Julia Laine

Partners: Devin Radzely. Geetika Chitturi

Section: 009

Lab: 14

AD2# 210321AA2E82

Date: 12/7/2024

Abstract

This project covers the theory, calculations, and results of the construction of a digital heart rate sensor. It utilizes an infrared sensor and an infrared receiver to measure the blood flow through the light absorption. The system has four stages that work together: the optical sensor to detect the heartbeat, the active filters to isolate the signal from the noise, an ADC to provide a reliable DC output, and an LED indicator to show the heartbeat visually. The values for the components were calculated theoretically for a starting point, then they were adjusted as necessary after the circuit was built and tested. Along with the four stages, an inverted boost converter was constructed to create a negative supply rail for the op-amps. Overall, the sensor successfully detected the heartbeat and the output successfully displayed it. Each subsystem worked individually and together for a successful system. When the power was cut, there was minor self oscillation, but other than that it worked as expected.

Introduction

Measuring heart rate is seen every day across the world. It can be used to keep people alive, monitor health, or teach 2k8 students. This project detects a heartbeat through PPG to see changes in the amount of infrared light received. The less infrared light received by the sensor, the more blood must be in the finger in the sensor. The goal of this project was to display a heartbeat between 40 BPM and 200 BPM on an LED. Simple components listed below were used to complete this.

Components

- LM324 (filters), LM339 (ADC), NE555 (inverting buck converter), IR204 (Infrared transmitter), PT204-6B (infrared receiver)
- Various resistors, capacitors, 2 breadboards, wires
- AD2 (power supply, oscilloscope), 2 nice lab partners

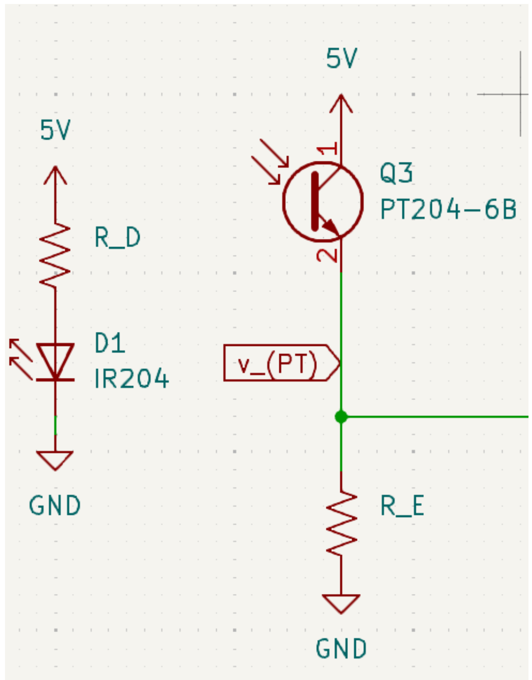
Theory

Full Schematic

The project contains an optical sensor, low pass filter, high pass filter, analog to digital converter, and an indicator. An inverted boost converter was also made to supply the -5v.

Optical Sensor

The optical sensor uses an IR204 (infrared photodiode) and a PT204-6B (infrared phototransistor) as a transmitter and receiver pair. As more infrared light is absorbed by the PT204-6B, more current passes through it. This sensor can sense heartbeats because of this, as blood absorbs significantly more infrared light than other parts of the body. By placing a finger between the infrared photodiode and the infrared phototransistor, a pulse can be measured based on the current output of the phototransistor.



Infrared Transmitter and Receiver Circuit

To design the transmitter circuit with the infrared photodiode, R_D must be chosen to maximize the current in the transmitter while keeping the current within the range that the resistor can handle. To find the current through the LED, the following equation was used:

$$I_D = \frac{V_{CC} - V_D}{R_D} \tag{1}$$

The resistors used in this lab are $\frac{1}{4}$ watt resistors, and the maximum forward current of the transmitter is 100mA, with a forward voltage of 1.4V. These values were applied to the current through the LED formula to ensure the ratings were not exceeded.

$$I_D = \frac{V_{CC} - V_D}{R_D} \;\; \Rightarrow \;\; .1 \geq \frac{V_{CC} - 1.4}{R_D} \tag{2}$$

On the other side, the PT204-6B transistor must stay within the saturation range. The equation for this is the following:

$$v_{PT} = i_{PT} R_E \tag{3}$$

Where v_{PT} is the voltage across the PT204-6B, R_E is the resistor between the source and the transistor, and i_{PT} is the current through the transistor. i_{PT} is proportional to the amount of received infrared light.

The collector-emitter saturation voltage at saturation ($V_{CE(sat)}$) is a maximum of .4V according to the datasheet. This means there needs to be more than .4V dropping across the transistor to stay in the desired region. The typical on-state collector current is 2mA. 1V is above the saturation voltage (.4V) and below the breakdown voltage (30V). These values can be subbed into the equation above to get a starting point for R_E, but it is difficult to calculate the amount of light transmitted through the finger, so R_E was tuned after the circuit was built.

Through ohms law, the voltage drop across the transistor (v_{PT}) is:

$$v_{PT} = V_{DD} - v_{ce} \tag{4}$$

Applying this formula gives the drop across the transistor in terms of known terms:

$$V_{DD} - v_{ce} = v_{PT} = i_{PT}R_E \quad \Rightarrow \quad R_E \geq \frac{V_{DD} - v_{ce}}{i_{PT}} \tag{5}$$

After substituting the values that were decided, the following starting point for R_E was found:

$$R_E \geq \frac{V_{DD} - v_{ce}}{i_{PT}} \Rightarrow R_E \geq \frac{V_{DD} - 1}{.2} \tag{6}$$

This starting point for R_E ensures no components will break and the transistor can be tested to find the best value for R_E.

Filters

After the optical sensor, the output (v_{PT}) of the sensor can be very noisy. Filters can be applied to isolate the heart rate from the noise. These filters also must provide gain since the v_{PT} output is very small.

