Electrocardiogram Amplifier

Grant Skidmore
Christopher Cheney

November 7, 2019

Contents

1 Design goal

The objective of this lab is to design and test an electrocardiogram (EKG) amplifier that measures, amplifies, and filters differential EKG signals from Ag/AgCl electrodes. The electrodes have a signal of $\pm 300mVDC \pm 1mVAC$ before amplification and a $1.65VDC \pm 1.498VAC$ signal after amplification that is capable of being read by PteroDAQ. The design of this lab requires the usage of an instrumentation amplifier (in-amp) to read the differential electrode signals; the design must incorporate such an in-amp constructed from a minimal number of MCP6004 operational amplifiers (op-amp). Once tested for proper functionality, the EKG amplifier is soldered onto a printed circuit board (PCB) in a more permanent, and stable configuration. The resulting soldered circuit is tested again and recorded voltage vs. time data is filtered with a digital band-pass filter to get a clean EKG output signal. This digital band-pass filter has corner frequencies of $f_{lo} = 0.5$Hz and $f_{hi} = 55$Hz.

2 Background: EKG Waves

While we know that we want to measure an EKG signal, it is important to understand what an EKG signal is in order to understand how to measure it. An EKG signal represents the heart's electrical behavior which can be plotted as a voltage versus time plot. The EKG signals come as a result of a single heartbeat: as blood moves through the heart, different segments of the heart respond to the electrical signals in the heart.

The EKG signal is broken down into 5 main waves. The first wave, the P-wave, is the first part of the heartbeat as the electrical heart signals move down from the SA node at the top left of the heart down toward the AV node. During this wave, the atria are depolarized to push blood through to the ventricles. The next few waves, the Q-, R-, and S-waves, represent the depolarization of the ventricles as they push blood out of the heart. The last wave, the T-wave, is simply the re-polarization of the ventricles as they reset for the next heartbeat.

In order to measure this signal, we need at least three leads attached to the body. We need one lead connected just under each shoulder as well as one node connected to the left hip. The configuration of the connected leads determines the shape and amplitude of the EKG signal. The standard EKG signal shown in Figure 1 corresponds to Lead I where the positive lead (Electrode$_+$) connected to the left shoulder, the negative lead (Electrode$_-$) connected to the right shoulder, and the reference lead (Electrode$_{ref}$) connected to the left hip. Lead II is where the positive lead is connected to the left hip, the negative lead connected to the right shoulder, and the reference node connected to the left shoulder. Lead III is where the positive lead is connected to the left hip, the negative lead connected to the left shoulder, and the reference node connected to the right shoulder.

3 The EKG Amplifier Design

3.1 High-Level Overview

In order to build the circuitry for our EKG amplifier, we must understand what signals we initially expect to see. The overview of our EKG can be seen in our block diagram in Figure 2. There are three different leads that our EKG is able to measure, known as Lead I, Lead II, and Lead III that are generated from the three different electrodes: Electrode$_+$, Electrode$_-$ and Electrode$_{ref}$. First, we must understand the electrodes have a worst-case DC voltage drift of 300mV, due to variations in the sweat and salt concentrations on the user's skin [6]. The electrodes have a maximum AC

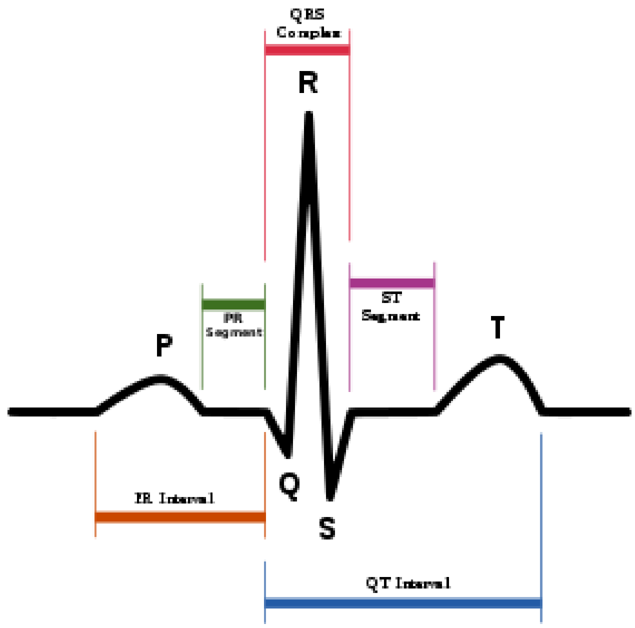


Figure 1: *Standard EKG Signal. This is an ideal voltage versus time EKG signal that we are looking to measure with our EKG amplifier. This signal is measured with the leads connected with the positive lead connected to the left shoulder, the negative lead connected to the right shoulder, and the reference node connected to the left hip.*
Image courtesy of Agateller [1].

