Electrocardiogram Circuit

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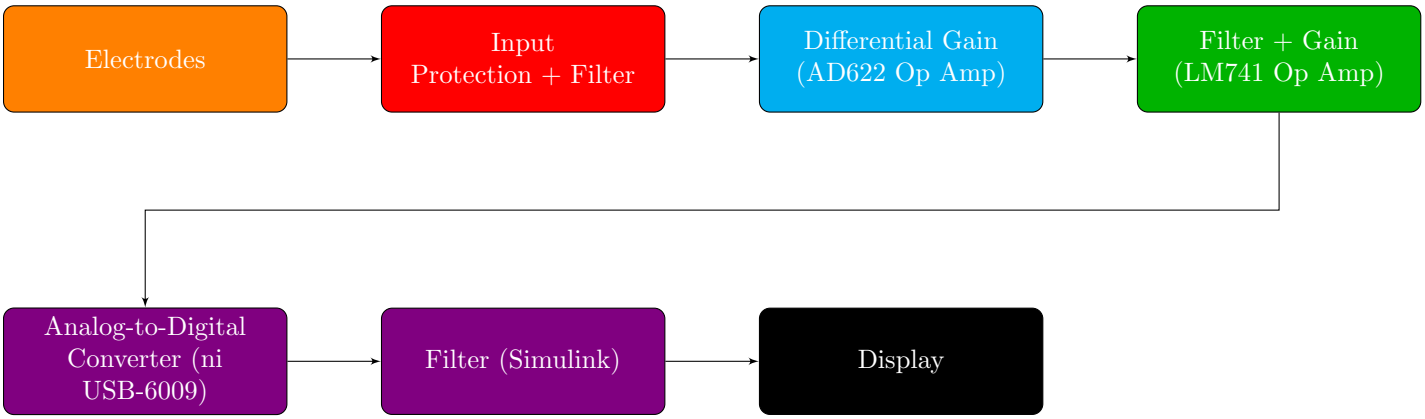
Biomedical Instrumentation Background

The heart generates bioelectric signals as it pumps blood throughout the body. These signals are crucial for understanding how the heart functions. Electrocardiograms (ECGs) are designed to capture these signals and display them to the user for further analysis of heart function.

Below is a flowchart illustrating how an ECG circuit works. The circuit measures the heart's electrical activity using Ag/AgCl electrodes attached to a human subject. These signals are then sent to hardware that amplifies and filters them. The processed signals are subsequently transmitted to an analog-to-digital converter (ADC), where they undergo further filtering with software to display an artifact-free signal.



An ECG circuit performs several functions: sensing, amplifying, and filtering biopotentials from the heart. An ECG signal is low level and relatively high impedance due to the skin and electrodes, but it is important to maintain high fidelity. Figures 1 and 2 illustrate the schematic of the ECG circuit designed and its layout on a breadboard, respectively. Each circled section of the circuit is color-coded to correspond to specific areas in the flowchart. The first part of the circuit in Figure 1, circled in red and blue, includes the biopotential amplifier, input protection, and filters. The second part of the circuit in Figure 1, circled in green, contains an active, non-inverting, bandpass filter.

