Abstract

This project delves into the construction of a digital heart rate sensor. Using photoplethysmography (PPG), the device measured changes in blood flow through changes in infrared (IR) light absorption. The system was designed and implemented in four stages: an optical sensor to detect the signal, active filters to isolate the heart rate frequency range (40-200 BPM), an analog to digital converter (ADC) with hysteresis to provide a stable digital output, and an LED indicator to visually display the detected heartbeat. After some physical tuning of component values based on experimental results, all stages functioned correctly. Extra credit was achieved by incorporating an inverting boost converter, enabling the system to operate with a single +5V power supply while generating ±5V to power the chips used in the circuit.

The sensor successfully detected and displayed heartbeats, with each subsystem functioning as expected based on theory and calculations performed in this report. Key results included accurate capture and subsequent filtering & amplification of the heart beat signal, as well as reliable digital conversion and visual feedback. However, minor oscillations occurred when the sensor stopped being used, attributed to stray capacitance in the breadboard setup. Despite this, the project achieved its primary goals and demonstrated the feasibility of creating an optical heart rate sensor.

Components Used:

- **Chips:** LM324 (quad opamp), LM339 (quad comparator), 555 timer (timer IC)
- **Sensors:** IR204 (infrared LED), PT204-6B (infrared phototransistor)
- **Misc:** resistors, capacitors, breadboard, jumper wires, and an AD2 for PSU/Oscilloscope

Introduction

Measuring heart rate is important for many medical, fitness, and other applications. This final project focuses on designing a circuit to measure a person's heartbeat. While there are many different methods to detect a heartbeat, this project specifically involves creating an optical heart rate sensors through use of photoplethysmography (PPG) to detect changes in blood flow by monitoring how infrared light (IR) is absorbed by the body. The goal of this project was to design and build a basic optical heart rate sensor that could detect a person's pulse and display it using an LED. The design needed to focus on detecting heartbeat signals, filtering out noise, and reliably identifying heart rates between 40 and 200 BPM. This would all be done using base electronic components, like opamps, comparators, diodes, receivers, and a ±5V supply (only a +5V supply for extra credit).

To achieve this, the system was divided into four main stages. Stage one, an IR transmitter and receiver to detect changes in IR. Stage two, active filters to isolate and amplify the heartbeat signal to reduce noise and boost the low amplitude signal from stage one. Stage three, an analog-to-digital converter (ADC) to produce a clear digital output. Finally, stage four, a visual indicator using an LED to display the heartbeat. Additionally, to obtain the extra credit, an inverting boost converter can be utilized to generate -5V from the +5V supply. This staged approach ensured each part of the system could be tested and adjusted independently before final integration.

1. Theory

1.1. Stage One: Optical Sensor

The optical sensors employ photoplethysmography (PPG). This technique relies on the fact that blood absorbs significantly more low-intensity infrared light compared to the other bodily materials. [1] Because of that, when blood is pumped into an area of the body more IR light will be absorbed as the new blood passes through, then the absorption will slowly fall until more blood is pumped in and the cycle repeats. Therefore, by placing a body part, like a finger, between an IR transmitter and an IR receiver, a person's pulse can be measured based on the wave generated from the receiver.

This section will utilize the IR204 transmitter and the PT204-6B receiver in the configuration seen below in Figure 1.

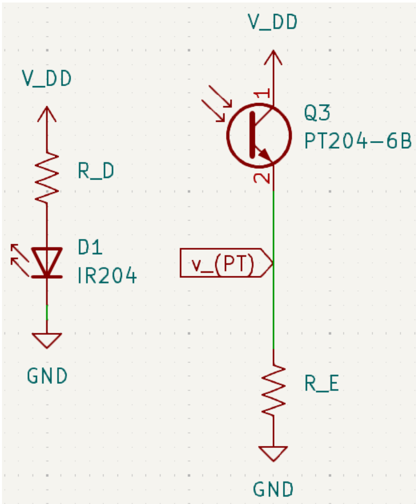

Figure 1: Infrared Transmitter & Receiver Circuit.

When designing the transmitter circuit, it is ideal to maximize the current of the IR204 transmitter so a strong and clear signal is created for the rest of the circuit. However, the current must be within specifications of components used in the circuit. Areas of concern for the transmitter circuit are the power rating on the resistor R_D and the max rated continuous forward current of the IR204 diode. The power rating of resistors used throughout this lab is 0.25 W, and the max continuous I_F for the IR204 is 100 mA, and a forward voltage (V_f) of 1.4V at that current [2]. To ensure those ratings are not exceeded, the current through that branch can be calculated by finding the voltage across the resistor (source voltage minus the drop across the diode) and applying Ohms law:

$$I_D = \frac{V_{DD} - 1.4}{R_D} \Rightarrow 100 \cdot 10^{-3} \geq \frac{V_{DD} - 1.4}{R_D} \tag{1}$$

In order for the receiver circuit to function consistently, it is important that the PT204-6B transistor stays well within the linear mode of operation. The saturation voltage $V_{CE_{sat}}$ is specified to be 0.4V [3], meaning that the voltage drop across the PT204-6B transistor must be kept above 0.4V to stay in saturation. This minimum value can be *rounded* up to 1V as a factor of safety to ensure the transistor stays in linear operation. Additionally, that factor of safety allows the assumption of the AC perturbations on V_{CE} to be negligible (in that they will not bring the transistor out of linear operation), so the design can be based upon keeping the DC operating point of $V_{CE} \geq 1$V, and a typical I_C of 2 mA [2].

$$V_{DD} - v_{CE} = v_{PT} = i_{PT} R_E \Rightarrow \frac{V_{DD} - 1}{2 \cdot 10^{-3}} \leq R_E \tag{2}$$

These equations will help find a starting value for R_E, but may need to be tuned on the physical circuit. Additional constraints to this circuit are component limitations, including the 0.25W power rating on the resistor R_E and keeping V_{CE} below the rated breakdown voltage of 30V [2].

1.2. Stage Two: Active Filters

The output of the receiver (v_{PT}) is likely to be very noisy from various possible sources. Therefore, it is advisable to create filters to isolate frequencies of the human heartbeat (40-200 BPM), so the final output signal clearly shows the heartbeat. This isolation will be done by combining a high pass and a low pass filter. The combined gain of the two filters will be between 100 - 1000 (linear gain) in order to provide a sufficient signal to stage 3. The total gain of the LPF in series with the HPF can be defined as $k_{total} = k_{HPF} \cdot k_{LPF}$. So the filter design is constrained by:

$$100 < k_{HPF} \cdot k_{LPF} < 1000 \tag{3}$$

Additionally, two filters needed to have ∼equal gain to avoid signals being improperly pushed in or out of cutoff due to the mismatched filter's interaction, so:

$$k_{LPF} \approx k_{HPF} \tag{4}$$

*Note: filter opamps in this section are the LM324.

1.2.1. Low Pass Filter (LPF)

In order to avoid rejecting heartbeat frequencies, the cutoff for the LPF (f_L) should fall just above the max heart rate of a human. Using the inverting LPF seen below in Figure 2, the following transfer function can be derived as:

$$H(s) = \frac{-\frac{R_2}{R_1}\frac{1}{R_2C_1}}{s + \frac{1}{R_2C_1}} \tag{5}$$

Which is inline with the standard first order filter form, $H(s) = \frac{k\omega_0}{\omega_0+s}$ yielding:

$$k_{LPF} = -\frac{R_2}{R_1} \tag{6}$$

$$\omega_{0_{LPF}} = \frac{1}{R_2C_1} \tag{7}$$

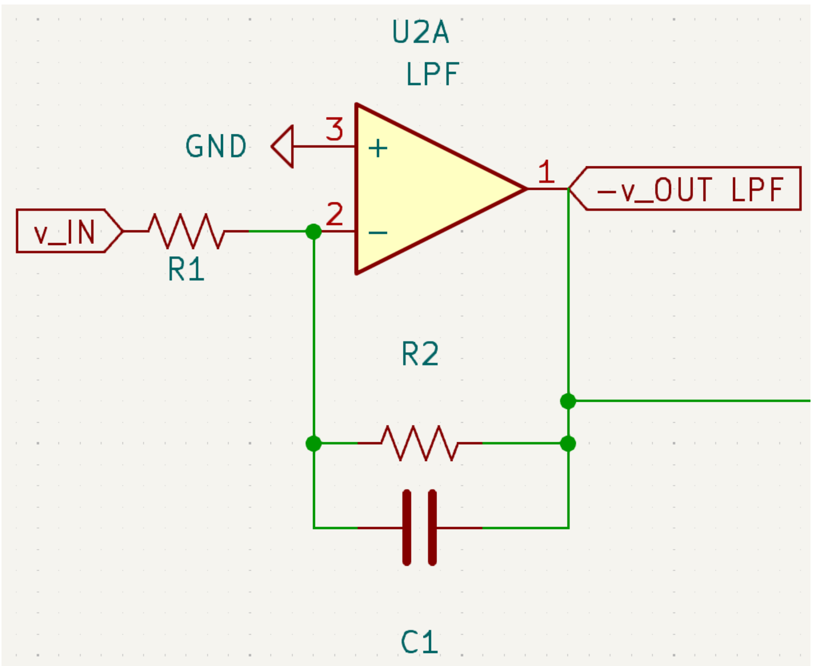

Figure 2: Inverting Low Pass Filter Circuit.