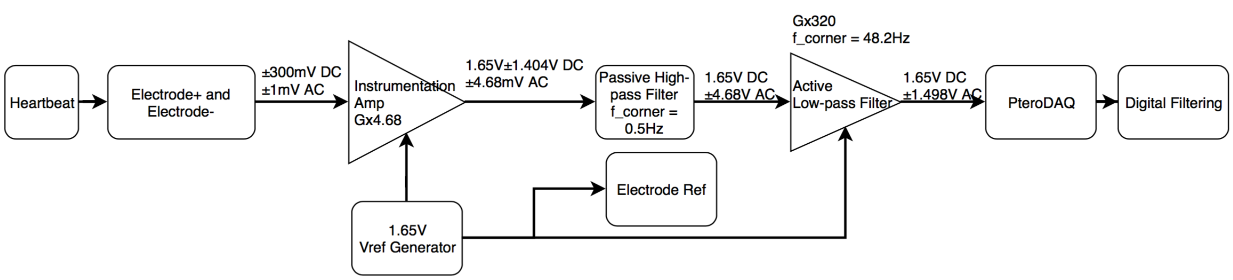


Figure 2: *This is the high-level block diagram of our design. The electrodes read electrical signals from the heart and are amplified by the in-amp first. Then a passive high-pass filter is used to remove DC offset and an active low-pass filter is used to remove 60 Hz noise and amplify the heartbeat signal. Digital filtering is done to obtain a cleaner signal. Figure created with draw.io software [4].*

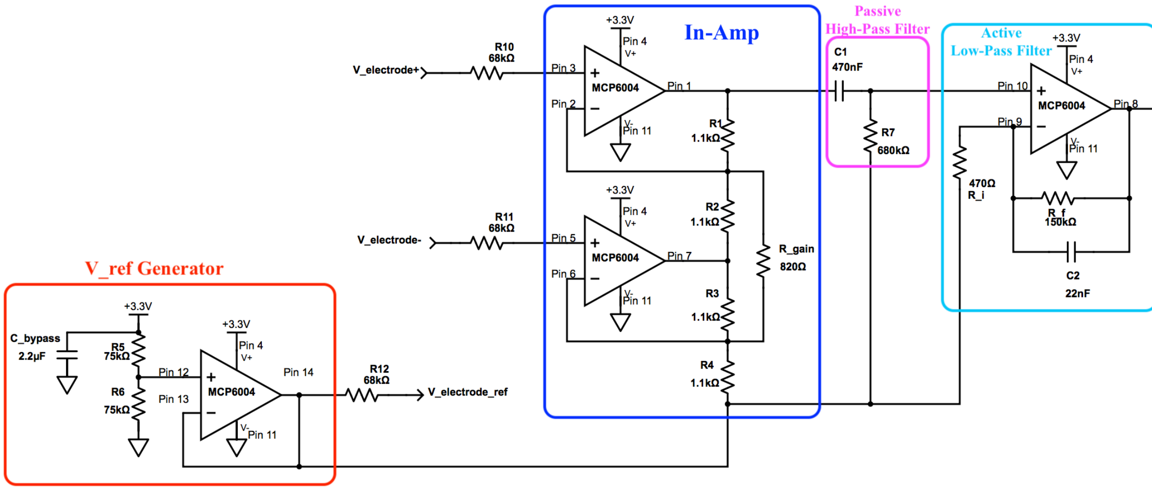


Figure 3: *EKG Amplifier Design. This design amplifies a* $\pm 300mV DC \pm 1mV AC$ *EKG input signal from the Ag-AgCl electrodes to a* $1.65V DC \pm 1.498V AC$ *output signal. The design utilizes a 2 op-amp in-amp that compares and amplifies the differential signal from the positive and negative electrode leads, as well as filters to remove DC drift and 60 Hz noise. Figure made with Digi-Key Scheme-It software [3].*

signal of approximately $\pm 1mV$, which represents the signal caused by the heart which is the signal we are interested in. In order to not get clipping caused by the DC offset, our in-amp gain must be relatively low.

While the in-amp amplifies the signal from the electrodes, the signal is still relatively small and subject to noise. There are two main noise signals that we wish to eliminate or reduce. The first one is to reduce and DC voltage offset caused by movement artifacts with electrodes attached. This can be accomplished by using a passive high-pass filter with an appropriately low corner frequency of $f_c = 0.5$Hz.

The other noise signal that we wish to eliminate is 60 Hz noise caused by electrical signals in the wall outlets in the lab room. We choose to filter out 60 Hz noise using an active low-pass filter with a corner frequency of $f_c = 48.2$Hz. Since this is an active low-pass filter, it contains an appropriate gain to amplify the remaining EKG signal of interest so that it can be read using PteroDAQ. This gain is 320 and will be discussed in Section 3.4.

While the two analog high-pass and active low-pass filters do an adequate job at removing noise, they are not perfect. To get a better filtered response, a digital 2nd-order Bessel filter was applied twice to simulate a band-pass filter with corner frequencies of $f_{lo} = 0.5$Hz and $f_{hi} = 55$Hz. The Python script for this digital filter was taken from Figure 20.6 from *Applied Analog Electronics* [6].

3.2 Instrumentation Amplifier

The EKG amplifier design revolves largely around the instrumentation amplifier. Using the MCP6004 op-amp chip from Microchip Technologies [8], our design is allotted four op-amps from the single chip. With this in mind, we decided to use an instrumentation amplifier design that utilizes only two op-amps rather than a standard three op-amp design. The inputs to the in-amp design are our

EKG electrode signals, which is how we measure a voltage signal from a heartbeat. These electrodes are connected to the positive op-amp terminals of the in-amp via current-limiting resistors. These resistors prevent killing the test subject with a potentially large current from the op-amp while maintaining the same voltage signal.

According to the ANSI/AAMI ES1 - 1993 standard for EKG electrodes, the current through an electrode to a body should be no larger than $50\mu A$ [2, 6]. The minimum resistance to the EKG electrodes from the maximum power supply voltage (3.3V) is given by the Ohm's Law equation,

$$V = IR, \tag{1}$$

which can be arranged to solve for current given a voltage and resistance:

$$R = \frac{V}{I} = \frac{3.3V}{50\mu A} = 66k\Omega.$$

Since we do not have a 66kΩ resistor, we chose to connect 68kΩ resistors to the electrodes from the in-amp.