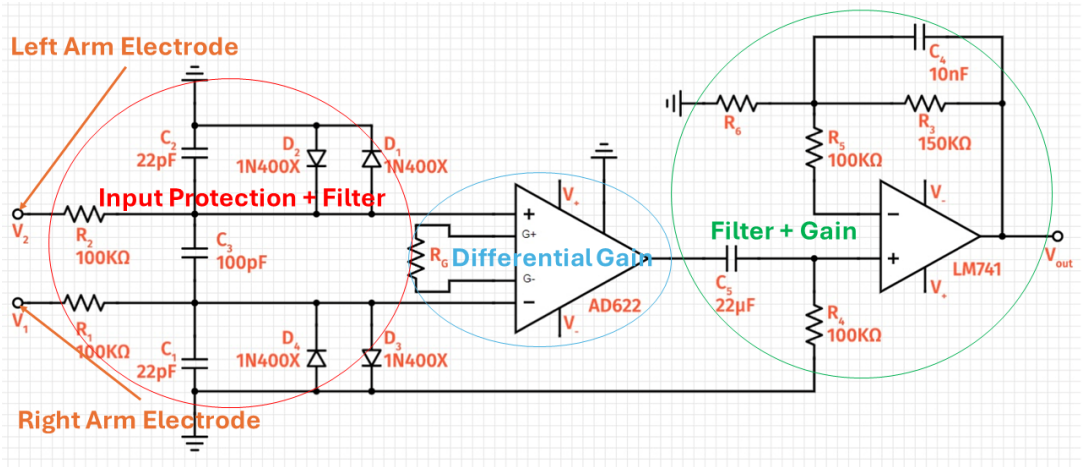


Figure 1: ECG Circuit Schematic

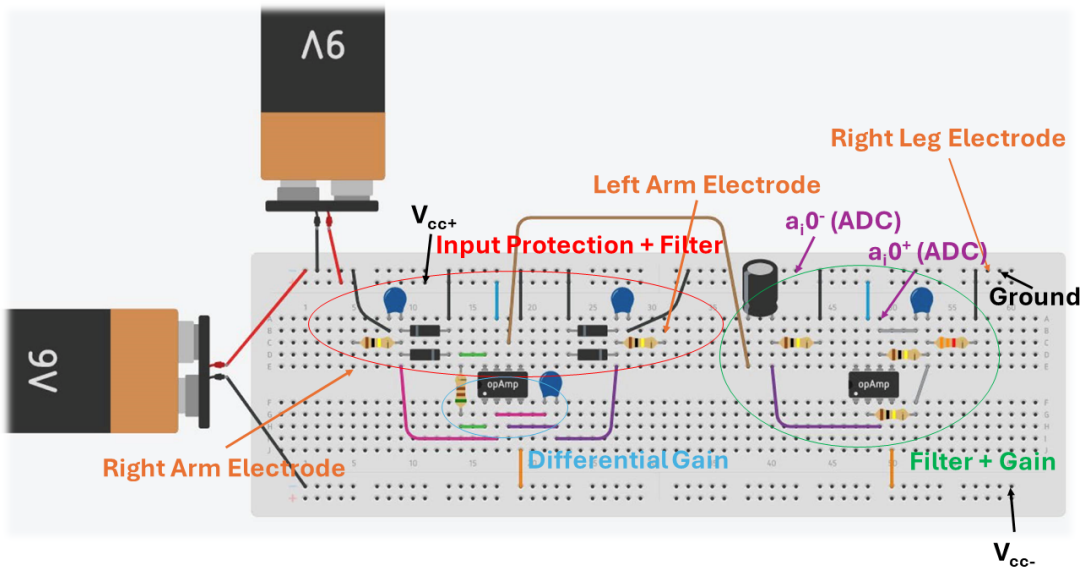


Figure 2: Virtual ECG Circuit Layout on a Breadboard Designed with Autodesk Tinkercad

Electrode placement is key to understanding the complete magnitude and direction of the biopotential. The simplest ECGs use three electrodes in a triangle configuration known as Einthoven's triangle. In this configuration, one electrode is placed on each arm and the last electrode is placed on the left leg or foot, as shown in Figure 3.