1.2.2. High Pass Filter (HPF)

In order to avoid rejecting heartbeat frequencies, the cutoff for the HPF (f_H) should fall just below the minimum heart rate of a human. Using the inverting HPF seen below in Figure 3, the following transfer function can be derived as:

$$H(s) = \frac{-\frac{R_2}{R_1}s}{s + \frac{1}{R_1C_1}} \tag{8}$$

Which is inline with the standard first order filter form, $H(s) = \frac{ks}{\omega_0 + s}$ yielding:

$$k_{HPF} = -\frac{R_2}{R_1} \tag{9}$$

$$\omega_{0_{HPF}} = \frac{1}{R_1C_1} \tag{10}$$

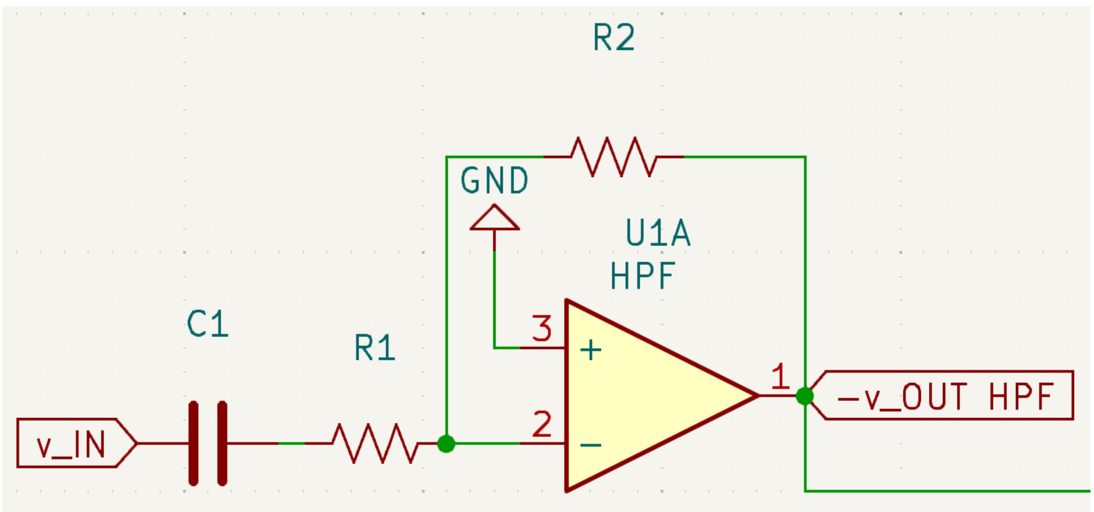

Figure 3: Inverting High Pass Filter Circuit.

1.3. Stage Three: Analog to Digital Conversion

The output from the filters (stage two) will be significantly less noisy than the output of stage one, it still won't be a completely clean signal. It would be far more useful to have the heartbeat signal as a clean DC signal. A comparator with hysteresis (seen below in Figure 4) is well suited to convert the filtered but potentially still noisy AC heartbeat signal to a DC signal. Unlike normal open loop comparators which are unstable from noisy signal inputs ($V_{IN}^+ - V_{IN}^-$) close to 0V, a comparator with hysteresis has *latch like behavior* in that the output does not switch from its current state until the input either reaches $+V_{th}$ leading to the output being pulled high or the input reaches $-V_{th}$ leading to the output being pulled low. This threshold voltage is defined by (where $v_{th} = \frac{v_{hyst}}{2}$) [4]:

$$v_{hyst} = (2V_{DD})\frac{R_1}{R_1 + R_2} \tag{11}$$

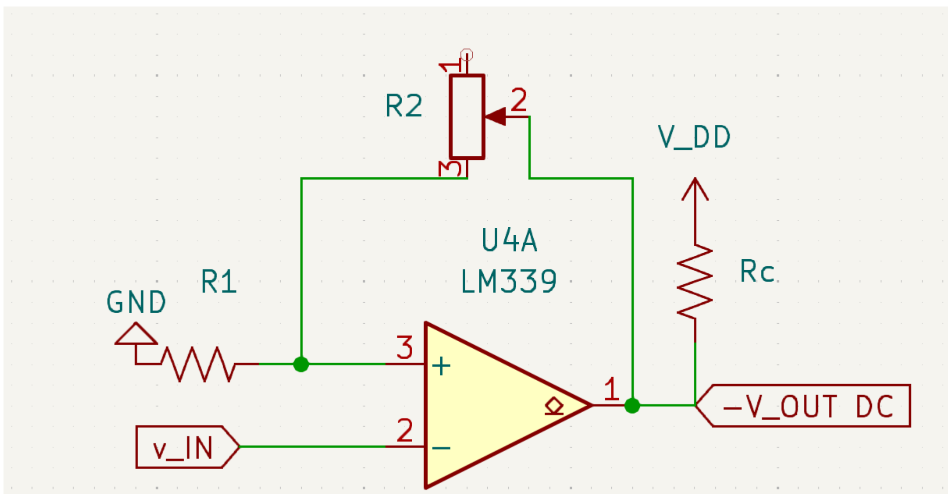

Figure 4: Inverting Comparator With Hysteresis Circuit. (powered by V_{DD} and $-V_{DD}$)

R_2 is shown as a variable resistor to allow v_{hyst} to be experimentally tuned to fit a given person's heartbeat, and a pull-up resistor R_c as specified by the datasheet [4].

It is also important to ensure that the input signal is centered around 0V, or the comparator will not function as designed. Therefore, a capacitor should be added to block any DC offsets the incoming signal may have. This can be used to further denoise the signal by implementing a passive high pass filter rather than just a capacitor, as seen below in Figure 5.

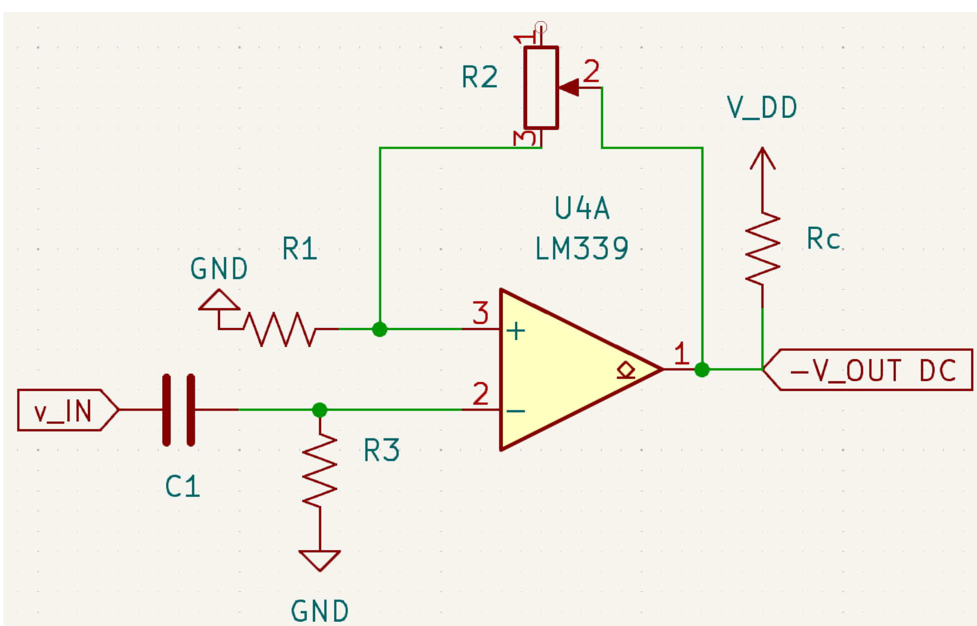

Figure 5: Inverting Comparator With Hysteresis Circuit W/ filtered input. (powered by V_{DD} and $-V_{DD}$)

The passive filter should pass similar frequencies as the active HPF in stage two. The passive filter's cutoff frequency (ω_0) is defined by:

$$\omega_{0_{HPFp}} = \frac{1}{R_3 C_1} \tag{12}$$

1.4. Stage Four: Visual Indicator

To make the output more useful, a visual indicator of the heartbeat will be added onto the output of the circuit. This will be done by adding an LED to indicate the beats of the heart, the circuit for this is shown below in Figure 6.

