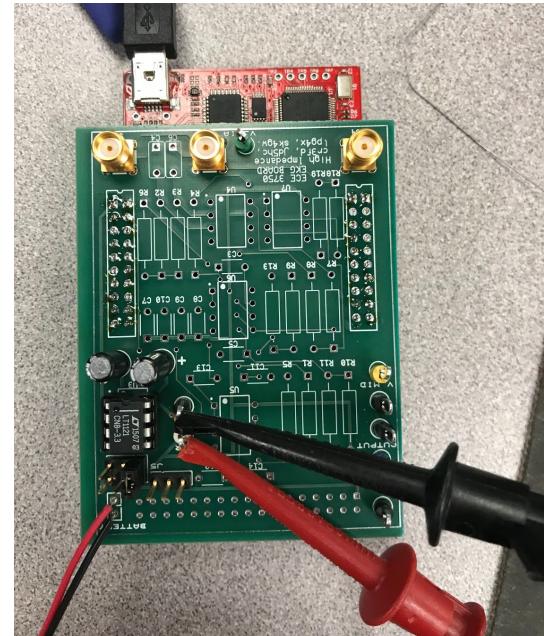


Figure 14 - Testing power subcircuit

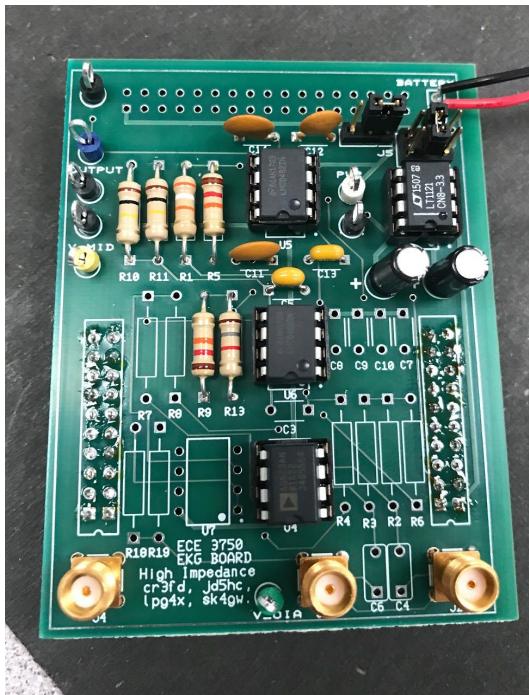


Figure 15 - Butterworth and Power subcircuits soldered onto board

The next part of the power subsystem is Vmid. We soldered in all of the associated components - R10, R11, C5, and U6 - and then placed a DMM on the V_{mid} testpoint. Then, we soldered and tested the Butterworth filter, an independent system. The salien key filters were soldered one at a time. Thus, U5, R9, R13, C11, and C13 were soldered in first. After performing visual inspections on the soldering job and connections, we continued to solder in R1, R5, C12, and C14. The circuit after the Butterworth components were soldered in is shown in Figure 15.

Lastly, we soldered in the components associated with the instrumentation amplifier, which consisted of all of the remaining parts. Again, we soldered in each part - integrator, IA, etc. - individually. We waited until all remaining components were connected before testing. The test plan was followed to ensure the correct order of connection and testing, as with the other subcircuits. The test plan flow charts for all three subcircuits can be found in the appendix. The circuit with all of its components soldered in is displayed in Figure 16.