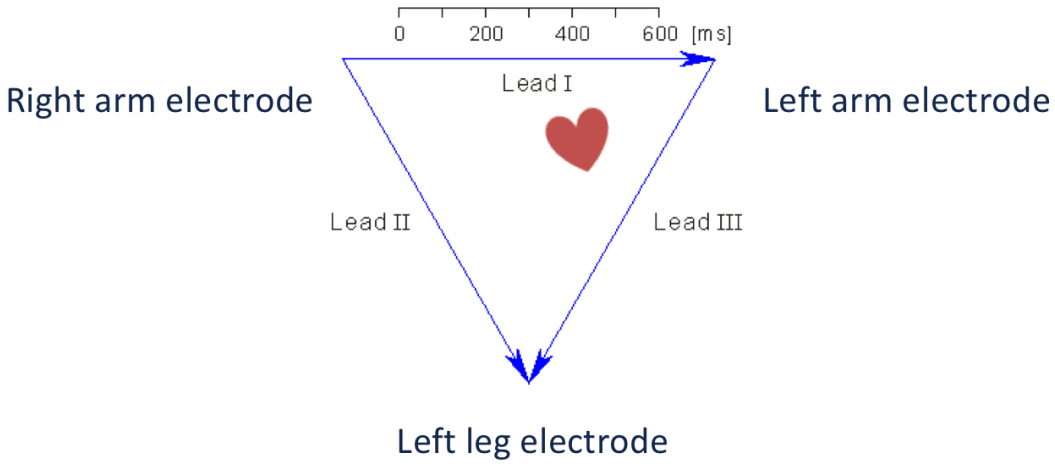


Figure 3: Einthoven's triangle with heart and ECG leads

Lead I is from the right arm to the left arm, lead II is from the right arm to the left leg, and lead III is from the left arm to the left leg. In each of these leads, direction matters because it defines which direction is a positive biopotential. Therefore, when building the ECG circuit, it was crucial to connect the correct lead to the non-inverting (positive) input of the instrumentation amplifier and the correct lead to the inverting (negative) input. More advanced ECGs have additional electrodes and up to 12 leads to fully understand the biopotential in all three dimensions. However, to simplify the circuit, only one lead was measured.

Biopotential Amplifier

The biopotential amplifier, circled in red and blue in Figure 2, accomplishes the following:

- High input impedance due to the 100 kΩ resistors and high input impedance of the AD622 instrumentation amplifier.
- Protection against high voltages at the inputs due to the diodes that can shunt dangerous currents to ground.
- Low output impedance to drive additional amplification and filtering.

- High gain in the frequency range (DC-1000 Hz) of interest.
- Differential amplification with a high common-mode rejection ratio due to the CMRR of the AD622 and the high tolerance (1%) input resistors.

The input circuitry is designed to protect both instrumentation and patients from high voltage shocks. The diodes ensure that the inputs to the amplifier cannot become greater than the turn-on voltage of the diodes. The capacitors offer a low impedance path to ground for voltage spikes while the resistors dissipate the energy from the shocks as heat. Additionally, the combinations of resistors and capacitors provide some initial low-pass filtering of the signals.

For the biopotential amplifier, a gain of 100 V/V is desired. According to the datasheet for the AD622, the equation for the gain is:

$$G = 1 + \frac{50.5\text{k}\Omega}{R_G} \tag{1}$$

As shown in Figure 2, R_G was selected to be 511 Ω. Substituting this value into the equation yields:

$$G = 1 + \frac{50.5 \cdot 10^3}{511} = 98.826 \tag{2}$$

This is within a 1% error margin of the desired 100 V/V.

To confirm the gain of the biopotential amplifier, a function generator was used to input a sinusoidal signal with a frequency of 100 Hz and an amplitude of 105 mV. V_2 was connected to ground (GND), while V_1 was connected to the function generator. The output of the biopotential amplifier is shown in Figure 4.