It is ideal to have the LED as bright as allowable, so it is easier to see, therefore I should be maximized. However, the limiting factor on that current will be the max rated current of the LED (the LED has lower rated current than the NMOS). In order to provide a small margin of safety, the voltage drop across the NMOS (v_{DS}) can be assumed to 0, yielding the relationship:

$$V_{DD} = V_R + V_{LED} \tag{13}$$

According to the datasheet, the TLHR6400 LED has a typical forward voltage of 2V. By applying Ohm's law, it's found that $I_{LED} = \frac{V_{DD}-2}{R_L}$. Applying the max continuous current of 30 mA specified by the datasheet [5] yields the constraint:

$$30 \cdot 10^{-3} < \frac{V_{DD}-2}{R_L} \Rightarrow R_L < \frac{V_{DD}-2}{30 \cdot 10^{-3}} \tag{14}$$

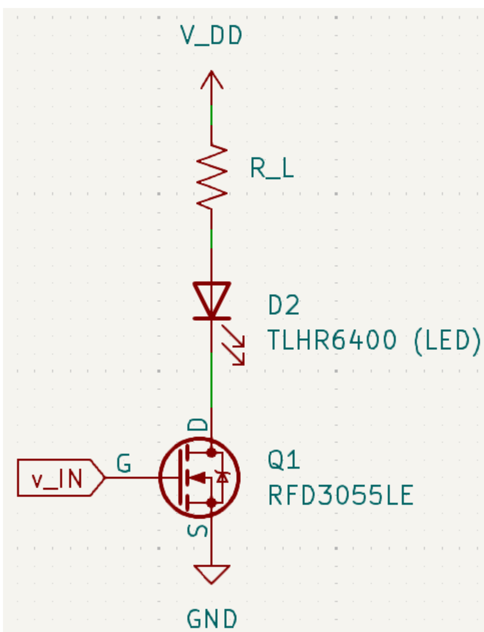

Figure 6: LED Indicator Circuit.

1.5. Extra Credit: $-V_{DD}$ Supply

Since this lab is constrained to only use a $+V_{DD}$ (to get the extra credit), an inverting boost converter will be utilized to provide the $-V_{DD}$ to power the LM339 and LM324 chips.

Since the inverting boost and 555 timer PWM circuits were explored in previous lab reports (lab 10 and lab 2 respectively), the theoretical derivations of the circuits have been omitted from this report, and the circuit as a whole is treated as a basic component, if further knowledge of either circuit is needed, refer back to the lab reports stated above.

The inverting boost converter below (Figure 7) is designed so that adjusting the potentiometer will adjust the duty cycle output by the 555 timer. Said duty cycle directly controls the voltage output of the inverting boost circuit. The circuit is design so that the potentiometer can be tuned manually until $V- = -V_{DD}$

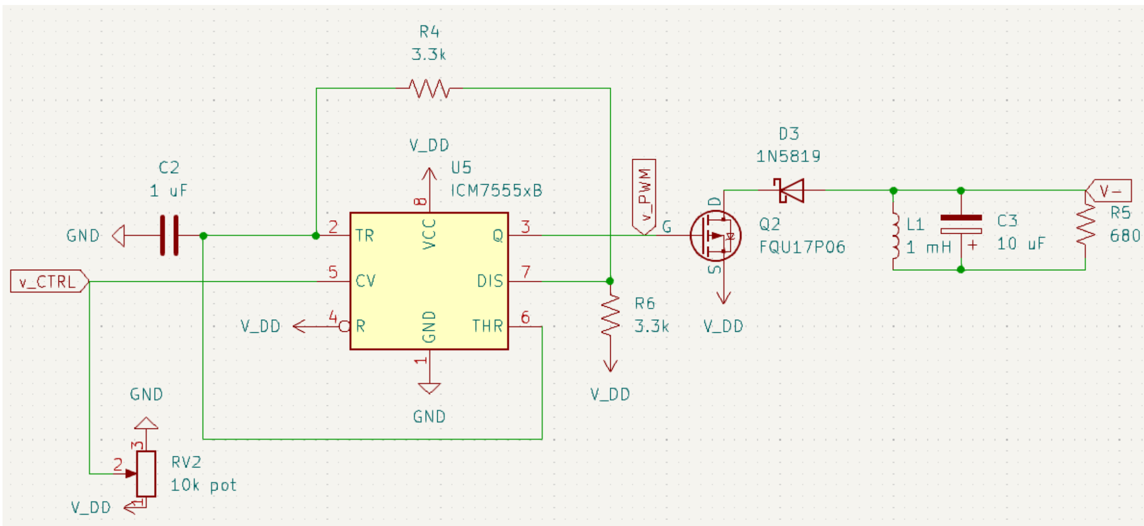

Figure 7: Inverting Boost Circuit. (V- is output)

1.6. Final Circuit Integration

On paper, each substage and stage could simply be connected one after the other. However, due to potential issues with loading, it is prudent to place a non-inverting buffer between the HPF and LPF stages, to cut off the direct path electrical signals have around the filters, and in doing so not needing to worry about issues with impedance and loading between the filters. This configuration is seen in the full circuit diagram (Figure 8).

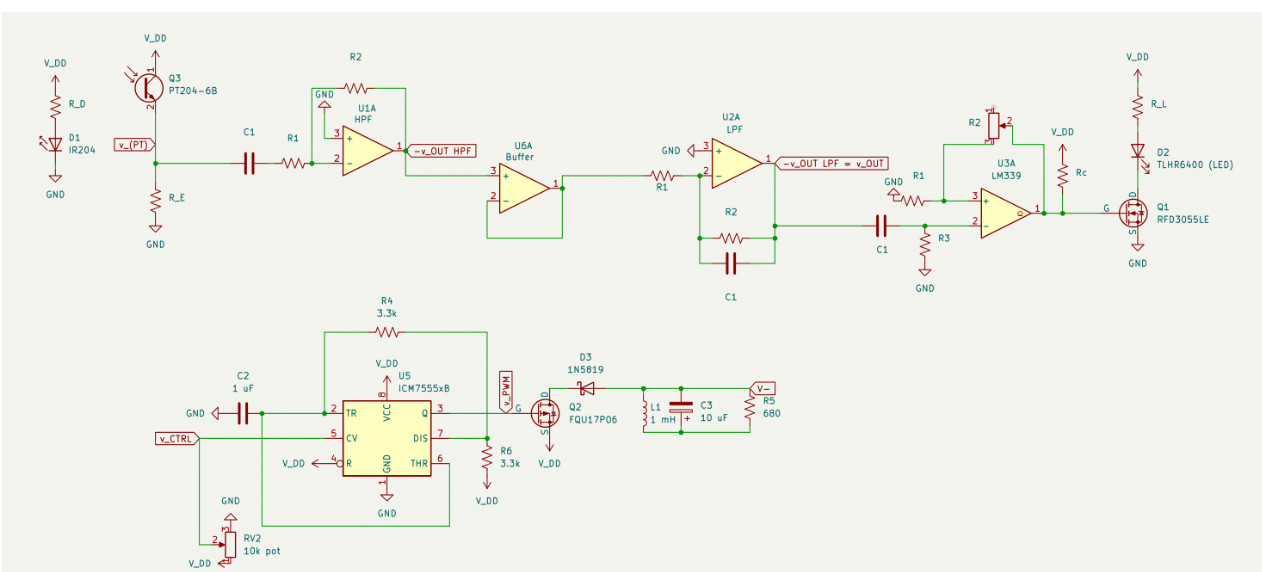

Figure 8: Full Circuit Diagram.

2. Design/Calculations

This lab will operate off a supply voltage of 5V ($V_{DD} = 5$V).

2.1. Stage One: Optical Sensor

Plugging in $V_{DD} = 5$V into equation 1 yields:

$$R_D \geq 36\Omega \tag{15}$$

A 100 Ω resistor was chosen based on component availability. However, it must also be checked that the resistor remains under 0.25W:

$$(100 \cdot 10^{-3})^2 \cdot R_D \leq 0.25 \Rightarrow R_D \geq 2.5m\Omega\checkmark \tag{16}$$

Plugging in $V_{DD} = 5$V to equation 2 yields:

$$\frac{5-1}{2 \cdot 10^{-3}} \leq R_E \Rightarrow 2k\Omega \leq R_E \tag{17}$$

A 2.2kΩ resistor was chosen based on component availability. However, it must also be checked that the resistor remains under 0.25W:

$$(2 \cdot 10^{-3})^2 \cdot R_D \leq 0.25 \Rightarrow R_D \geq 62.5n\Omega\checkmark \tag{18}$$

Additionally supply voltage (5V) is less than 30V, so breakdown voltage is not a concern for the transistor.

Based on the above calculations, the schematic for the first stage can be constructed and seen below in Figure 9.

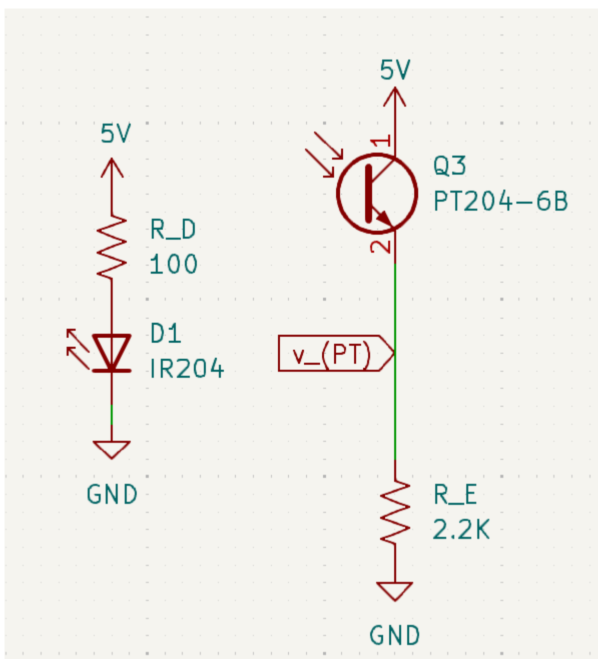

Figure 9: Infrared Transmitter & Receiver Circuit w/ Component Values.