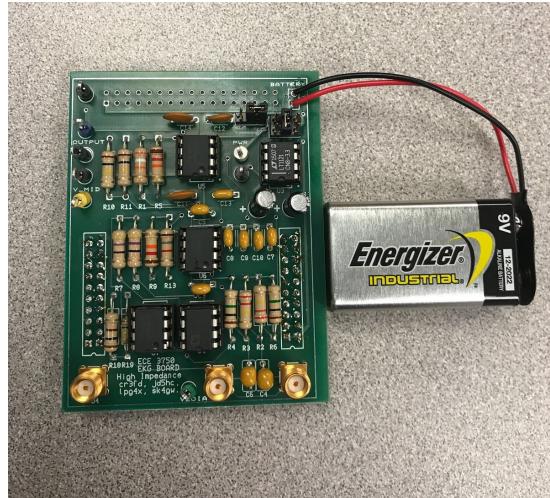


Figure 16 - Completed board soldering

5.2 Verification

To test the power, we plugged in the battery and MSP430 one at a time to their connectors, and placed appropriate jumpers on J5 and J6 to ensure the board received power from the correct source. We placed a digital voltmeter to test at the 3.3V test point. The result, after the voltage regulator, of using a 9V battery as the voltage supply is shown in Figure 17. It is, rounded to the tenths place, exactly 3.3V and what we expected.

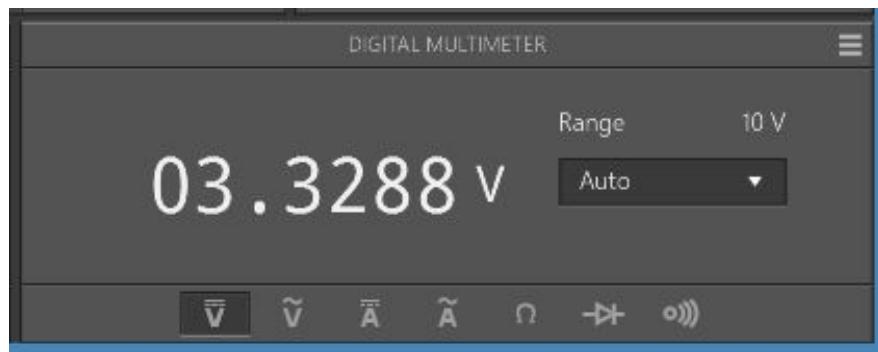


Figure 17 - Power test with battery

The output on the power test point using the MSP430 is in Figure 18. Since it does not go through a voltage regulator, it matches whatever the MSP outputs. In this case, the MSP provided 3.60 V of power, more than the 3.3V we expected. For this reason, we used the battery to test the remaining parts of the circuit.

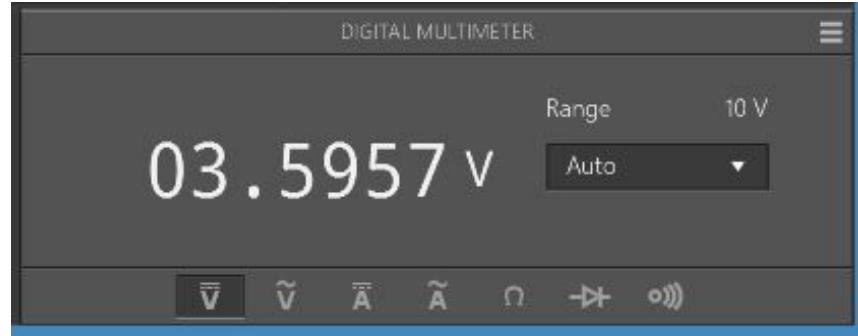


Figure 18 - Power test with MSP

The output on the V-Mid test point using the battery is in Figure 19. We expected about $3.3/2 = 1.65$ V, and read 1.67 V, well within the error bounds associated with the resistors