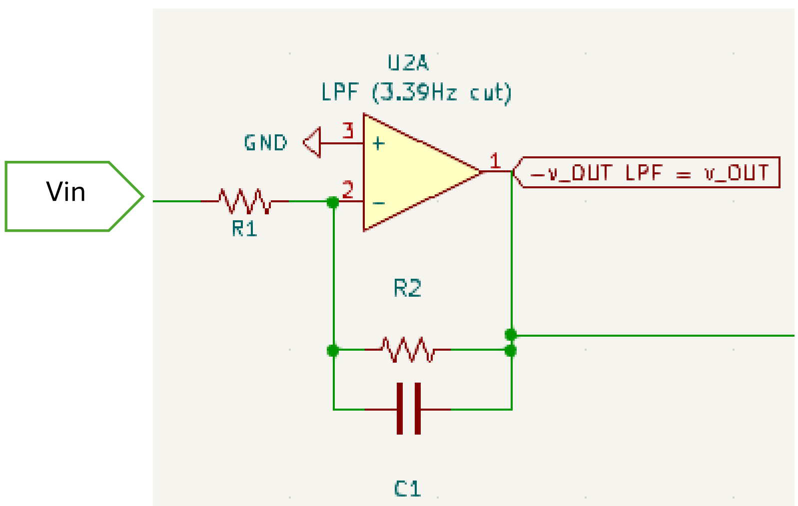
The heartbeat range is from 40-200 bpm, so a high pass filter will allow slow heart rates, and a low pass filter cascaded in series will allow the faster heart rates.

The filters must have a very large and ~equal gain, although there are constraints on how much gain is allowed. If the gain is too high, the internal offset voltage and/or the DC voltage between inputs can cause the output signal to saturate at the wrong times. Capacitors can battle this, but each capacitor will act as a passive high pass circuit.

With these constraints, the total gain ($k_{total} = k_{high\ pass} * k_{low\ pass}$) must be between 100 and 1000, and the gain of each filter must be about the same gain.

Low pass filter

The low pass filter has a cutoff for signals higher than 200BPM. Using an LM324, an active low pass filter can be made to cutoff the high frequency signals. A first order inverting low pass filter (as shown below) can be used for this.



Inverting low pass filter circuit

The transfer function for this circuit can be derived as:

$$H(s) = \frac{-\frac{R_2}{R_1}\frac{1}{R_2C_1}}{s + \frac{1}{R_2 + C_1}} \tag{7}$$

The first order filter form is $H(s) = \frac{k\omega_0}{\omega_0 + s}$, so the gain of the LPF can be found as $k_{LPF} = -\frac{R_2}{R_1}$ and the ω_0 can be found as $\omega_{0_{LPF}} = \frac{1}{R_2C_1}$.

High pass filter

Similar to the low pass filter, the high pass filter cuts off non heartbeat frequencies, too. The high pass filter only allows heart rates above the minimum heart rate, so the cutoff frequency should be just below the minimum heart rate.

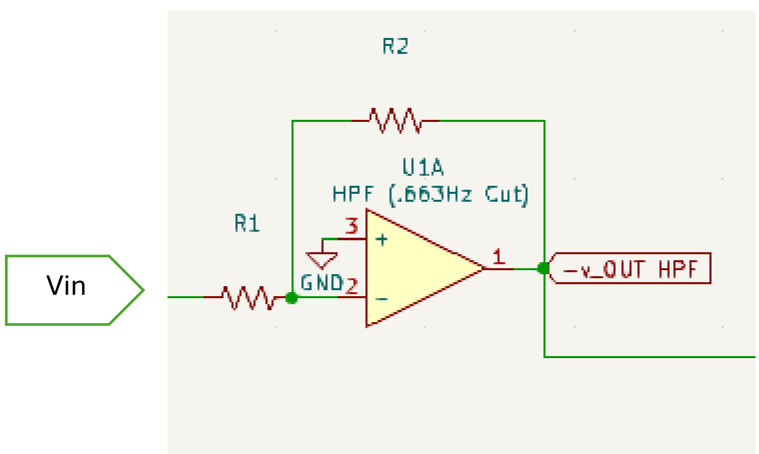
Similarly to the low pass filter, the high pass filter is also inverting and first order. From the circuit below, the transfer function can be found as:

$$H(s) = \frac{-\frac{R_2}{R_1}s}{s + \frac{1}{R_1 C_1}} \tag{8}$$

The first order filter form ($H(s) = \frac{ks}{\omega_0 + s}$) gives the gain and ω_0 as:

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

$$\omega_{0_{high\ pass}} = \frac{1}{R_1 C_1} \tag{10}$$



Inverting high pass filter circuit

Analog to digital conversion

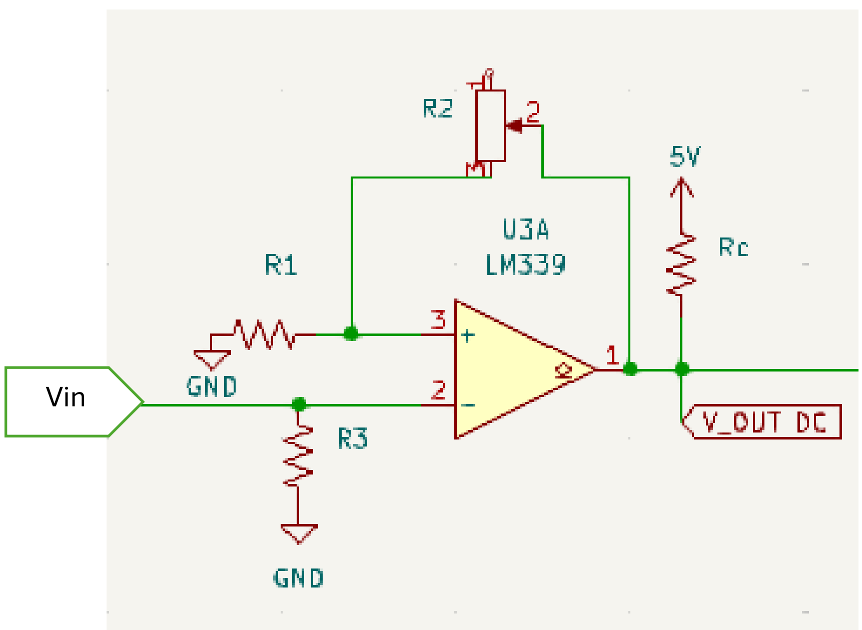
After going through the filter circuits, the output signal is significantly less noisy than the raw output from the sensor. For the signal to be more useful and readable, a comparator is used to make a clean DC signal. A comparator with hysteresis is able to convert the filtered AC signal into a DC signal. A comparator with hysteresis is required because normal comparators are sensitive to noisy signal inputs, while a comparator with hysteresis is not due to its latch like behavior. The output does not switch until the input reaches $-V_{th}$ or $+V_{th}$, so small noise does not interfere.

This threshold voltage is found as:

$$v_{th} = \frac{v_{hyst}}{2} \tag{11}$$

The v_{hyst} is the difference between the threshold voltages. It is found by:

$$v_{hyst} = (2V_{DD})\left(\frac{R_1}{R_1 + R_2}\right) \tag{12}$$

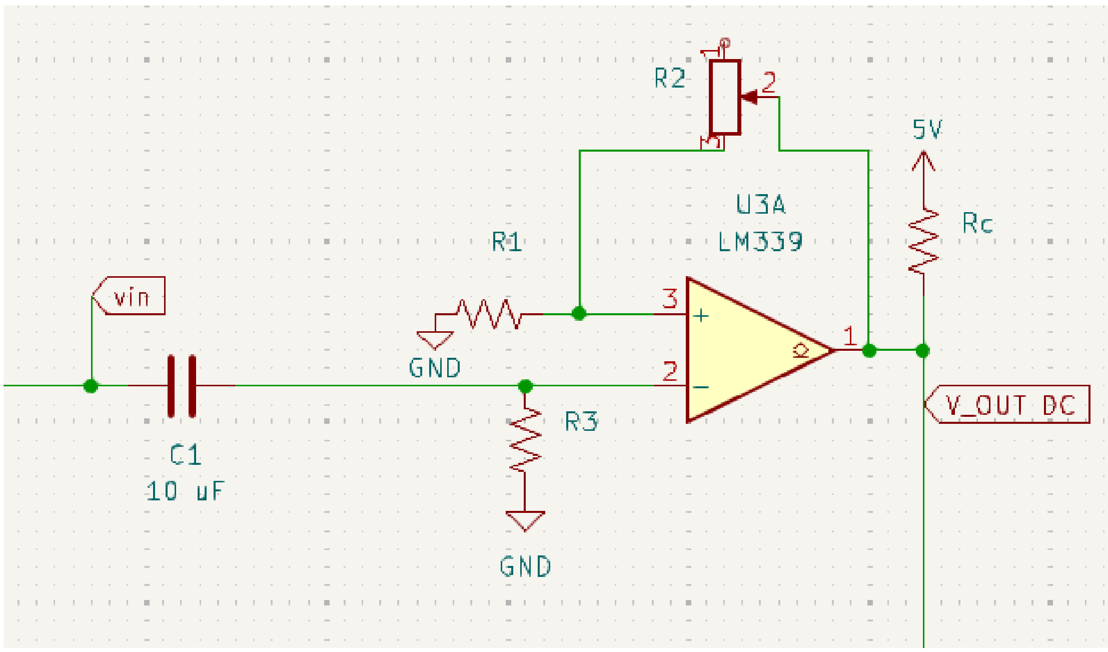


Inverting comparator with hysteresis circuit

Since the amount of hysteresis is determined by the resistance of R_1 and R_2, a decade box was used to vary the resistance of R_2 so that v_{hyst} could be tuned experimentally. R_c was added as a pull-up resistor as mentioned by the datasheet.

To make sure that the input is centered around 0V so the comparator can work, a capacitor is added before the circuit to block DC offsets. This capacitor also acts as a passive high pass filter and can help filter any leftover low frequency signals. This capacitor also acts as a passive high pass filter and can help filter any leftover low frequency signals. This capacitor must have similar cutoff frequency to the one in the active high pass filter (about 4.2). To calculate the cutoff frequency:

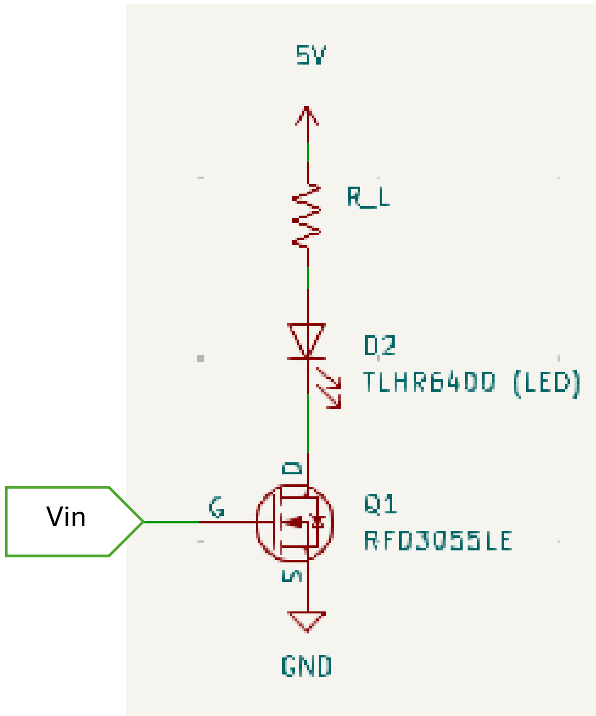
$$\omega_{0_{HPF}} = \frac{1}{R_3 C_1} \tag{13}$$



Inverting comparator with hysteresis with capacitor before the input

Visual Indicator

This heartbeat sensor would not be super useful without a visible output. Using the DC output from the ADC converter, the LED blinks with the heartbeat pulse.