2.2. Stage Two: Active Filters

Based on equation 3 a gain of ∼100 can be chosen. Then, based on equation 4, a target gain of slightly ∼10 (in magnitude, the gains of both filters will be negative since they are inverting) can be chosen for both filters.

2.2.1. Low Pass Filter

The max rate for a heartbeat in this project is assumed to be 200 beats per minute, which can be converted to Hz:

$$200\frac{beats}{\cancel{min}} \cdot \frac{1\cancel{min}}{60sec} \approx 3.33Hz = f_{0_{LPF}} \tag{19}$$

That frequency can then be converted to ω:

$$f \cdot 2\pi = \omega \Rightarrow \omega_{0_{LPF}} = 20.9\frac{rad}{s} \tag{20}$$

Plugging $\omega_0 \approx 20.9$ into equation 7 and $|k| \approx 10$ into equation 6 yields the solution:

$$\begin{aligned} C_1 &= 1\mu F \\ R_1 &= 4k\Omega \\ R_2 &= 47k\Omega \end{aligned} \tag{21}$$

Plugging these values back into 7:

$$\omega_{0_{LPF}} = \frac{1}{47k\Omega \cdot 1\mu F} \Rightarrow \omega_{0_{LPF}} = 21.28\frac{rad}{sec} \tag{22}$$

This is slightly above the target of 20.9, so this filter will allow all wanted frequencies to pass, with a small buffer zone, but not enough to make the signal extremely noisy. (ω_0 ✓)

Plugging these values back into 6:

$$k_{LPF} = -\frac{47k\Omega}{4k\Omega} \Rightarrow k_{LPF} = -11.75 \tag{23}$$

The gain (magnitude) is about 10. (k ✓)

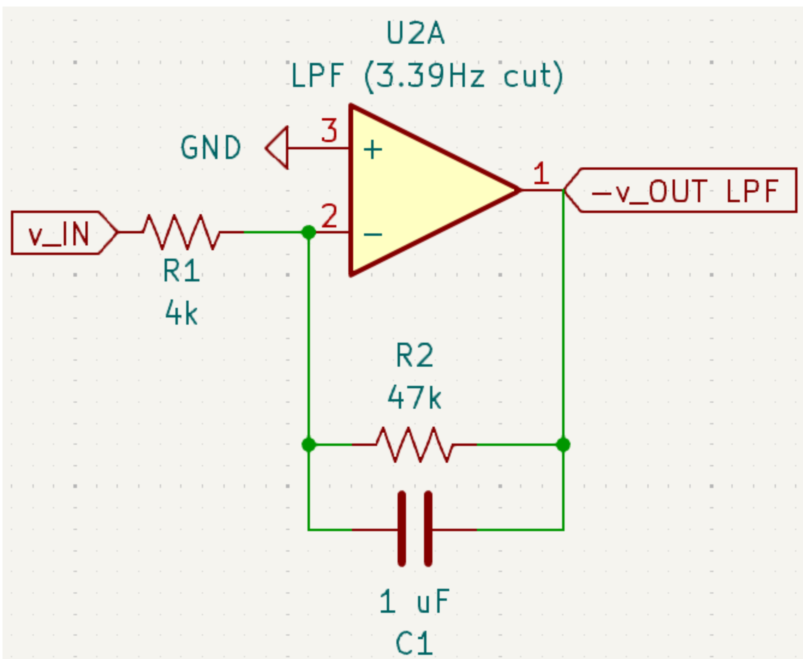

Figure 10: Inverting Low Pass Filter Circuit w/ Component Values.

2.2.2. High Pass Filter

The minimum rate for a heartbeat in this project is assumed to be 40 beats per minute, which can be converted to Hz:

$$40\frac{beats}{\cancel{min}} \cdot \frac{1\cancel{min}}{60sec} \approx .67Hz = f_{0_{HPF}} \tag{24}$$

That frequency can then be converted to ω:

$$f \cdot 2\pi = \omega \Rightarrow \omega_{0_{HPF}} = 4.2\frac{rad}{s} \tag{25}$$

Plugging $\omega_0 \approx 4.2$ into equation 10 and $|k| \approx 10$ into equation 9 yields the solution:

$$C_1 = 10\mu F$$
$$R_1 = 25k\Omega$$
$$R_2 = 240k\Omega \tag{26}$$

Plugging these values back into 10:

$$\omega_{0_{HPF}} = \frac{1}{25k\Omega \cdot 10\mu F} \Rightarrow \omega_{0_{HPF}} = 4\frac{rad}{sec} \tag{27}$$

This is slightly below the target of 4.2, so this filter will allow all wanted frequencies to pass, with a small buffer zone, but not enough to make the signal extremely noisy. (ω_0 ✓)

Plugging these values back into 9:

$$k_{HPF} = -\frac{240k\Omega}{25k\Omega} \Rightarrow k_{HPF} = -9.6 \tag{28}$$

Plugging this gain and the K_{LPF} found in equation 23 to equation 3:

$$100 < -9.6 \cdot -11.75 < 1000 \tag{29}$$

A total gain of 112.8 falls between the desired 100 - 1000 and is just above the target 100. (k ✓)

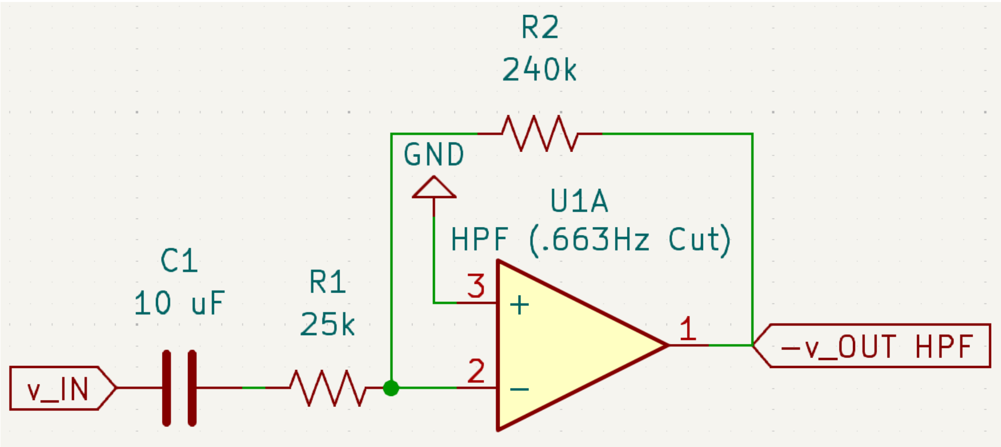

Figure 11: Inverting High Pass Filter Circuit w/ Component Values.

2.3. Stage 3: Analog to Digital Conversion

By plugging in $V_{DD} = 5$V and $500k\Omega$ pot $= R_2$ (as that was what is available and is well suited with high impedance) into equation 11 it's found that:

$$\frac{5R_1}{R_1 + 500k}V \leq v_{th} \leq 5V \tag{30}$$

In order to have the capability to accommodate all signals, even weak ones, a minimum adjustable threshold value of ∼1V will be targeted, which yields the most suitable available component of $R_1 = 100k\Omega$ which puts the following limits on v_{th}:

$$0.83V \leq v_{th} \leq 5V \tag{31}$$

In order to get a passive high pass filter with $\omega_0 \approx 4.2$ equation 12 can be used:

$$\omega_{0_{HPFp}} = \frac{1}{R_3 C_1} \Rightarrow 4.2 = \frac{1}{R_3 C_1} \tag{32}$$

Which can be achieved using components on hand with the values:

$$C_1 = 10\mu F$$

$$R_3 = 150k\Omega \tag{33}$$

Plugging these values back into equation 12 yields $\omega_0 = 0.67\frac{rad}{sec}$✓

The pull-up resistor R_c can be a 1 kΩ based on recommended values from the manufacturer. [4]