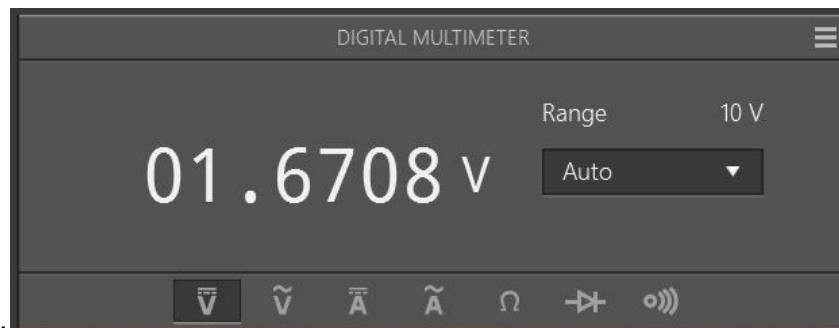


Figure 19 - Vmid test

To test the frequency response of the Butterworth filter, we used the VOIa test point as an input to the system by placing a function generator on the test point and measured the response of the system at the output test point. We first tested the circuit in the bandpass region, and compared it to the expected gain of 1. Next, we tested the circuit at 2500 Hz, and compared it to the expected gain of -80dB. Both of these gave the expected results, so we moved on to an AC sweep between these values. The sweep results are shown in Figure 20. At the cutoff frequency of 250 Hz, the gain was -6.55 dB. Since the circuit cascaded two filters with a fc of 250 Hz, the expected gain at this point was $(-3) + (-3) = -6$ dB. For our purposes, our measured gain was within range. After -40 dB gain, the output signal was too small to measure an amplitude, and at 2500 Hz the signal appeared to be fully attenuated as expected.

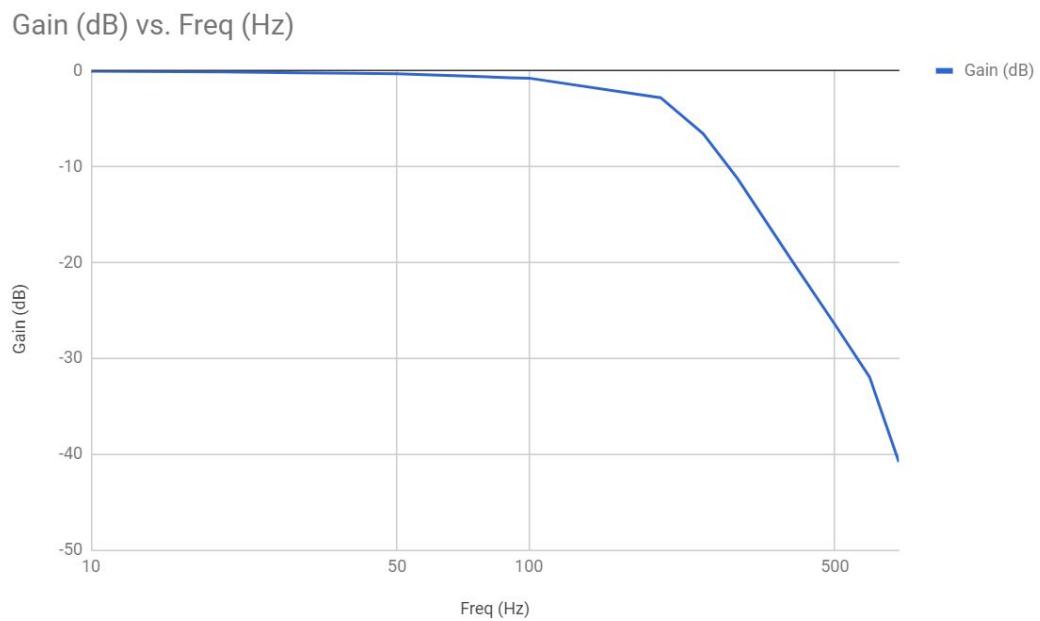


Figure 20 - AC Sweep

5.3 Testing of Assembled Board

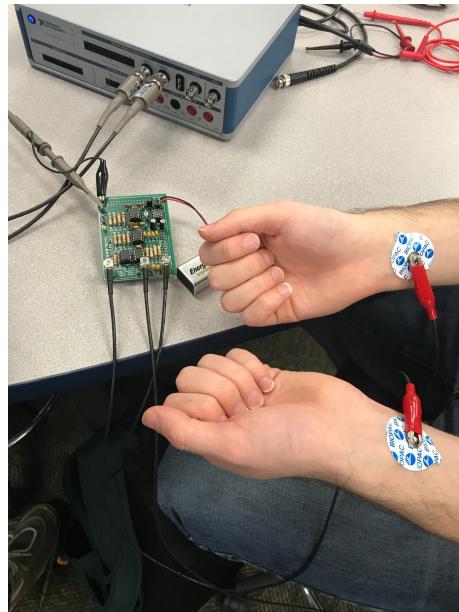


Figure 21

To test the final assembly of the board, we connected the electrodes to a test subject's wrists, and connected a third reference probe to their ankle. We first analysed the output at V_o_IA which was the voltage produced by the instrumentation amplifier. The wave we analysed at this point was as shown in blue in figure 22.