Visual Indicator Circuit

To be able to see the LED clearly, it is best to have it as bright as possible without exceeding its ratings. To maximize the brightness, the current should be increased. The voltage drop across the MOSFET can be assumed to be zero, so the drop across the resistor can be found as:

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

The datasheet for the TLHR6400 LED has a 2V typical forward voltage, and a maximum continuous current of 30mA. Through Ohm's law, I_{LED} is found to be $\frac{V_{DD}-2}{R_L}$. I_{LED} needs to be less than the maximum continuous current. Using this relationship, R_L can be estimated.

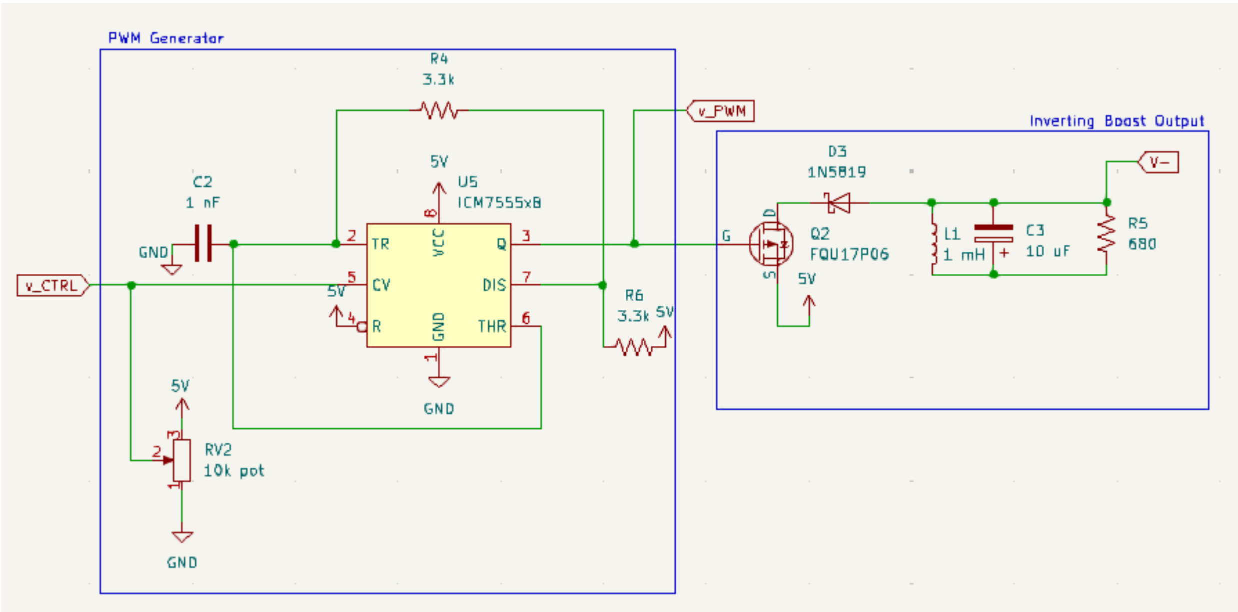
$$I_{LED} < \frac{V_{DD}-2}{R_L} \Rightarrow R_L < \frac{V_{DD}-2}{I_{LED}} \tag{14}$$

So, this gives:

$$R_L < \frac{V_{DD}-2}{.3} \tag{15}$$

Extra credit: -5V Supply

Inverting Boost Circuit

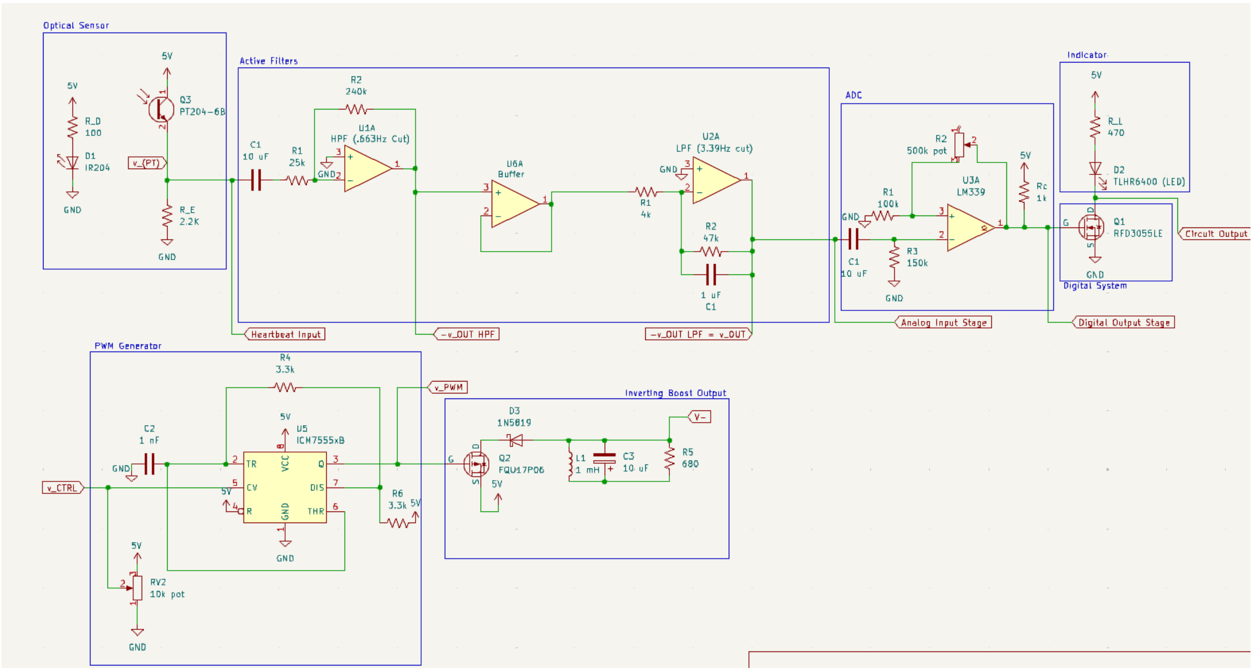


This lab requires 2 supplies: a +5v and a -5v. This can be done by using the ±5v supplies from the AD2, or an inverted boost converter circuit can use the +5v from the AD2 to create the -5v and only one power rail is required.

Using the inverting boost and PWM circuits derivations from previous labs 10 and 2, an inverting boost converter circuit can be used to power the -Vin pins for the LM339 and the LM324 chips.

The inverting boost converter was designed so using the potentiometer adjusts the duty cycle of the PWM generator, thus controlling the voltage output. This potentiometer lets the circuit be tuned manually without tedious calculations.

Full Circuit Diagram



Full Circuit Diagram (with buck converter)

In theory, each substage should be connected output to input in order (sensor, filters, ADC, then indicator). In practice, loading causes an issue for the filters and a non-inverting buffer was added between the HPF and LPF during testing to eliminate the need to worry about impedance and loading between the filters. The full circuit diagram includes the buffer and the -5v supply circuit.

Design/Calculations

This lab uses a single supply voltage of +5v. The components used are an IR204, PT204-6B, NE555, FQU17P06, 1N5819, LM324, LM339, RFD3055LE, resistors, capacitors, and an LED.

Individual Subsystems

Optical Sensor

Using the equations derived earlier, the required values can be found.

Plugging the V_{DD} value (+5V) into equation 2 gives 36Ω. A 100Ω resistor was used due to availability.

The 100Ω resistor still works with these components:

$$.1^2 * R_D \leq .25, so\ R_D \geq 2.5m\Omega$$

For R_E, $+5V$ is plugged in for V_{DD} in equation 6. This gives:

$$\frac{5-1}{.2} \leq R_E, so\ 2k\Omega \ \leq R_E$$

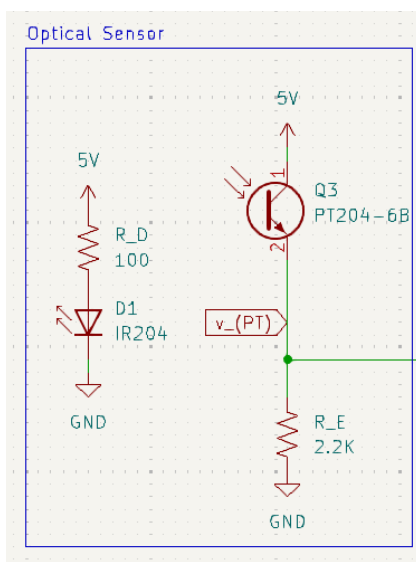
A 2.2kΩ resistor was used due to component availability (just as before).

The 2.2kΩ resistor does still work and remain under .25W, as shown below:

$$.2^2 * R_D \leq .25, so\ R_D \geq 62.5n\Omega$$

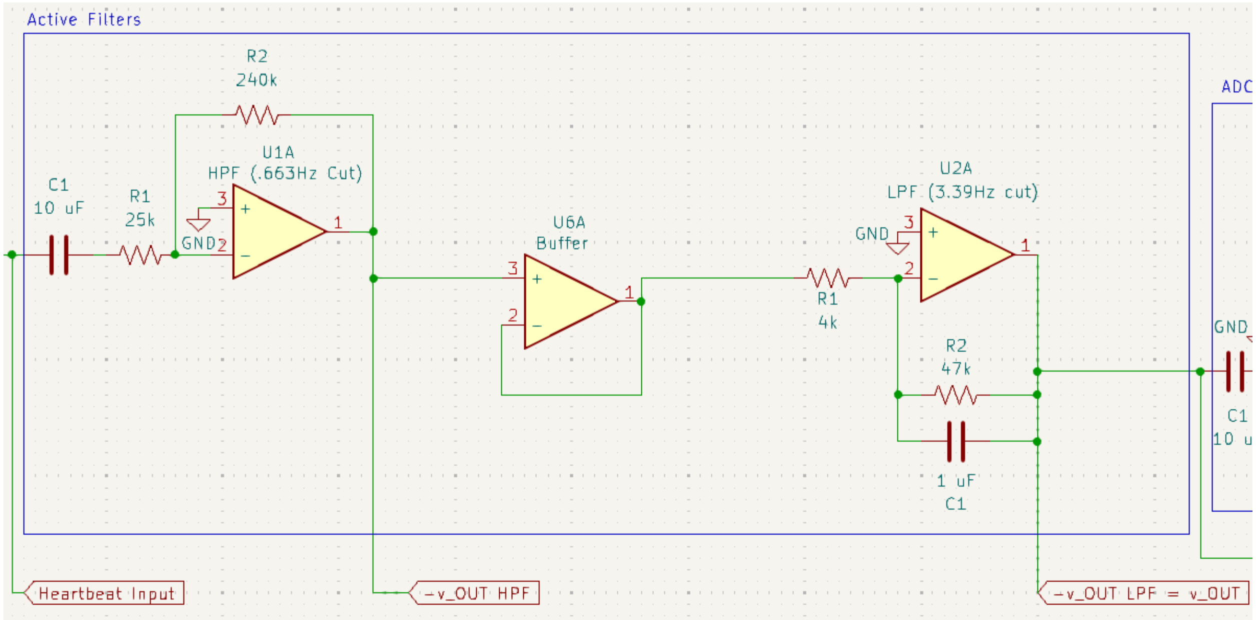
The breakdown voltage is at 30V, so the 5v supply does not have the ability to cause a problem. Using the found values, the circuit with the real values can be seen below:

Circuit



Infrared Transmitter and receiver circuit (with real values)

Filters:



Since

Since it is known that $100 < k_{HPF} * k_{LPF} < 1000$, a gain of around 100 can be chosen. This means a gain of ~10 for both filters.