The design process of the instrumentation amplifier has a couple specific choices. Using Figure 3 as a reference, to simplify the design of the in-amp, we decided to use the same resistor values for R_1, R_2, R_3, and R_4. As a result, our in-amp design simplifies to a single equation in terms of $R_1 = R_2 = R_3 = R_4$, R_{gain}, and our total in-amp gain is

$$V_{out} - V_{ref} = \Big(1 + \frac{R_1}{R_2} + \frac{2R_1}{R_{gain}}\Big)(V_p - V_m), \tag{2}$$

where V_{out} is our instrumentation amplifier gain, V_{ref} is our 1.65V reference voltage, and V_p and V_m are the positive and negative electrode leads respectively. Before we determine our in-amp gain, we need to understand that there is likely to be voltage drift from the electrodes, where the DC voltage offset can be as high as 300mV [6]. Therefore, we need to make sure that our in-amp output input does not clip to either the positive or negative rails as a result of a large gain when we have a maximum voltage offset drift with our ±1mV amplitude input signal [6]. Therefore, we can calculate a maximum gain via the equation:

$$V_{out} - V_{ref} = (Gain_{max})(V_p - V_m). \tag{3}$$

Using this equation, we get a maximum in-amp gain of,

$$Gain_{max} = \frac{3.3V - 1.65V}{300mV + 1mV} = 5.48.$$

This means our in-amp gain must be no greater than 5.48. By equating this calculated maximum gain to Equation 2, we get an equation for R_1 through R_4 as well as R_{gain} given by:

$$Gain_{max} = 2 + \frac{2R_1}{R_{gain}}\,, \tag{4}$$

[6]. Since we want an in-amp gain roughly around 5, we chose to arbitrarily use 1.1kΩ resistors for R_1 through R_4, which gives a value of R_{gain} as:

$$Gain_{max} = 2 + \frac{2(1.1k\Omega)}{R_{gain}} = 5; \quad R_{gain} = \frac{2(1.1k\Omega)}{5-2} = 733\Omega.$$

Since we do no not have a 733Ω resistor, we went with an 820Ω resistor, which brought the gain down slightly. A slightly small in-amp gain makes sure that our in-amp output signal does not result in clipping. Using these component values, we can calculate our actual in-amp gain using Equation 4 as

$$Gain_{max} = 2 + \frac{2(1.1k\Omega)}{820\Omega} = 4.68.$$

When we take this actual gain and our expected input signals, we get an in-amp output of:

$$\text{In-Amp Output} = (\mathbf{1.65V \pm 1.4V})\mathbf{DC} \pm \mathbf{4.68mV} \quad \mathbf{AC}.$$

3.3 High-Pass Filter

Now that we have a rough approximation of our in-amp output, we can design the rest of the circuit. While we would have liked to use an active high-pass filter, the design constrictions of only 2 remaining op-amps means that we resorted to using a passive high-pass filter.

The purpose of the high-pass filter is to remove the DC component of the in-amp output caused by the DC voltage drift of the electrode inputs, while still retaining the 1.65V bias. In order to keep our high-pass filter offset at 1.65V, the reference node at the bottom of the high-pass filter cannot be connected to ground. Instead, it must be connected to V_{ref} to prevent the filter output from being centered at ground. While connected to ground, we would get clipping of the negative signals as PteroDAQ cannot read any signal below 0V. So to retain the full EKG signal and recenter the high-pass filter at 1.65V, we decided to connect the high-pass filter reference to V_{ref} instead of ground.

We want our high-pass filter to have a corner frequency low enough to see an EKG signal, but also block the DC component. For this, we want a corner frequency of roughly 0.5Hz. Therefore, using the following equation for corner frequency,

$$f_c = \frac{1}{2\pi RC}, \tag{5}$$

we can calculate our component values for the RC filter. After choosing a capacitor value of 470nF, we can calculate the resistor value needed to get the correct corner frequency using Equation 5:

$$f_c = \frac{1}{2\pi RC}; \quad R = \frac{1}{2\pi C f_c} = \frac{1}{2\pi 470nF \cdot 0.5Hz} = 677k\Omega.$$

The closest resistor value we have is a 680kΩ resistor, which gives an actual corner frequency of

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi 680k\Omega \cdot 470nF} = 0.50Hz.$$

Taking into account this corner frequency, our high-pass filter output will be **1.65V ± 4.68mV**.

3.4 Active Low-Pass Filter

After the high-pass filter, we have a low-pass filter. The purpose of this filter is to remove the bulk of the noise on the amplifier. The most noise from the input in this amplifier design will come from 60 Hz noise off the power line. The problem is that while the noise may be very small at the input, we are also amplifying the input by a total factor of approximately 1500, so our noise is no longer non-negligible. The low-pass filter, while not perfect, will attenuate out the majority of this 60 Hz noise while keeping the entirety of the EKG signal.