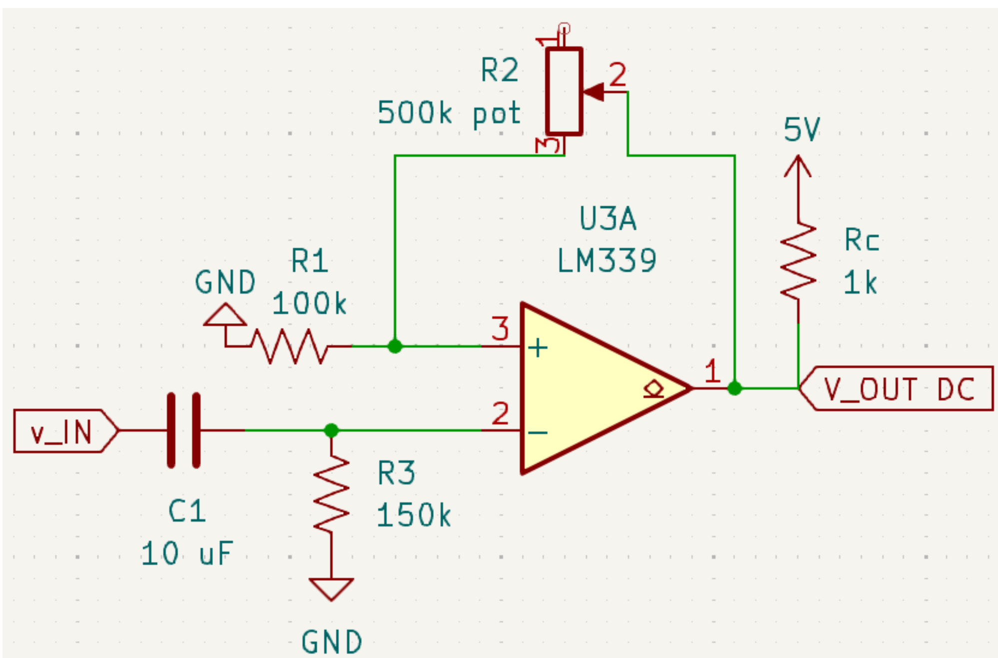

Figure 12: ADC and High Pass Filter w/ Component Values.

2.4. Stage 4: Visual Indicator

Plugging in $V_{DD} = 5\text{V}$ into equation 14 yields:

$$R_D \geq 100\Omega \tag{34}$$

However due to the lab kit LED's propensity to get very hot when used for prolonged periods of time near their max rated a current, a 470 Ω resistor was chosen to protect the board and components around the LED, while still maintaining sufficient brightness. However, it must also be checked that the resistor remains under 0.25W (assuming 3V across R_L):

$$\frac{3^2}{R_D} \leq 0.25 \Rightarrow R_D \geq 36\Omega\checkmark \tag{35}$$

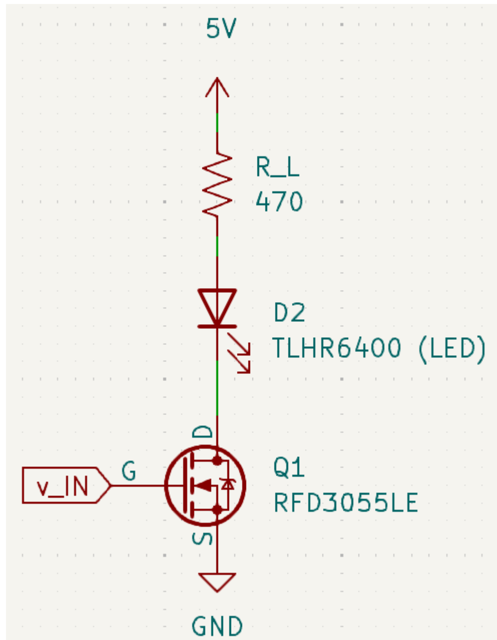

Figure 13: LED Indicator Circuit w/ Component Values.

2.5. Final Circuit Integration (with EC)

Putting the component values solved for throughout this section into the full schematic seen in Figure 8 yields:

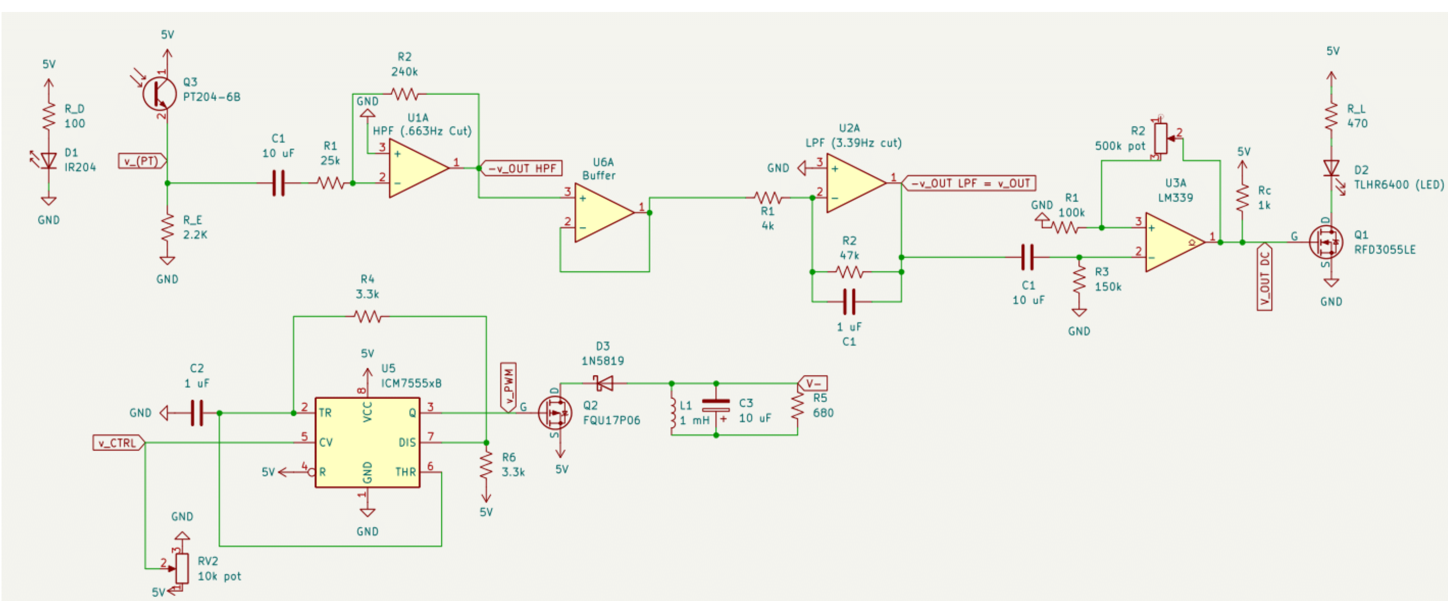

Figure 14: Full Circuit Diagram w/ Component Values.

3. Physical Tuning/Final Circuit

All stages of the circuit worked from the calculated values (including adjusting potentiometers made to be adjustable), except for the active filter stage that required some physical tuning. The two active filters worked as expected when tested in isolation, however when combined together and with the rest of the circuit, their cutoff frequencies were thrown off due to interactions with the other components of the circuit. Both R_1 and R_2 resistors for both filters were changed out until both gain and cut-off frequencies were accurate when used in the total circuit.

The final values for the HPF:

$$R_1 = 33k\Omega$$
$$R_2 = 330k\Omega$$
$$C_1 = 10\mu F \text{ (unchanged)} \tag{36}$$

The final values for the LPF:

$$R_1 = 6.8k\Omega$$
$$R_2 = 75k\Omega$$
$$C_1 = 1\mu F \text{ (unchanged)} \tag{37}$$

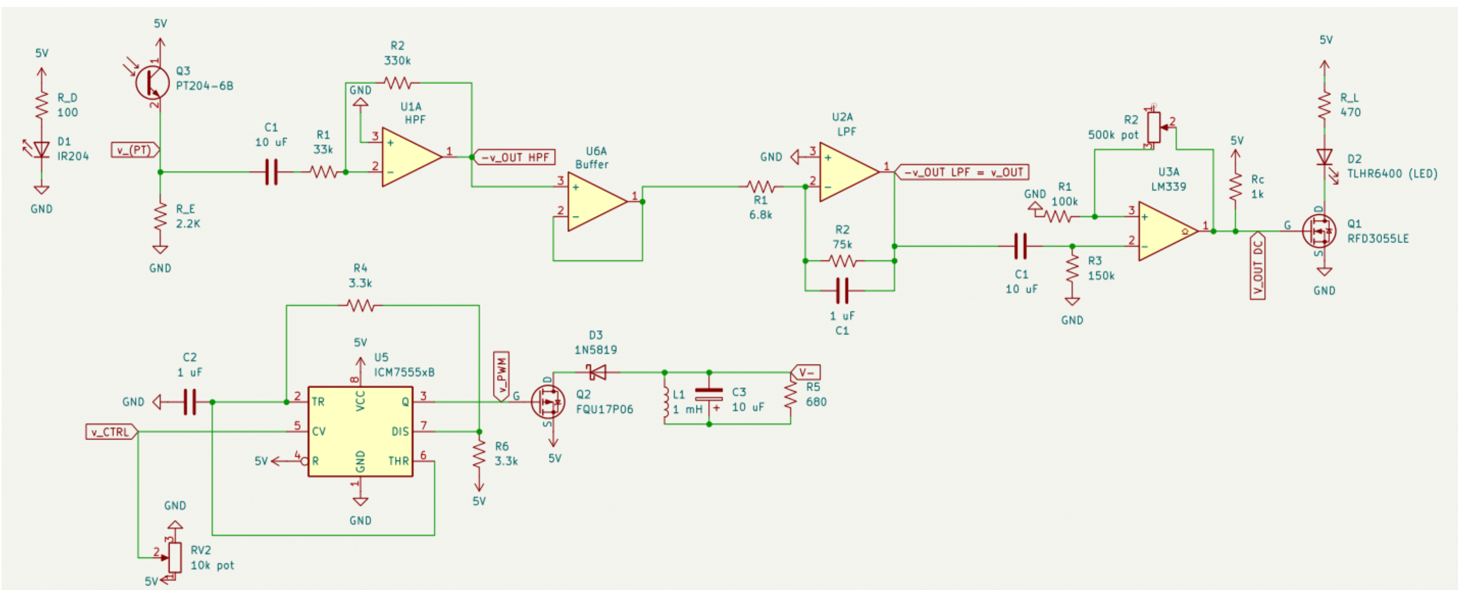

Figure 15: Full Circuit Diagram w/ Component Physically Tuned Component Values.