Low pass filter

The maximum heartrate this project is assumed to be around 200 BPM. In Hertz, this is:

$$200\frac{beats}{min} * \frac{1\ min}{60\ sec} = 3.33Hz = f_{0_{LPF}}\ \ or:\ \ 2\pi f_{0_{LPF}} = \omega_0 = 20.9\frac{rad}{s}$$

Using equation 8, the approximate gain (|k|≈10) gives the following values:

$$C_1 = 1\mu F$$

$$R_1 = 4k\Omega$$

$$R_2 = 47k\Omega$$

With these values, equation 9 yields the solution:

$$\omega_0 = \frac{1}{R_2 C_1} = \frac{1}{47k\Omega * 1\mu F} = 21.28\frac{rad}{s}$$

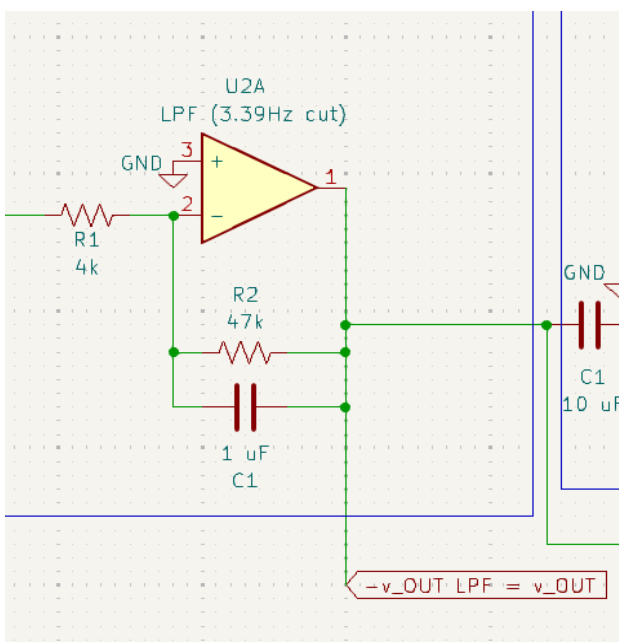
This ω_0 is slightly above the desired 20.9, so the filter will allow the wanted frequencies to pass. These values will work for the low pass filter.

Using these values in equation 8 give the following gain:

$$k_{LPF} = -\frac{R_2}{R_1} = \frac{-47k\Omega}{4k\Omega} = -11.75$$

The magnitude of this gain is approximately 10, so these values for the filter will work.

Circuit



Inverting low pass filter circuit

High pass filter

The minimum heart rate that can be detected in this circuit is 40 BPM. Converted to Hz, like for the LPF, the heart rate frequency is about .667 Hz, or 4.187 $\frac{rad}{s}$.

Using equation 11 with an approximate gain of 10, the following values are found:

$$C_1 = 10\mu F$$

$$R_1 = 25k\Omega$$

$$R_2 = 240k\Omega$$

With these values and equation 12, the values can be checked with the value found:

$$\omega_0 = \frac{1}{R_1 C_1} = \frac{1}{25k\Omega * 10\mu F} = 4\frac{rad}{s}$$

This value is slightly below the target, so the filter will allow the frequencies wanted to pass.

To check the gain with these values, equation 11 is used again:

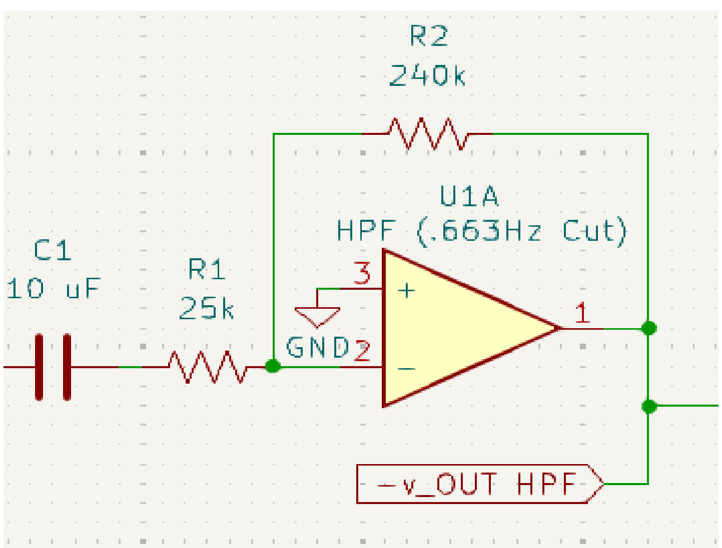
$$k_{HPF} = -\frac{R_2}{R_1} = -\frac{240k\Omega}{25k\Omega} = -9.6$$

The magnitude of the gain is about 10, as desired. To check if the two filters in series work together, the total gain of the filters is found by multiplying their gains together. The total gain should be between 100 and 1000, as stated earlier.

$$9.6 * 11.75 = 112.8$$

The total gain 112.8 falls between 100 and 1000, so it will work as expected.