For this low-pass filter, we decided to make it an active non-inverting filter to so we can further amplify our input signal. This means that our signal from the high-pass filter will feed into the positive terminal of the op-amp and the negative terminal will be supplied by V_{ref}. Since we want our final output to be around a 1.5V amplitude to avoid clipping the signal, we can calculate the approximate gain needed for this second gain stage. Since our in-amp has a gain of 4.68, we calculate that our active low-pass filter needs a gain of:

$$Gain_{total} = Gain_{in\ amp} \cdot Gain_{lpf}; \quad Gain_{lpf} = \frac{Gain_{total}}{Gain_{in\ amp}} = \frac{1500}{4.68} = 320.$$

This is a fairly large pass-band gain, so we need to make sure that R_f is significantly larger than R_i. If we arbitrarily use a 150kΩ resistor for R_f, we can calculate what R_i needs to be using the equation for a non-inverting amplifier,

$$Gain = 1 + \frac{R_f}{R_i}; \quad R_i = \frac{R_f}{Gain - 1} = \frac{150k\Omega}{320 - 1} = 470\Omega.$$

Since we actually have a 470Ω resistor, this works out perfectly for an gain of 320.

The corner frequency for the low-pass filter can be calculated in the same way that we calculated the corner frequency for the high-pass filter. This means that we can use Equation 5 to get a component value for the capacitor. For this calculation, we used our high-resistance R_f resistor and a 50Hz corner frequency to attenuate as much of the 60 Hz noise as possible. This gives a value of the capacitor of:

$$f_c = \frac{1}{2\pi RC}; \quad C = \frac{1}{2\pi 150k\Omega \cdot 50Hz} = 2.1nF.$$

Therefore, the actual capacitor value we choose to use is a 2.2nF capacitor which gives an actual corner frequency of:

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi 150k\Omega \cdot 22nF} = 48.2Hz.$$

Now we calculate the output of our low-pass filter, and subsequently our V_{out} for the entire EKG amplifier using the equation for a non-inverting amplifier:

$$V_{out} = V_{ref} + V_{in}\left(1 + \frac{R_f}{R_i}\right) = 1.65V(\pm 4.68mV)(320) = \mathbf{1.65V} \pm \mathbf{1.498V}.$$

3.5 Vref Generator

While the previous three sections have all referenced it, we have not specifically discussed the V_{ref} generator. This is where the final op-amp gets used as a unity gain buffer. We simply want to use a voltage divider to get a signal at $0.5 \cdot V_{dd}$ and run it into the positive terminal of the op-amp. The negative terminal connects directly to the output terminal which basically sets the output signal to the same value as the signal on the positive input terminal.

As for component values here, any large, current-limiting resistor with a resistance >1kΩ will suffice, so we decided to use a pair of 75kΩ resistors. We set them in series and take the voltage out at the node in between the resistors while connecting one to power and one to ground to get a signal at $\mathbf{0.5 \cdot V_{dd} = 1.65V}$. The V_{ref} generator output is then connected to the reference voltage electrode, as well as all three stages to complete the design shown in Figure 3.

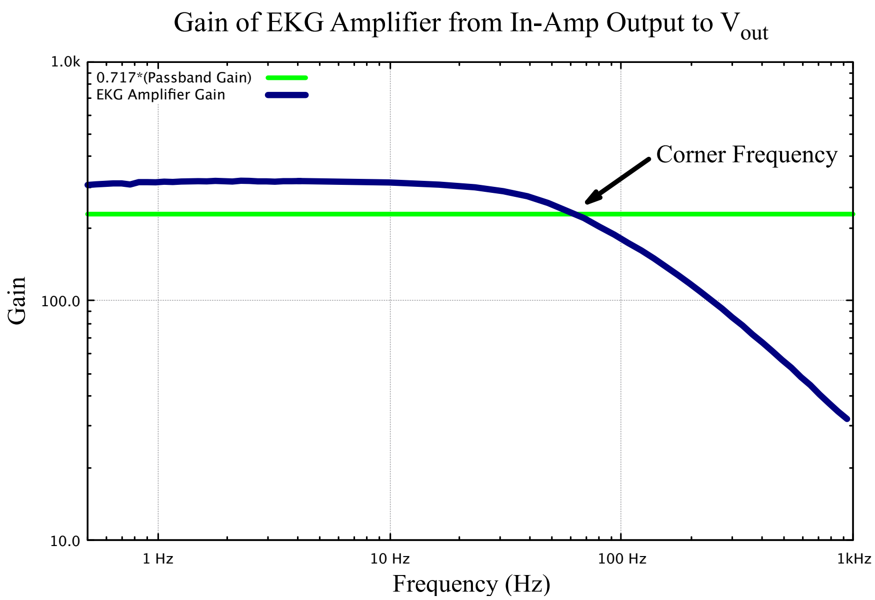


Figure 4: *Plots the gain of the in-amp output to the final output as a function of frequency. The gain attenuates near our higher corner frequency. Since our lower corner frequency is at 0.5Hz, this attenuation is not visible. Figure made with gnuplot software [5].*

3.6 Confirming the Gain using the AD2 Network Analyzer

In order to verify that the gain of our circuit was what we computed, the Analog Discovery 2's Network Analyzer was used. Since the electrodes take in a differential signal, the AD2 was used just to measure the gain after the in-amp to the final output. A voltage divider was used to reduce the input signal to approximately 4.7mV to simulate the output of the in-amp. By measuring the input and the output of the circuit over the frequency range of 0.5Hz to 1kHz, Figure 4 was generated. As expected, the gain in the passband is 320 and the gain begins to attenuate near our corner frequency of 48.2Hz.

4 Soldering and Filtered Results

Our circuit design was soldered onto a PCB as shown in Figure 5. The reference voltage V_{ref} is represented by a white wire and other color wires are used to represent other nodes. Due to a limited number of wire colors, each node could not properly be represented with a different color wire.