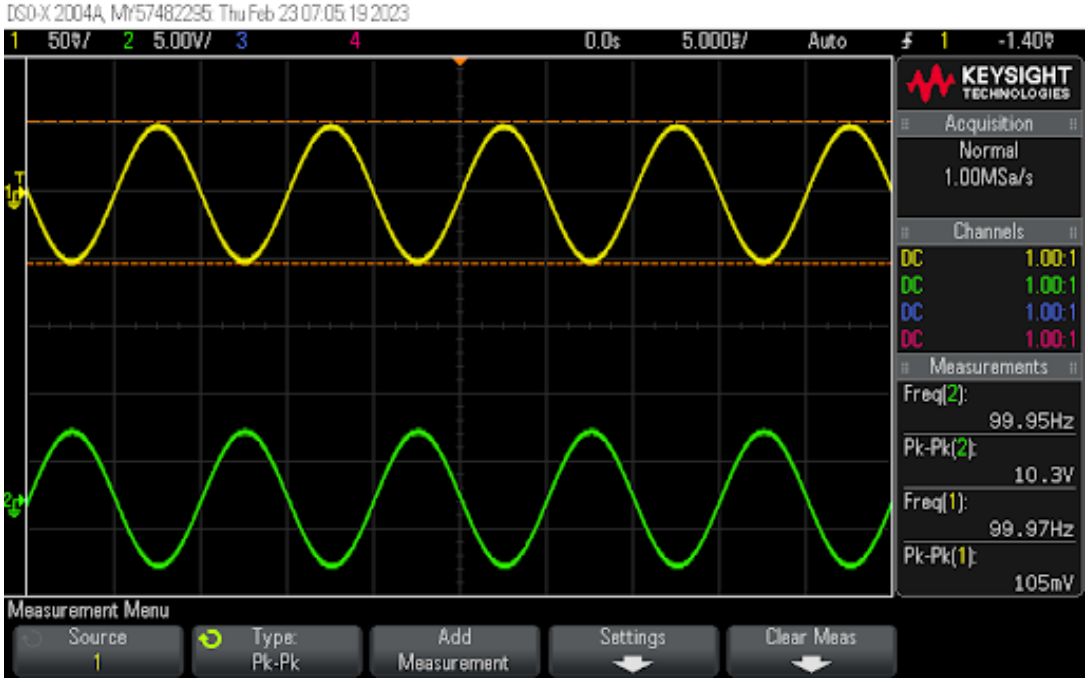


Figure 4: BenchVue Capture for Confirming Gain of Biopotential Amplifier

$$G = \frac{V_{\text{out}}}{V_{\text{in}}}$$

As seen in Figure 4, $V_{\text{out}} = 10.3\,\text{V}$ and $V_{\text{in}} = 0.105\,\text{V}$. Thus,

$$G = \frac{10.3}{0.105} = 98.095$$

The gain of the biopotential amplifier is as expected. As previously mentioned, the biopotential amplifier provides initial low-pass filtering. To determine the cutoff frequencies of the biopotential amplifier, the AD622 datasheet was referenced, which provides two equations for these frequencies. The first equation determines the cutoff frequency formed by R_2, C_2,

and C_3, which affects only the differential voltage. The second equation determines the cutoff frequency formed by R_1 and C_1, which affects only the common-mode voltage.

$$f_{c,\text{diff}} = \frac{1}{2\pi R_2(2C_3 + C_2)} \tag{3}$$

$$f_{c,\text{cm}} = \frac{1}{2\pi R_1 C_1} \tag{4}$$

Based on the Figure 1, $R_2 = 100\,\text{k}\Omega$, $C_2 = 22\,\text{pF}$, and $C_3 = 100\,\text{pF}$. Plugging these values into $f_{c,\text{diff}}$ yields:

$$f_{c,\text{diff}} = \frac{1}{2\pi \cdot (100 \cdot 10^3) \cdot (2(\cdot 100 \cdot 10^{-12}) + 22 \cdot 10^{-12})} = 7,169.14\,\text{Hz} \tag{5}$$

Similarly, based on Figure 1, $R_1 = 100\,\text{k}\Omega$ and $C_1 = 22\,\text{pF}$. Plugging these values into $f_{c,\text{cm}}$ yields:

$$f_{c,\text{cm}} = \frac{1}{2\pi \cdot (100 \cdot 10^3) \cdot (22 \cdot 10^{-12})} = 72,343.15\,\text{Hz} \tag{6}$$

The biopotential amplifier's differential mode filtering, with a cutoff frequency of 7,169.14 Hz, attenuates high-frequency noise in the heart signal, ensuring a clean measurement. The common-mode filtering, with a cutoff frequency of 72,343.15 Hz, reduces environmental interference affecting both inputs equally. These filtering mechanisms ensure that the ECG signal is primarily composed of relevant biopotentials from the heart.

Figure 5 shows the test to confirm the input diodes turn on properly and to determine when this happens. A probe was placed at the circuit's input and another at the input of the AD622. The signal from the function generator was increased while observing the oscilloscope. The output voltage, capped at 800 mV, is shown in green.