4. Results/Measurements

4.1. Stage One: Optical Sensor

The IR sensor and receiver were able to pick up a heartbeat when a finger was placed between them, this is shown by the scope readout of the receiver output (V_{pt} from Figure 1) below:

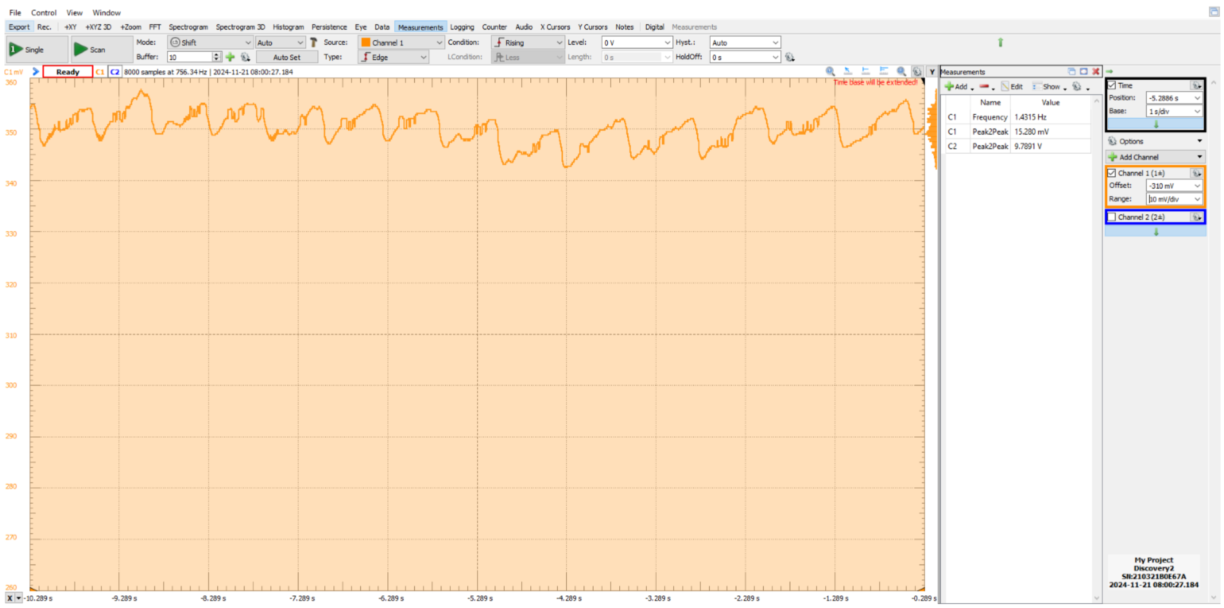

Figure 16: Optical Sensor Readout w/ Finger in Sensor.

4.2. Stage Two: Active Filters

4.2.1. Low Pass Filter

Running FRA on the isolated low pass filter seen in Figure 10:

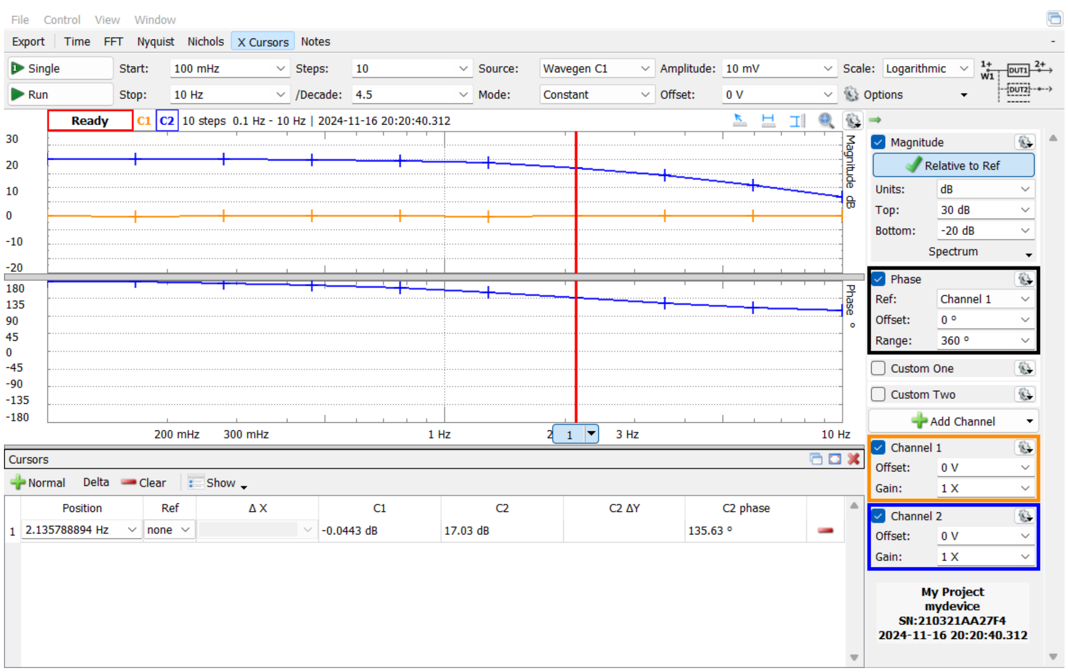

Figure 17: Low Pass Filter FRA.

$$f_{0_{LPF}} = 2.136 \text{ Hz} \tag{38}$$

Although this cutoff is far lower than the targeted, 3.33 Hz, when the two filters are combined together the filter works as intended (see Figure 19 band pass).

4.2.2. High Pass Filter

Running FRA on the isolated high pass filter seen in Figure 11:

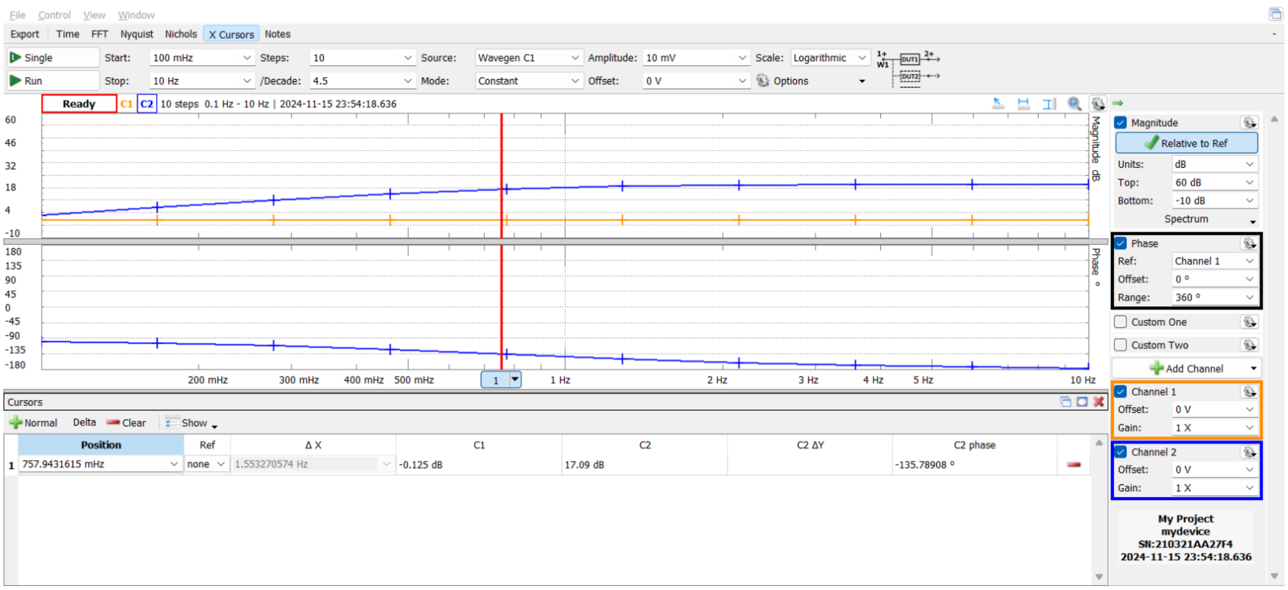

Figure 18: High Pass Filter FRA.