Circuit



High Pass filter with the component values

Analog to digital

Using the supply voltage of 5v for V_{DD} and a 500kΩ potentiometer for R_2, the values are plugged into equation 14:

$$v_{hyst} = (2V_{DD})\left(\frac{R_1}{R_1 + R_2}\right) = (2 * 5V)\left(\frac{R_1}{R_1 + 500k\Omega}\right)$$

The v_{th} must be in between this voltage and V_{DD}. To allow weak and strong signals,, the minimum v_{th} should be around 1V. With this, R_1 is set to 100kΩ.

$$.83V \leq v_{th} \leq 5V$$

To create the passive high pass filter with $\omega_0 \approx 4.2$, equation 13 is used:

$$\omega_{0_{HPF}} = \frac{1}{R_3 C_1} = 4.2$$

Using components available in the lab kit, the following values were calculated to be suitable:

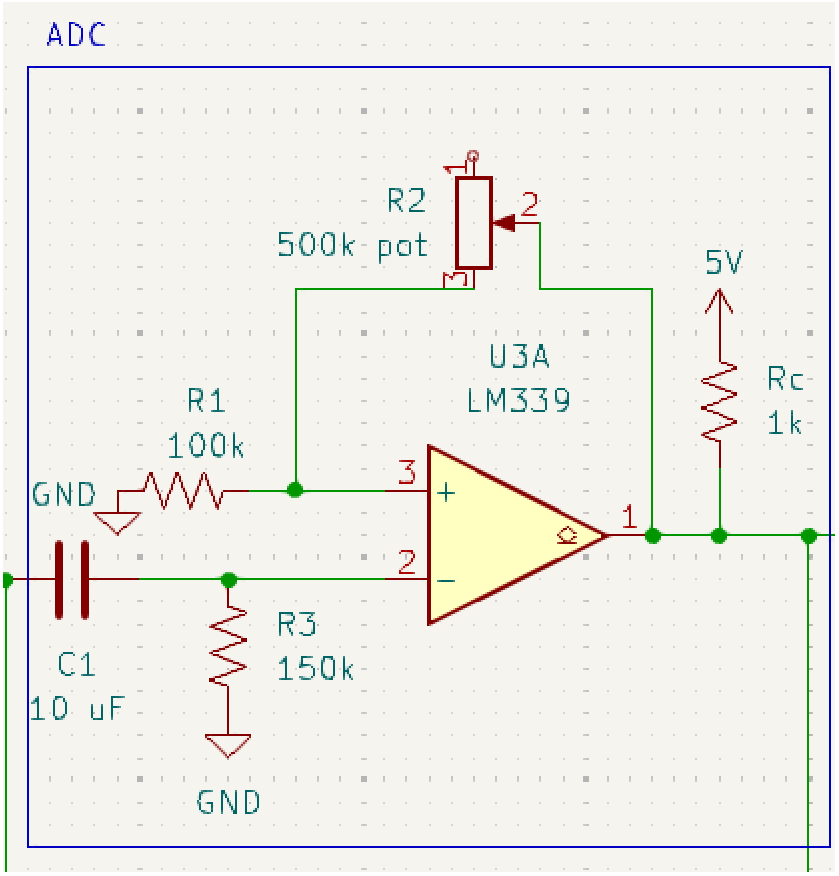
$$C_1 = 10uF$$

$$R_3 = 150k\Omega$$

To check these, the values are plugged back into the equation to get a $\omega_0 \approx .67\,\frac{rad}{s}$

The pull up resistor shown in the circuit (R_C) is chosen to be a 1kΩ resistor based on the datasheet.

Circuit



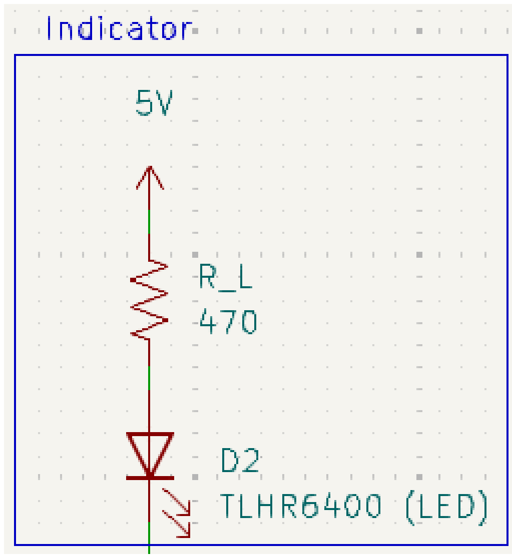
ADC Circuit with High pass filter and component values

Visual Indicator

Using the equation 16 and $V_{DD} = 5V$, R_D is found to be $R_D \geq 100\Omega$. However, when the 100Ω is used in lab, it gets very hot and a 470 Ω resistor was used in its place. The 470 Ω resistor is check to make sure the LED remains below .25W (with 3V across R_L):

$$\frac{3^2}{R_D} \leq .25 \rightarrow R_D \geq 36\Omega$$

Circuit



LED indicator circuit

Final Circuit

Physical Tuning

In lab, all the stages were built using the theoretical values. It was expected for the values to need adjustments to be more accurate.