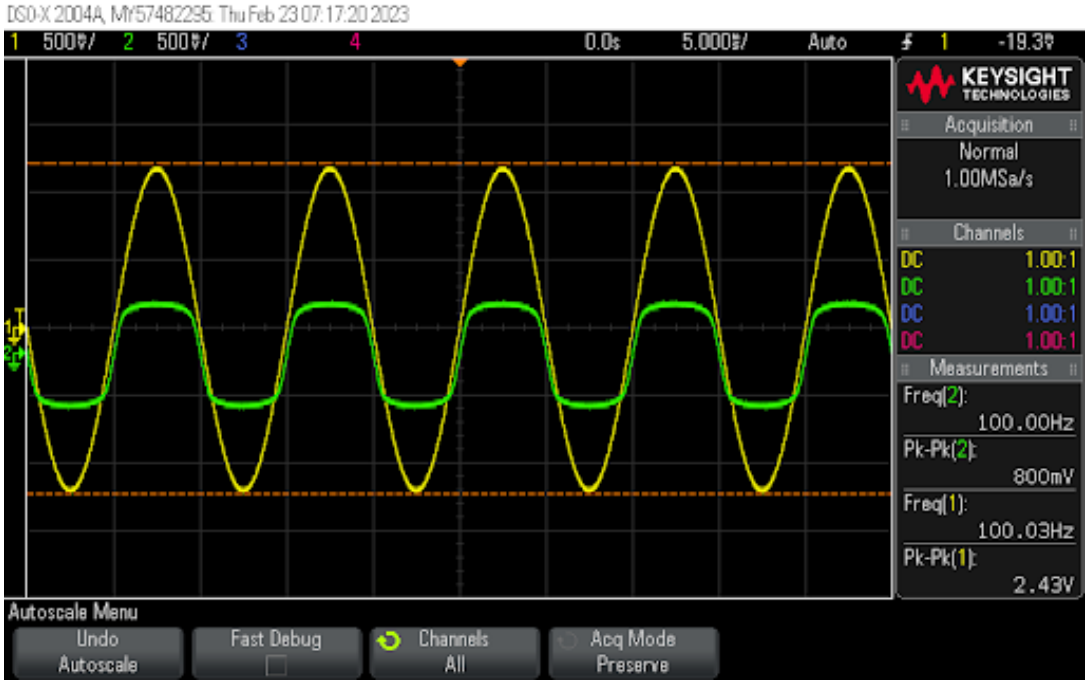


Figure 5: BenchVue Capture for Confirming Gain of Biopotential Amplifier

Bandpass Filter & Gain

To measure the ECG, the output of the biopotential amplifier required additional gain and filtering. This was achieved using the active bandpass filter, circled in green in Figure 1.

The capacitor C_5 and resistor R_4 combine to make the high-pass part of the filter. The capacitor C_4 and resistors R_3 and R_6 combine to make a non-inverting low-pass filter to complete the bandpass filter.

The gain of the bandpass filter can be calculated using the following formula:

$$G = 1 + \frac{R_3}{R_6}$$

Given $R_3 = 150\,\text{k}\Omega$ and $R_6 = 5.1\,\text{k}\Omega$, plugging in the values:

$$G = 1 + \frac{150 \cdot 10^3}{5.1 \cdot 10^3} = 30.4$$

Given that the gain of the AD622 is 100 and the gain of the LM741 is 30, the overall gain of the circuit is 3000.

The equation for the cutoff frequency of the high-pass filter is:

$$f_{c,\text{hp}} = \frac{1}{2\pi R_4 C_5} \tag{7}$$

Based on the figure, $R_4 = 100\,\text{k}\Omega$ and $C_5 = 22\,\mu\text{F}$. Plugging these values in:

$$f_{c,\text{hp}} = \frac{1}{(100 \cdot 10^3) \cdot (22 \cdot 10^{-6})} = 0.455\,\text{Hz} \tag{8}$$

The equation for the cutoff frequency of the low-pass filter is:

$$f_{c,\text{lp}} = \frac{1}{2\pi R_3 C_4} \tag{9}$$

Based on the figure, $R_3 = 150\,\text{k}\Omega$ and $C_5 = 10\,\text{nF}$. Plugging these values in:

$$f_{c,\text{lp}} = \frac{1}{(150 \cdot 10^3) \cdot (10 \cdot 10^{-9})} = 106.1\,\text{Hz} \tag{10}$$

Thus, signals with frequencies above 0.455 Hz and below 106.1 Hz will pass through unattenuated.