$$f_{0_{HPF}} = 0.758 \text{ Hz} \tag{39}$$

4.2.3. Band-pass Filter (Combined HPF & LPF)

Running FRA on the low pass and high pass filter connected together:

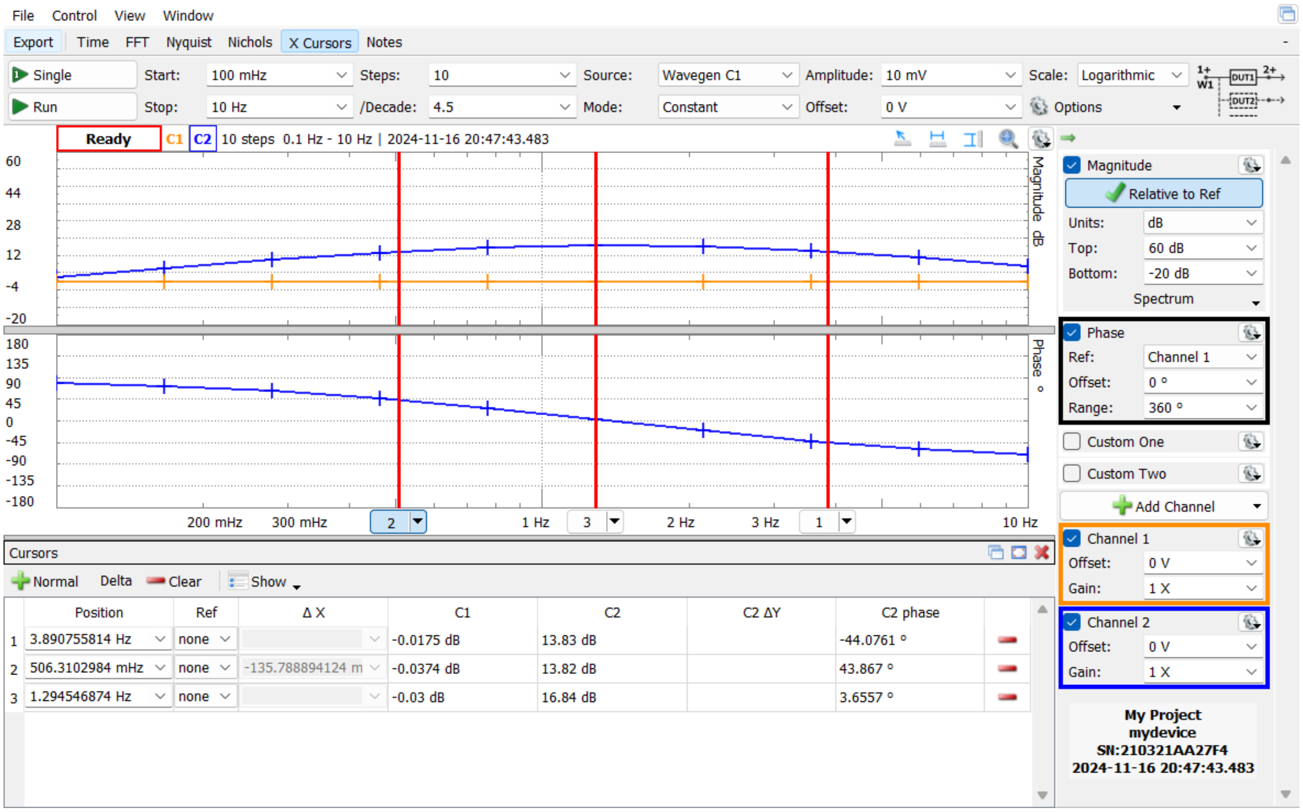

Figure 19: Band-pass Filter FRA. **ignore gain reading in this scope readout, reference signal was not connected to input (but still relative to same ref, so cutoffs are accurate)*

$$
\begin{aligned}
f_H &= 0.506\text{Hz} \\
f_c &= 1.295\text{Hz} \\
f_L &= 3.891\text{Hz}
\end{aligned} \tag{40}
$$

The cut-off frequencies shifted back to their intended values when the filters were connected together.

Additionally, the gain is show to be ∼100 from the output of the receiver (input to the filter stage) being ∼20 mV_{PP} (see Figure 20) and the output of the filter stage being ∼2 V_{PP} (see Figure 21).

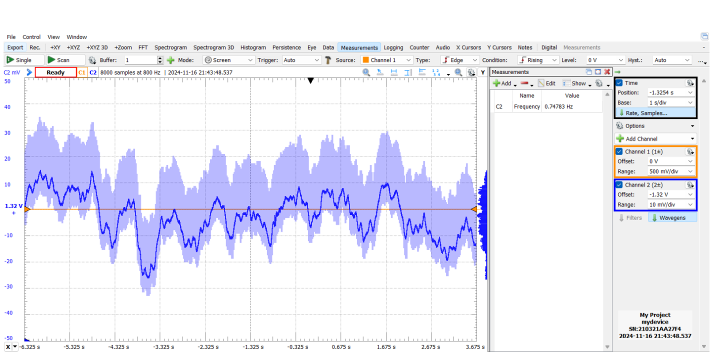

Figure 20: Receiver Output (Filter Input)

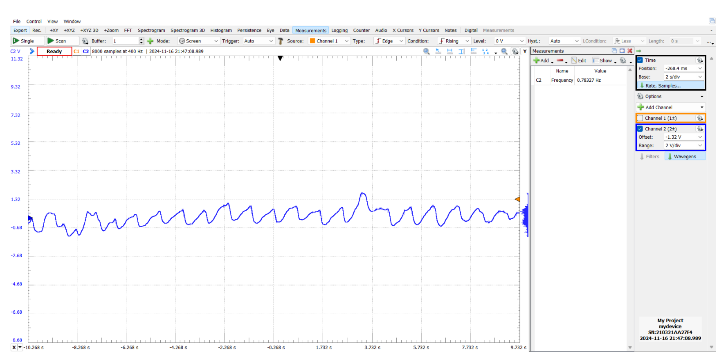

Figure 21: Filter Output

4.3. Stage 3: Analog to Digital Conversion

To test the ADC a 1V 1Hz sin wave was input to v_{IN} (ch1) and ch2 was connected to $V_{\mathrm{OUT\ DC}}$ of the circuit shown in Figure 5, the result is shown in the figure below:

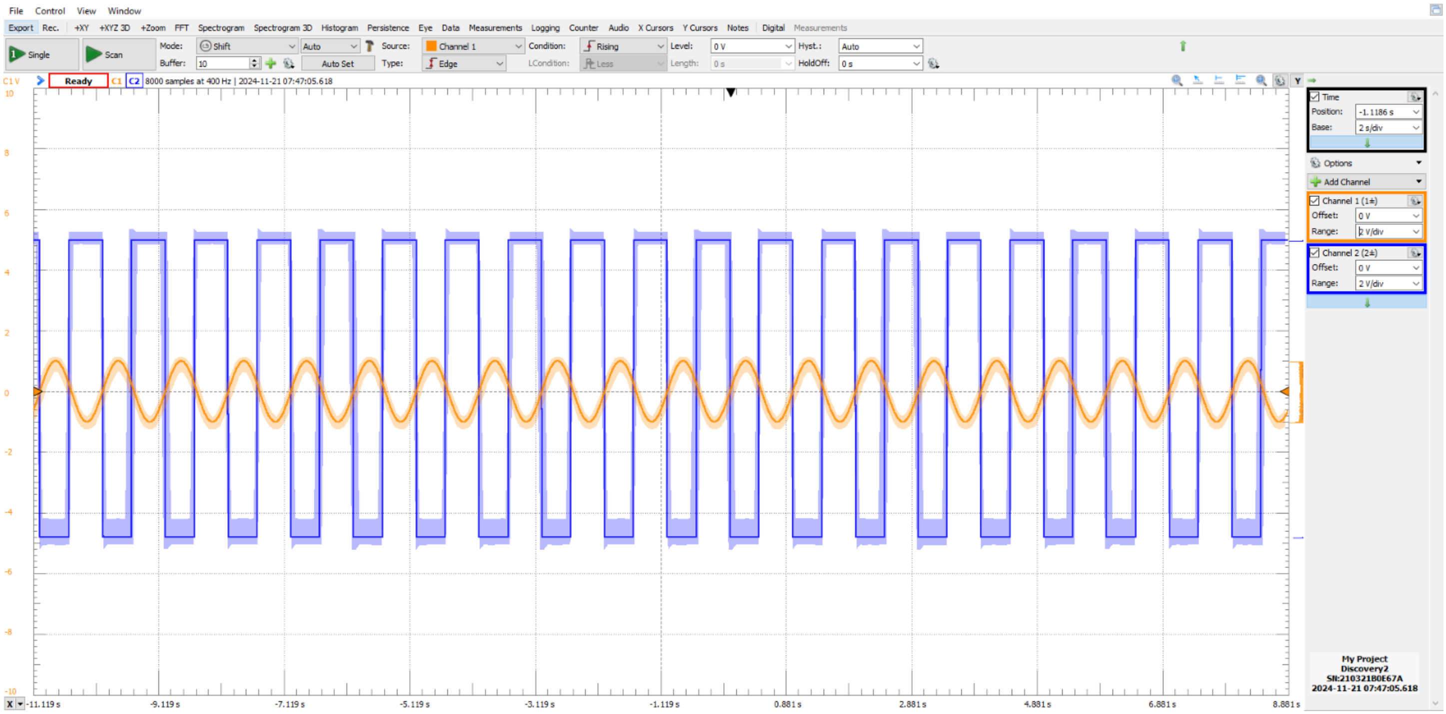

Figure 22: ADC Isolated Test.