The output of our circuit was measured at several points. First, we claimed that we expect the electrodes provided an AC signal of $\pm$1mV [6]. In order to confirm this, the output of the electrode signal was plotted for each Lead in Figure 6. Since the two electrodes (Electrode$_+$ and Electrode$_-$) are differential signals, it was not possible to measure their differential voltage. This was attempted using the differential inputs of the Teensy LC, however it resulted in too much noise to be of any use. Instead, the output of the in-amp was measured. This output was divided by the gain of the in-amp in order to find the signal from the electrodes themselves. At it's maximum amplitude in Lead II, an amplitude of $\pm$1mV is seen, confirming our claim.

As seen in Figure 6a, each of the signals are relatively noisy. This is due to both remaining

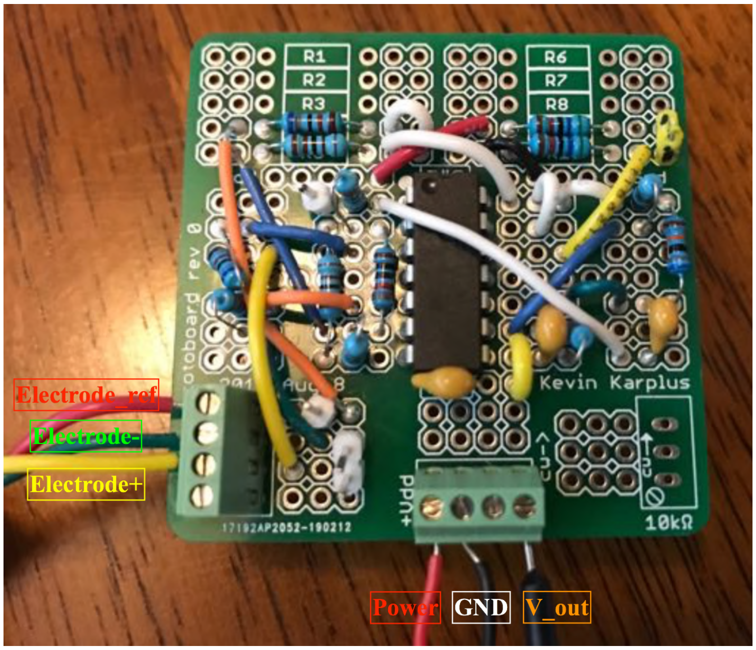
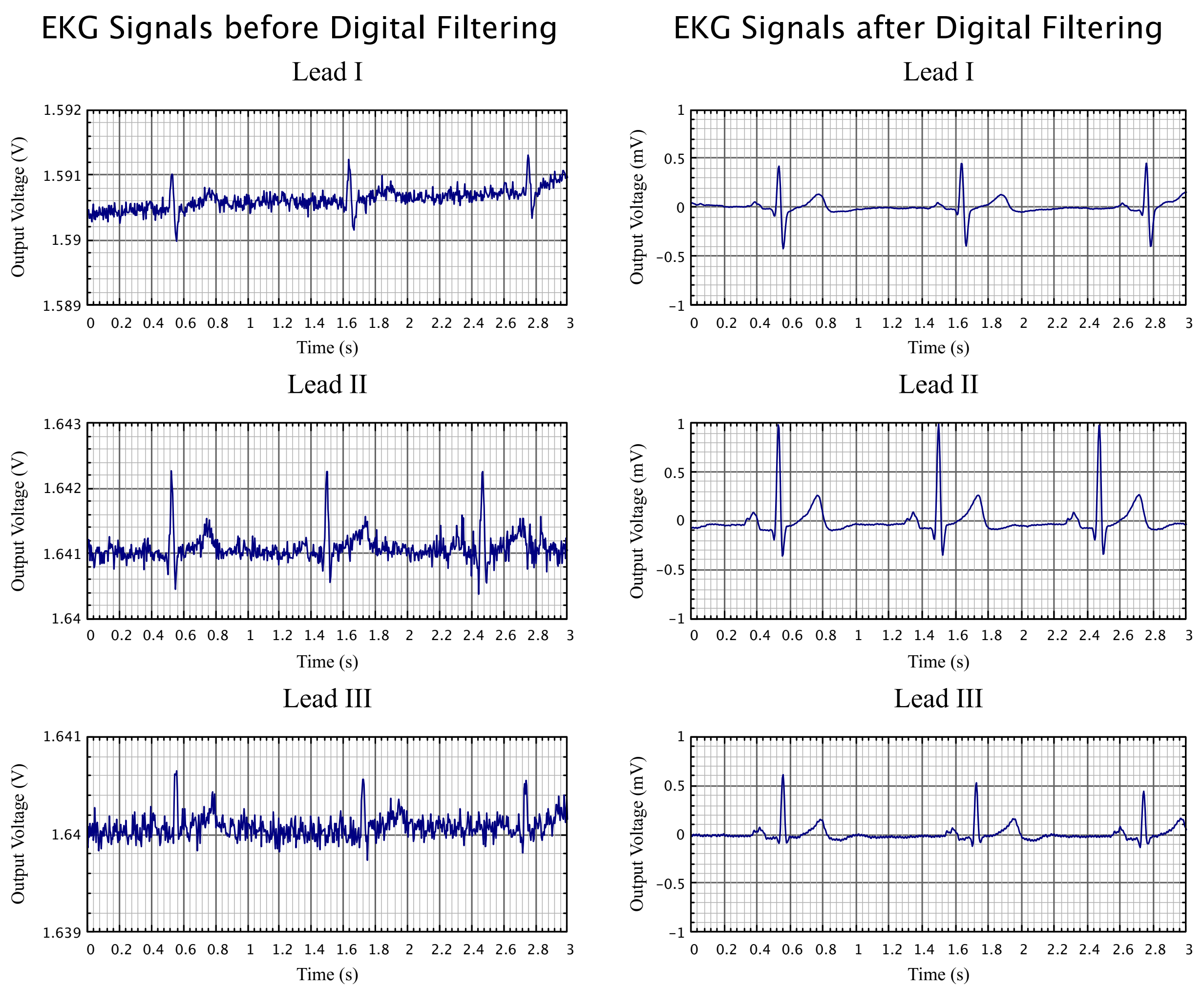