Analog-to-Digital Conversion

Although the hardware provides initial filtering of the ECG signal, further filtering with software is necessary to attenuate 60 Hz power-line interference. To acquire the analog data and send it to the PC for processing, a data acquisition (DAQ) device must perform the analog-to-digital conversion.

There are two steps to the conversion from analog to digital. The first step is sampling and the second is digitization. It might seem intuitive to sample as often as possible; however, practical limitations, such as hardware constraints in the ADC and the available data storage on the device, must be considered when determining a sample rate. The maximum sample rate in the NI USB-6009 DAQ is 48 kHz (or kS/s). Oversampling, which involves processing a signal at a frequency higher than twice its bandwidth, helps avoid aliasing. The primary reason for oversampling is to achieve a high-resolution signal, which is crucial for capturing an accurate shape of the ECG signal. Given that the low-pass cutoff frequency is 106 Hz, the minimum sampling frequency should be 212 Hz. Ideally, the sampling frequency should be 2-5 times the Nyquist frequency, so approximately 500 Hz is optimal.

To begin capturing the ECG signal, Ag/AgCl electrodes were attached to the subject's right arm, left arm, and left leg. Once the electrodes were in place, the analog ECG signal was sampled, completing the first step. The second step was digitization, which involved converting each voltage sample into a digital representation for storage, where voltage values were encoded as binary numbers.

The NI USB-6009 DAQ handled this conversion and sent the digital signal to a bandstop filter, as depicted in Figure 6. This filter allowed frequencies above and below 60 Hz to pass while attenuating the 60 Hz frequency. Both the raw signal and the filtered signal were then sent to the scope and spectrum analyzer block to display the ECG and power spectrum, as shown in Figure 7.