Figure 22

We then used a digital moving average filter to see the signal with no noise, seen in red in figure 23.

Once we had analysed the output of the instrumentation amplifier, we tried analysing the overall output of the board, which produced a filtered version of the signal we observed at V_o_IA. We were anticipating a signal similar to what we measured in our digital filtering, what we got is shown in red in figure 24.

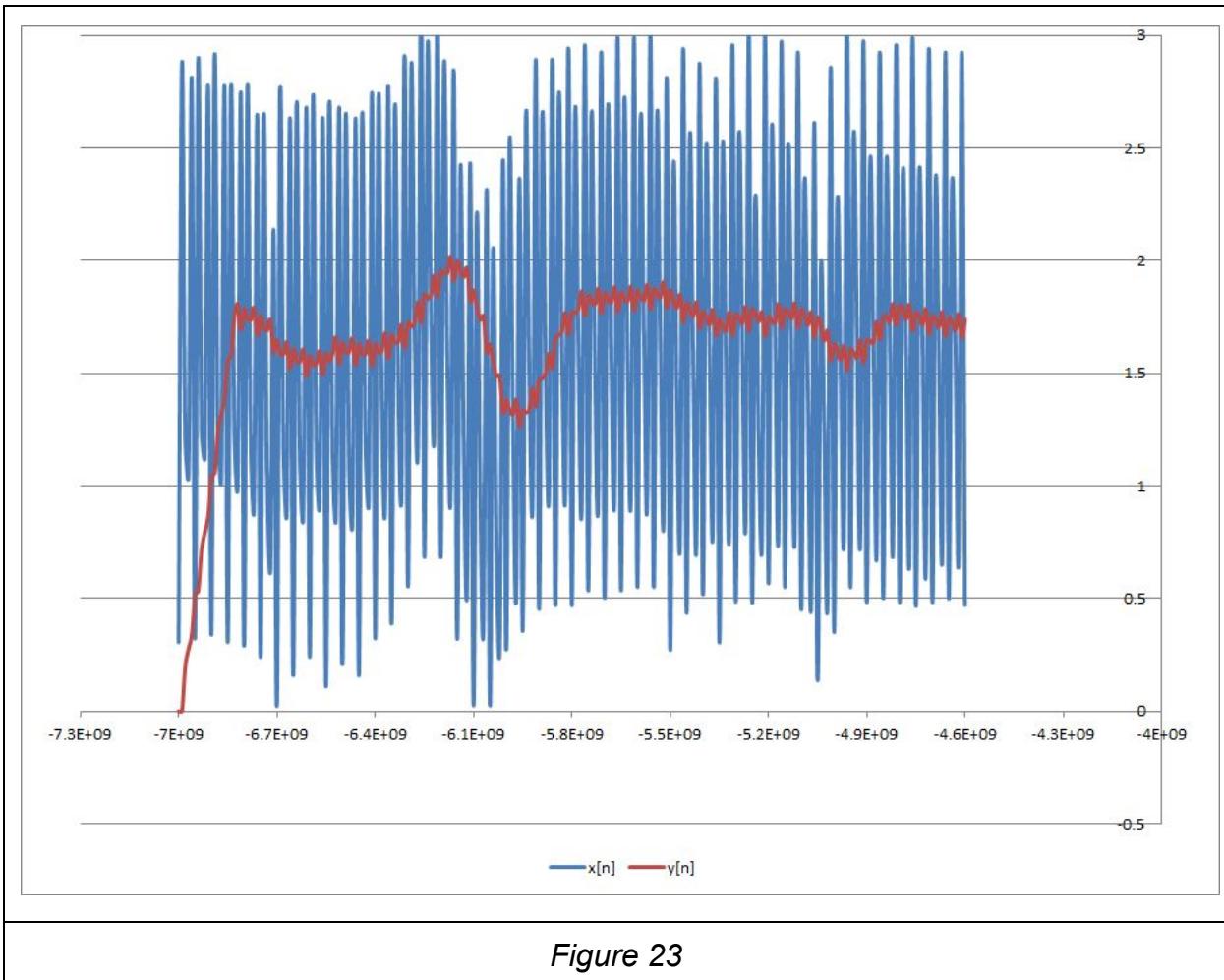




Figure 24

5.3.1 Difficulties

We experienced several difficulties measuring the output from our board. The first problem we experienced was that the signal we were looking for was not discernible from the background noise. We eventually realized that the placement of the probes was not ideal, and after measuring our own pulses with our fingers we found a better spot to place them.

After we successfully measured the output at V_o_IA we struggled to replicate the result from our digital filter in the output of the board itself. We noticed that at times the heart rate was very clear, and then the signal would become indiscernible from noise. We eventually had to settle for capturing a short period of time over which the signal was clear, and discarding the noisy parts.

6 Conclusion

Overall, our board design was aesthetically pleasing and we were happy with the way our project turned out. There were a few errors when designing the board that we didn't anticipate as being critical to our end result. When designing the placement of our components for our design, we should have been more careful when deciding where to

place each filter. As it turns out, we had not anticipated that the placement of our probes would hinder our results. Hence, we were unable to successfully obtain results using the MSP430.