Figure 5: *This shows the soldered EKG amplifier on a PCB designed by Kevin Karplus [7]. The three electrodes, power, ground, and the final output are connected via two screw terminals.*

60 Hz noise and the limited accuracy of the Analog to Digital Converter on the Teensy LC. Lead I experiences a positive DC drift due to movement artifacts during the the recording. In order to reduce this noise, the post-processing was done through a digital band-pass filter. This resulted in a cleaner signal without as much noise and without any DC drift, resulting in a signal centered at 0V as seen in Figure 6b. While each Lead experiences different magnitudes of voltage, all of them exhibit a similar pattern representing the contraction of the heart.

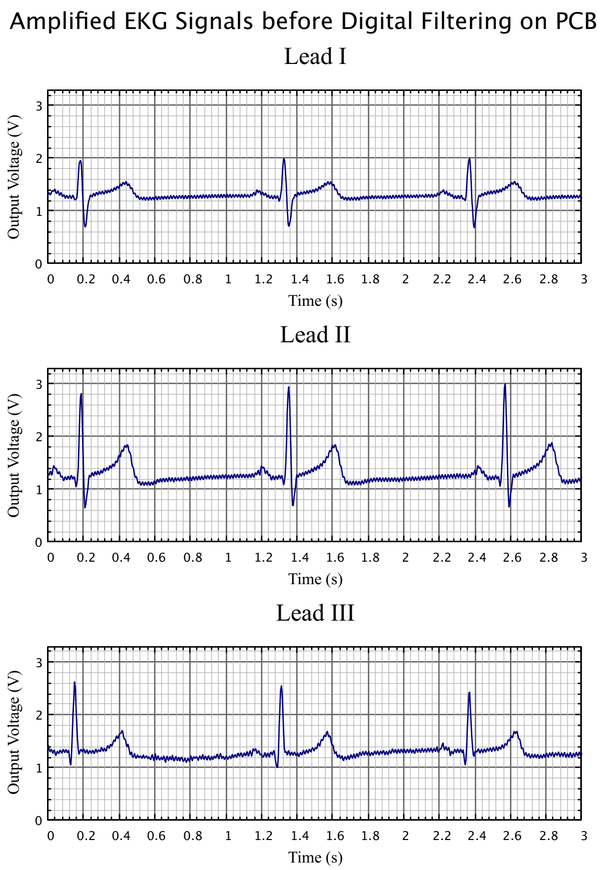
A similar process was done for the final amplified signal, which is seen in Figure 7. Unlike the signal from the electrodes, this signal has been filtered by our high-pass and active low-pass filters resulting in significantly less noise. Again, a band-pass digital filter was used to reduce some of the noise and DC drift that was not filtered out through analog methods. This is shown in Figure 7b and looks very similar to the standard EKG signal of Figure 1.



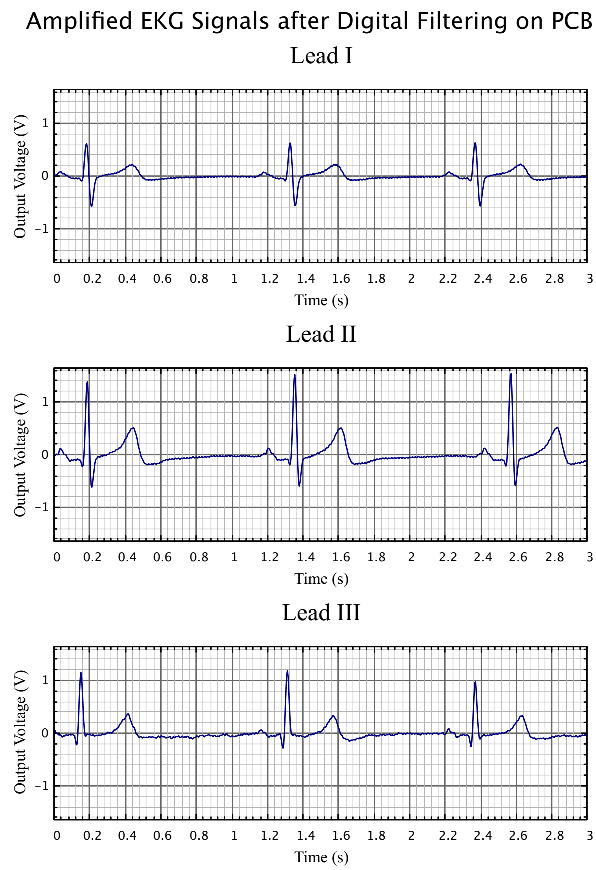
(a) *Before digital filtering. Substantial noise is present due to a small AC signal. DC drift caused by muscle movements in Lead I can be seen.*