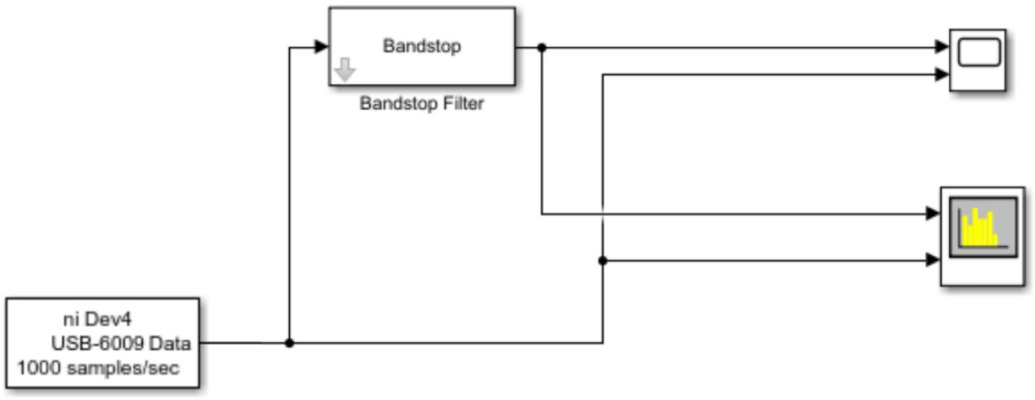


Figure 6: Bandstop Filter in Simulink

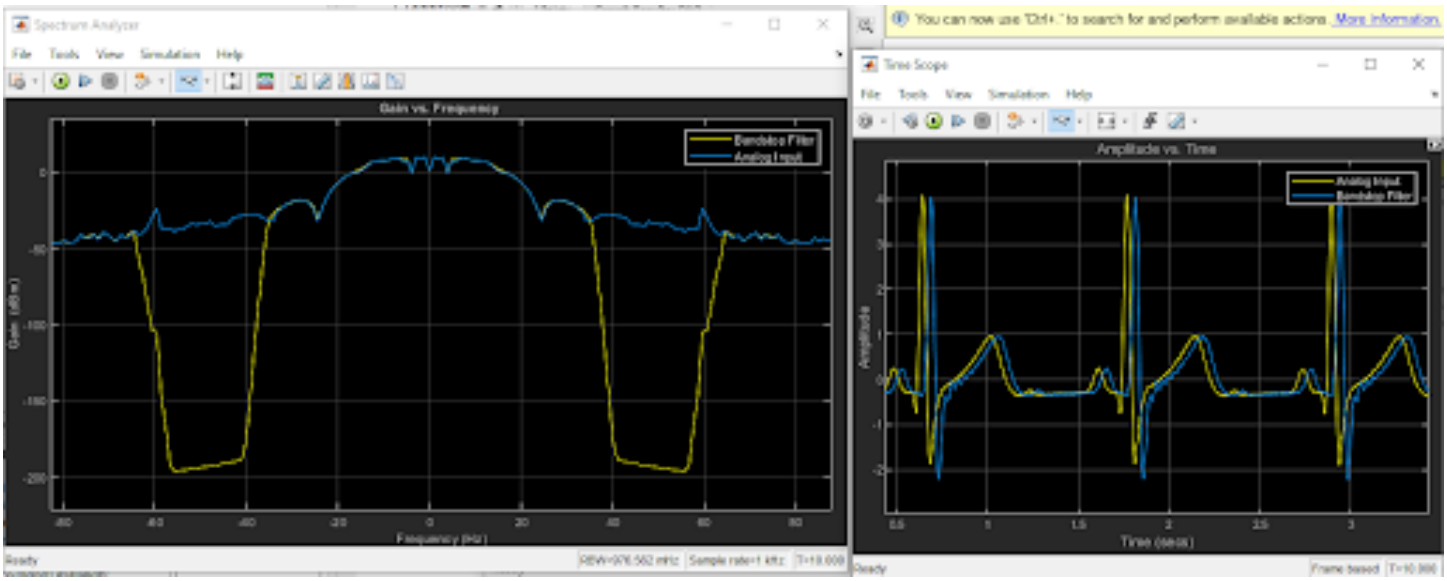


Figure 7: Power Spectrum and Waveform of Human ECG Signal Before and After Attenuation of 60 Hz Powerline Interference

As seen in the power spectrum in Figure 7, the 60 Hz frequency was successfully attenuated. While the filters introduced a slight delay to the ECG signal, they effectively reduced noise. Although the input signal had minimal noise, the output signal was even cleaner.

Display

Figure 8 shows a fully captured human ECG signal using multiple leads. In contrast, Figure 9 demonstrates the ECG signal captured by the designed circuit, which uses only one lead, making the U wave indiscernible. As shown on the right-hand side, the signal had a frequency of 1.463 Hz, equivalent to a heart rate of 87.78 BPM. The features of the waves within a single period were annotated in red.

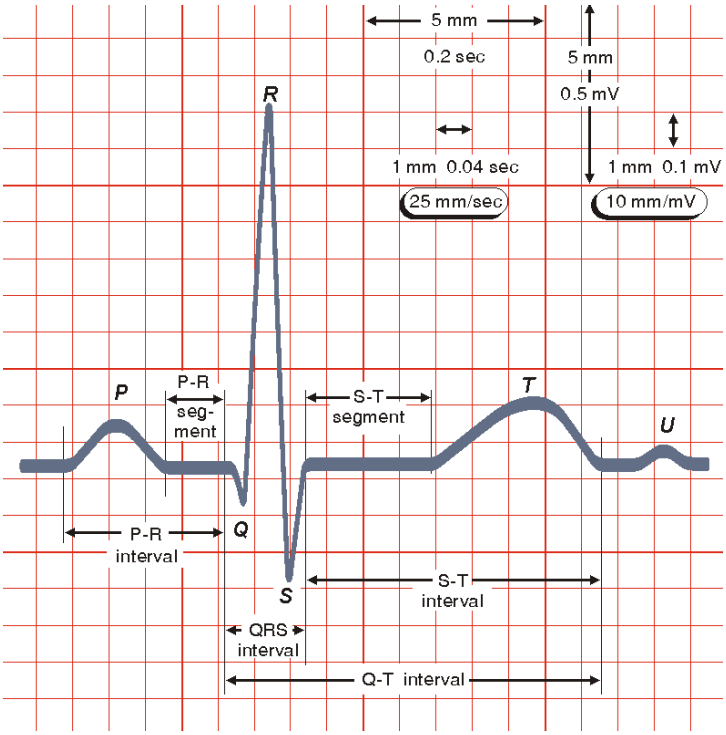


Figure 8: Normal ECG Waveform

Figure 9: Filtered Human ECG