The overall project was very useful in understanding the practical uses in the different filters that we used. In addition, we were able to appreciate the detail it requires to build a circuit of such calibre. The project was useful in understanding the practical uses of such topologies. In addition, we enjoyed the overall purpose of the project. Creating a board that would measure heart rate with such success allowed us to appreciate the practicality of electrical engineering.

For next time, however, we think there should be a strong emphasis on detailing project board before finally executing. We found that our lack of detail caused us to not fully meet our board's potential.

7 Appendix

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

$$Q = \frac{\sqrt{R_1 R_2 C_1 C_2}}{R_1 C_1 + R_2 C_2}$$

For overall $Q=0.707$,
 $Q_1=0.5412$, $Q_2=1.3065$

$$f_c = 250 \quad R_1=mR \quad R_2=R \quad C_1=C \quad C_2=nC$$

$$\Rightarrow f_c = 250 = \frac{1}{2\pi\sqrt{m^2 n^2}} \Rightarrow RC = \frac{1}{500\pi\sqrt{mn}}$$

$$Q = \frac{\sqrt{m^2 n^2}}{mR + RC} = 0.5412 \Rightarrow \frac{\sqrt{mn}}{m+1} = 0.5412 \text{ choose } m=5, n=2.108$$

$$C_1=0.1\mu F \quad C_2=0.2\mu F \quad R = \frac{1}{500\pi\sqrt{mn} \cdot C} = 1460\Omega \rightarrow \text{choose } 1.8k\Omega \quad R_2=5 \cdot R \approx 10k\Omega$$

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} = 265.258 Hz \quad Q = \frac{\sqrt{R_1 R_2 C_1 C_2}}{R_1 C_1 + R_2 C_2} = 0.508$$

$$RC = \frac{1}{500\pi\sqrt{mn}} \quad Q = \frac{\sqrt{mn}}{m+1} = 1.3065 \quad \text{choose } m=4 \quad n=10.668$$

$$C_1=0.01\mu F \quad C_2=0.1\mu F \quad R = \frac{1}{500\pi\sqrt{mn} \cdot C} = 4745 \rightarrow \text{choose } 10k\Omega \quad R_2=4 \cdot R \approx 39k\Omega$$

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} = 254.852 Hz \quad Q = \frac{\sqrt{R_1 R_2 C_1 C_2}}{R_1 C_1 + R_2 C_2} = 1.274$$