As seen by the scope readout, the AC input is properly being pulled to -5V when it goes high and +5V when it goes low, as expected from this inverting ADC.

4.4. Stage 4: Visual Indicator

The LED worked properly, clearly illuminating when $V_{\mathrm{OUT\ DC}}$ was high. This functionality was confirmed in lab during the demonstration.

4.5. Extra Credit: -5V Supply

The inverting boost circuit successfully created a -5V supply when powered by +5V, as shown below:

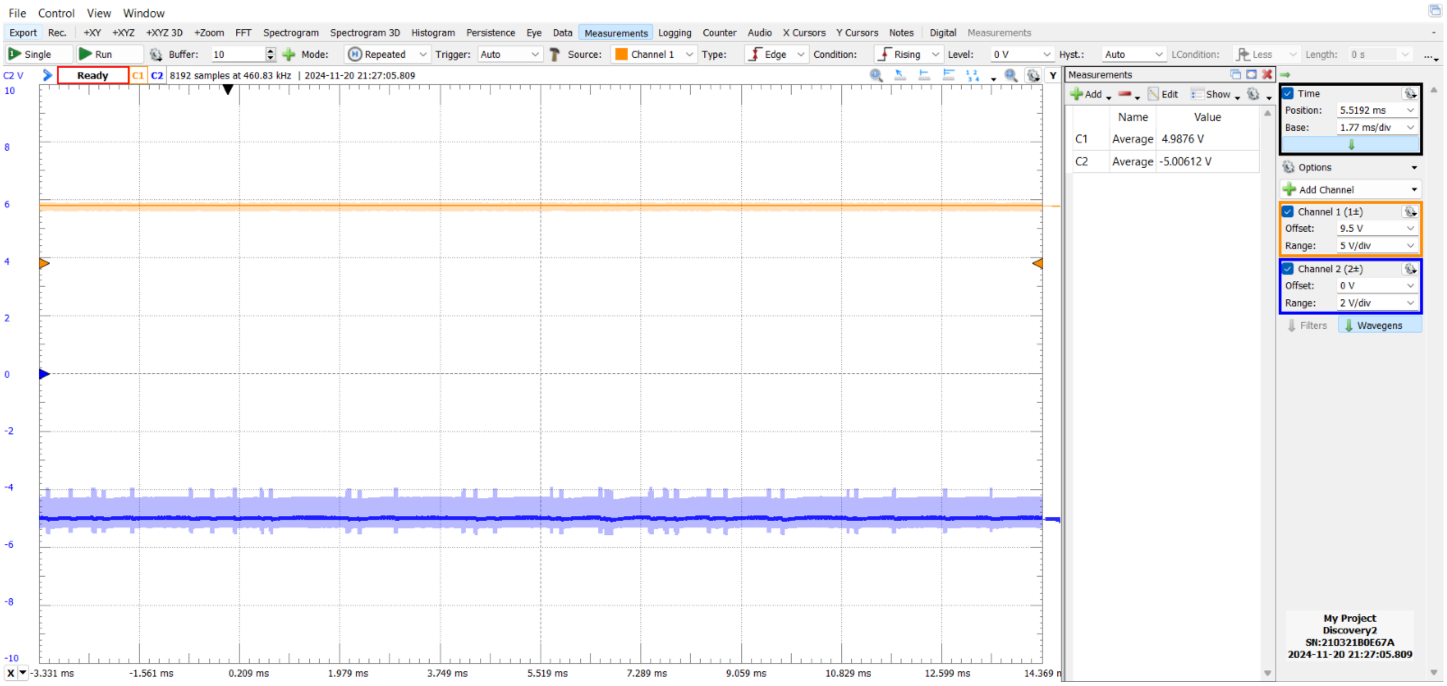

Figure 23: Rail to Rail Chip Supply Generated by Inverting Boost.

4.6. Full Circuit Testing

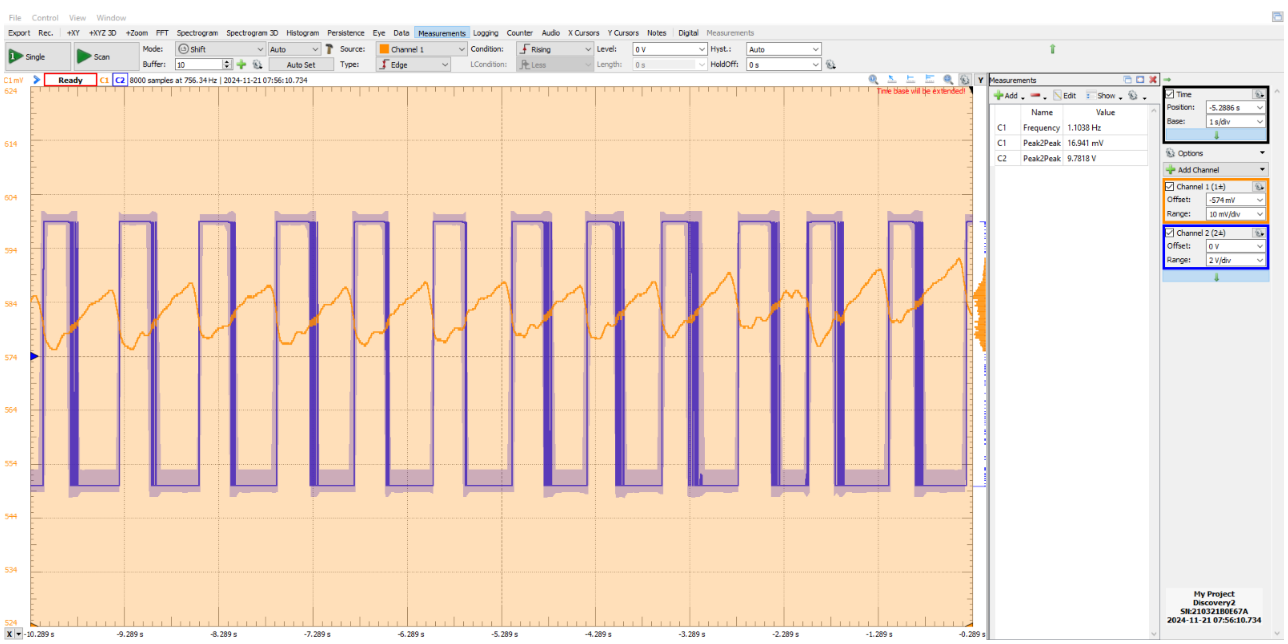

Figure 24: Full Circuit Test w/ CH1: V_{pt} & CH2: $V_{\text{OUT DC}}$ from Figure 15.

5. Conclusions

This project successfully demonstrated the ability to create an optical heart rate measurement device utilizing photoplethysmography to detect pulses of the heart. The optical sensor stage achieved its goal of detecting and transmitting the heartbeat signal through changes in infrared light intensity. The active filter stage effectively isolated the heart rate frequency band, with final values for the high pass and low pass filters adjusted during physical tuning to compensate for loading effects. The ADC stage provided reliable digital outputs by implementing hysteresis and another (passive) high pass filter to minimize noise and ensure stable signal transitions. Finally, the visual indicator stage added a practical element by providing a clear LED-based signal to show heartbeats. Additionally, the extra credit was also successfully achieved by utilizing an inverting boost converter, allowing the system to function with a single +5V supply, with each chip powered by ±5V.

While the heart rate sensor worked flawlessly when measuring a heartbeat, its main and only error came when the device stopped being used. When the subject took their finger out of stage one the output signal oscillation for a small amount of time then ultimately stabilized at either high or low consistently (due to the latch-like behavior of the ADC, whether the system will stay pulled high or pulled low when not being used depends on the last state it was in when in use. Therefore, it is assumed that the device will be either high or low when not being used). Based on probing the input to the ADC it became clear from the slowly decreasing amplitude of the input after the finger was taken out from the detector that this error stemmed from stray capacitance of the circuit interacting with the load of the circuit creating an underdamped system. This is not surprising based on the size of the circuit on a relatively cheap (high capacitance) breadboard. While this behavior was unintended, it did not affect the ability to detect heart beats (the purpose of this project) so it was allowed to remain in the final design. However, it could have been addressed by implementing the circuit on a PCB which would allow it to be made more compact and have lower stray capacitance. Despite this limitation, the project successfully achieved its objectives, providing a reliable heart rate measurement device.

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