(b) *After digital band-pass filter with corner frequencies of* $f_{low} = 0.5Hz$ *and* $f_{high} = 55Hz$. *The DC drift of Lead I has been removed.*

Figure 6: *This figure represents the EKG signals from the electrodes directly before any amplification. This was created by measuring the output of the in-amp and dividing the signal by the in-amp gain. Each Lead corresponds to a different pulse trial. The P-, QRS- and T-waves can all be easily seen. Lead I has a pulse of 54.8 beats/minute (bpm), Lead II has a pulse of 50.3 bpm and Lead III has a pulse of 54.1 bpm. Figure made with gnuplot software [5]. Figure inspired by Figure 41.2 and digital filtering script provided by Figure in 20.6 in* Applied Analog Electronics *[6].*



(a) *Before digital filtering. 60 Hz noise is present still.*



(b) *After digital band-pass filter with corner frequencies of $f_{low} = 0.5Hz$ and $f_{high} = 55Hz$. Most of the noise is removed.*

Figure 7: *This figure represents the EKG signals after all amplification recorded by PteroDAQ. Each Lead corresponds to a different pulse trial. The P-, QRS- and T-waves can all be easily seen. Lead I has a pulse of 53.9 bpm, Lead II has a pulse of 61.7 bpm and Lead III has a pulse of 54.9 bpm. Figure made with gnuplot software [5]. Figure inspired by Figure 41.2 and digital filtering script provided by Figure in 20.6* Applied Analog Electronics *[6].*

5 Conclusion

This EKG amplifier lab revolved around building and testing an EKG amplifier that received signals from EKG electrodes and outputted a cleaned and amplified voltage signal. Said EKG amplifier was mainly comprised of an instrumentation amplifier that compared and amplified the EKG electrodes' differential signals. Following the in-amp are consecutive high-pass and low-pass filters to attenuate out random noise and amplification as well as make the EKG signal visible. The full circuit was then soldered onto a PCB for stability and simplified usage.

After recording voltage vs. time data measured from the output of the EKG amplifier, we ran the recorded data through a digital band-pass filter to precisely remove 60 Hz noise and DC drift, which accounted for the majority of the noise on the EKG electrode signals. After digitally filtering the output signal, we calculated the pulse rate for each of the three lead layouts.

6 Acknowledgements

We received guidance and debugging help from Professor Karplus, and the BME 51B group tutors, Ali Fallahi, Amr Makhamreh and Daniel Brenner.

References

[1] Anthony Atkielski. *Sinus Rythem Labels*. URL: https://en.wikipedia.org/wiki/Electrocardiography#/media/File:SinusRhythmLabels.svg (visited on 06/09/2019).

[2] Enrique Company-Bosch and Eckart Hartmann. *ECG Front-End Design is Simplified with MicroConverter*. URL: https://www.analog.com/en/analog-dialogue/articles/ecg-front-end-design-simplified.html (visited on 06/11/2019).

[3] Digi-Key. *Scheme-It: Free Online Schematic Drawing Tool*. URL: https://www.digikey.com/schemeit (visited on 03/28/2019).

[4] *Draw io*. URL: https://www.draw.io (visited on 04/03/2018).

[5] *GNUPlot Homepage*. URL: http://www.gnuplot.info (visited on 01/14/2019).

[6] Kevin Karplus. *Applied Analog Electronics: a first course in electronics*. LeanPub, 2018. URL: https://leanpub.com/applied_analog_electronics (visited on 06/02/2019).

[7] Kevin Karplus. *Op Amp Proto Board Rev 0*. URL: https://users.soe.ucsc.edu/~karplus/bme51/pc-boards/op-amp-proto-rev0/ (visited on 06/11/2019).

[8] Microchip Technologies. *MCP6004 Operational Amplifier*. URL: http://ww1.microchip.com/downloads/en/DeviceDoc/21733j.pdf (visited on 06/04/2019).

Appendix

A Network Analyzer Script

This script plots the gain of our in-amp output to the final output as a function of frequency. It was used to plot Figure 4.

```
# @Author: Grant Skidmore and Chris Cheney
# @Date: 06/11/19

# @Usage: Plots the transfer function of our EKG amplifier design.
#         Transfer functions are split up by specific block.

load 'definitions.gnuplot'
set style data lines
set xrange[*:*]
unset yrange
unset arrow
unset label

fc = 0.717*321  # 321 is the expected gain
Scale = 2.1

set logscale xy
set title 'Gain of EKG Amplifier from In-Amp Output to V_{out}' font "Times New Roman, 18"
set xlabel 'Frequency (Hz)' font "Times New Roman, 16"
set ylabel 'Gain' font "Times New Roman, 16"
set grid
set key top left Left
set format x "%.0s%cHz"
set format y "%.1s%c"

set arrow from 131, 391 to 71.14, 258.6 lw 3
set label 'Corner Frequency' at 140, 410 font "Times New Roman, 16"

plot fc lw 3 lc 'green' title '0.717*(Passband Gain)', \
        'Network_Analyzer.txt' u 1:3 lw 4 lc 'navy' title 'EKG Amplifier Gain'
```

B Electrode Signal Scripts

B.1 Before Digital Filtering

This script plots the electrode voltages for each of the three Leads before digital filtering is done. It was used to plot Figure 6a.

```
################ LEAD 1 EKG SIGNAL BEFORE DIGITAL FILTERING ################
set style data lines
set xtics 0.2
set mxtics 5
set ytics 0.001
set mytics 5
set style line 1 linetype 1 linecolor rgb "grey40" lw 1
set style line 2 linetype 1 linecolor rgb "grey70" lw 0.5
set grid xtics ytics mxtics mytics ls 1, ls 2
set multiplot layout 3, 1 title "EKG Signals before Digital Filtering" font "Times New Roamn, 20"
set title "Lead I" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[*:*]
plot "Small_Signal_Lead1.txt" u ($1-5.6):((($3-1.59)/(4.68) + 1.59)) lw 1 lc "navy" notitle

################ LEAD 2 EKG SIGNAL BEFORE DIGITAL FILTERING ################
set title "Lead II" font "Times New Roman, 18"
```

```
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[*:*]
set xrange[0:3]
plot "Small_Signal_Lead2.txt" u ($1-0.2):((($3-1.65)/4.68 + 1.65)) lw 1 lc "navy" notitle

################ LEAD 3 EKG SIGNAL BEFORE DIGITAL FILTERING ################
set title "Lead III" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[*:*]
set xrange[0:3]
plot "Small_Signal_Lead3.txt" u ($1-2):((($3-1.65)/4.68 + 1.65)) lw 1 lc "navy" notitle
unset multiplot
```

B.2 After Digital Filtering

This script plots the electrode voltages for each of the three Leads after digital filtering is done. It was used to plot Figure 6b.

```
################ LEAD 1 EKG SIGNAL AFTER DIGITAL FILTERING ################
set style data lines
set xtics 0.2
set mxtics 5
set ytics 0.0005*1000
set mytics 5
set style line 1 linetype 1 linecolor rgb "grey40" lw 1
set style line 2 linetype 1 linecolor rgb "grey70" lw 0.5
set grid xtics ytics mxtics mytics ls 1, ls 2
set multiplot layout 3, 1 title "EKG Signals after Digital Filtering" font "Times New Roamn, 20"
set title "Lead I" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (mV)" font "Times New Roman, 12"
set yrange[-1:1]
set xrange[0:3]
plot "Small_Signal_Lead1_Filtered.txt" u ($1-5.6):($3/320/4.68*1000) lw 1 lc "navy" notitle

################ LEAD 2 EKG SIGNAL AFTER DIGITAL FILTERING ################
set title "Lead II" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (mV)" font "Times New Roman, 12"
set yrange[-1:1]
set xrange[0:3]
plot "Small_Signal_Lead2_Filtered.txt" u ($1-0.2):($3/320/4.68*1000) lw 1 lc "navy" notitle

################ LEAD 3 EKG SIGNAL AFTER DIGITAL FILTERING ################
set title "Lead III" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (mV)" font "Times New Roman, 12"
set yrange[-1:1]
set xrange[0:3]
plot "Small_Signal_Lead3_Filtered.txt" u ($1-2):($3/320/4.68*1000) lw 1 lc "navy" notitle
unset multiplot
```

C Final EKG Output Signal Scripts

C.1 Before Digital Filtering

This script plots the final EKG output voltages for each of the three Leads before digital filtering is done. It was used to plot Figure 7a.

```
################ LEAD 1 BEFORE DIGITAL FILTERING ################
set style data lines
set multiplot layout 3, 1 title "Amplified EKG Signals before Digital Filtering on PCB" \
        font "Times New Roamn, 17"
set title "Lead I" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[0:3.3]
set xrange[0:3]
plot "Final_Heartbeat_Lead1_Trial2.txt" u ($1-11.5):2 lw 1 lc "navy" notitle

################ LEAD 2 BEFORE DIGITAL FILTERING ################
set title "Lead II" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[0:3.3]
set xrange[0:3]
plot "Final_Heartbeat_Lead2.txt" u ($1-10.5):2 lw 1 lc "navy" notitle

################ LEAD 3 BEFORE DIGITAL FILTERING ################
set title "Lead III" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[0:3.3]
set xrange[0:3]
plot "Final_Heartbeat_Lead3.txt" u ($1-10.5):2 lw 1 lc "navy" notitle
unset multiplot
```

C.2 After Digital Filtering

This script plots the final EKG output voltages for each of the three Leads after digital filtering is done. It was used to plot Figure 7b.

```
################ LEAD 1 AFTER DIGITAL FILTERING ################
set style data lines
set multiplot layout 3, 1 title "Amplified EKG Signals after Digital Filtering on PCB" \
        font "Times New Roamn, 17"
set title "Lead I" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[-1.65:1.65]
set xrange[0:3]
plot "Final_Heartbeat_Lead1_Trial2_Filtered.txt" u ($1-11.5):3 lw 1 lc "navy" notitle

############### LEAD 2 AFTER DIGITAL FILTERING ################
set title "Lead II" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[-1.65:1.65]
set xrange[0:3]
```

```
plot "Final_Heartbeat_Lead2_Filtered.txt" u ($1-10.5):3 lw 1 lc "navy" notitle

################ LEAD 3 AFTER DIGITAL FILTERING ################
set title "Lead III" font "Times New Roman, 18"
set xlabel "Time (s)" font "Times New Roman, 12"
set ylabel "Output Voltage (V)" font "Times New Roman, 12"
set yrange[-1.65:1.65]
set xrange[0:3]
plot "Final_Heartbeat_Lead3_Filtered.txt" u ($1-10.5):3 lw 1 lc "navy" notitle
unset multiplot
```