Final Values:

HPF:

$$R_1 = 33k\Omega$$

$$R_2 = 330k\Omega$$

$$C_1 = 10uF\ (unchanged)$$

LPF:

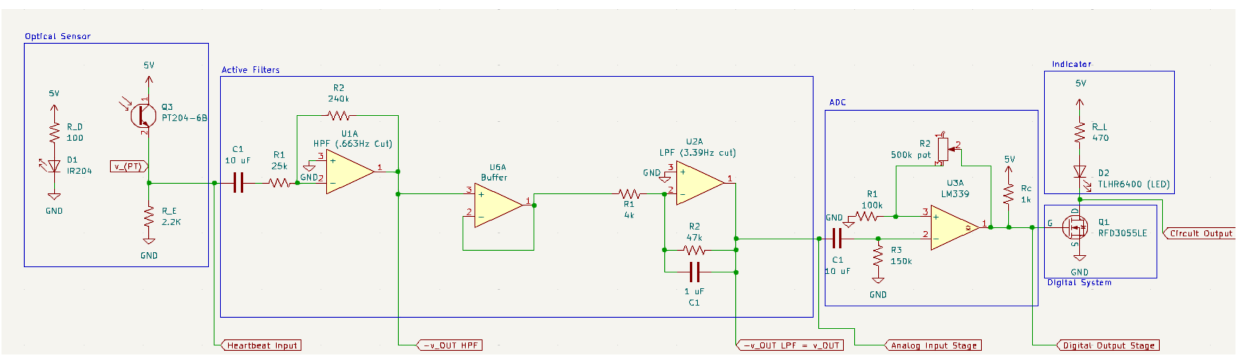
$$R_1 = 6.8k\Omega$$

$$R_2 = 75k\Omega$$

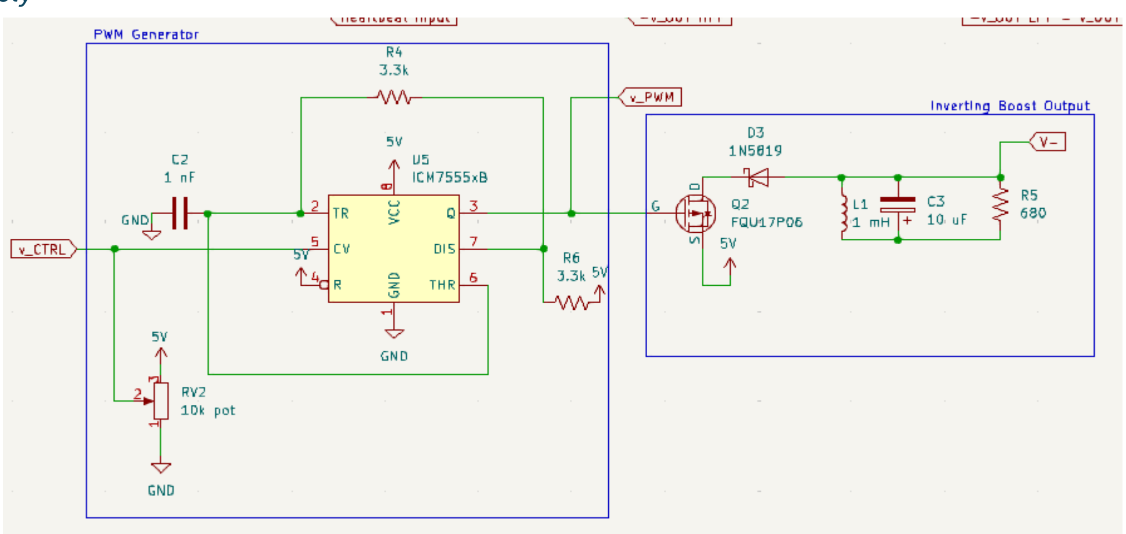
$$C_1 = 1uF\ (unchanged)$$

Final Circuit schematic with values:

Circuit



-5v Supply

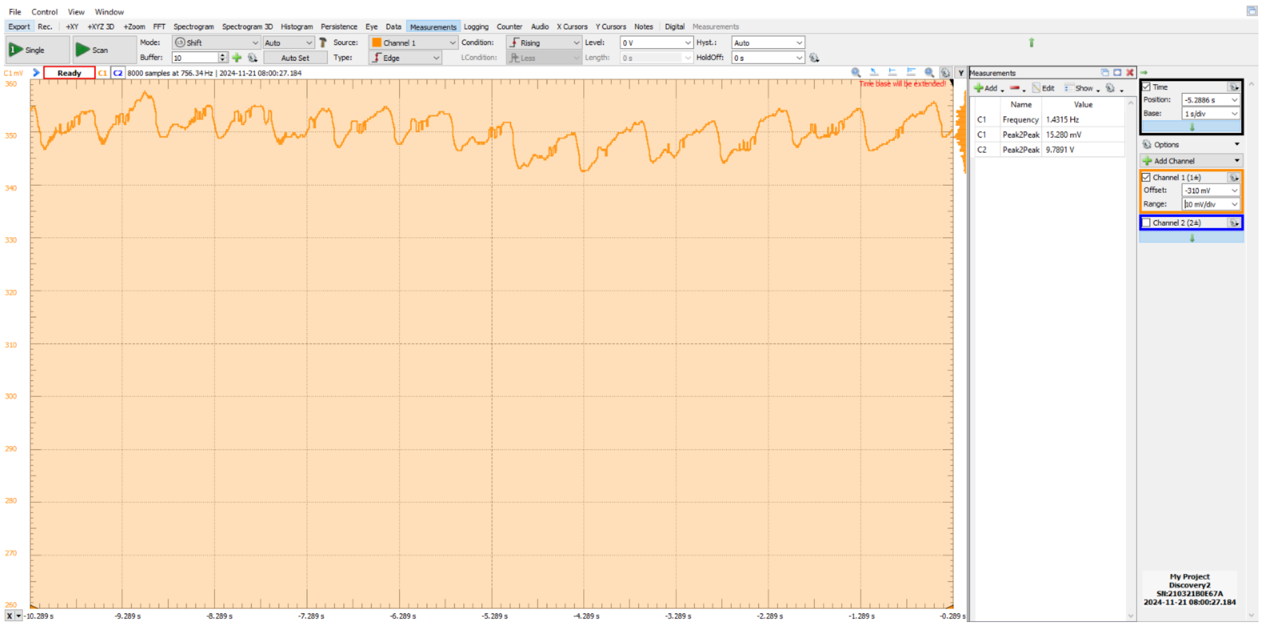


Results

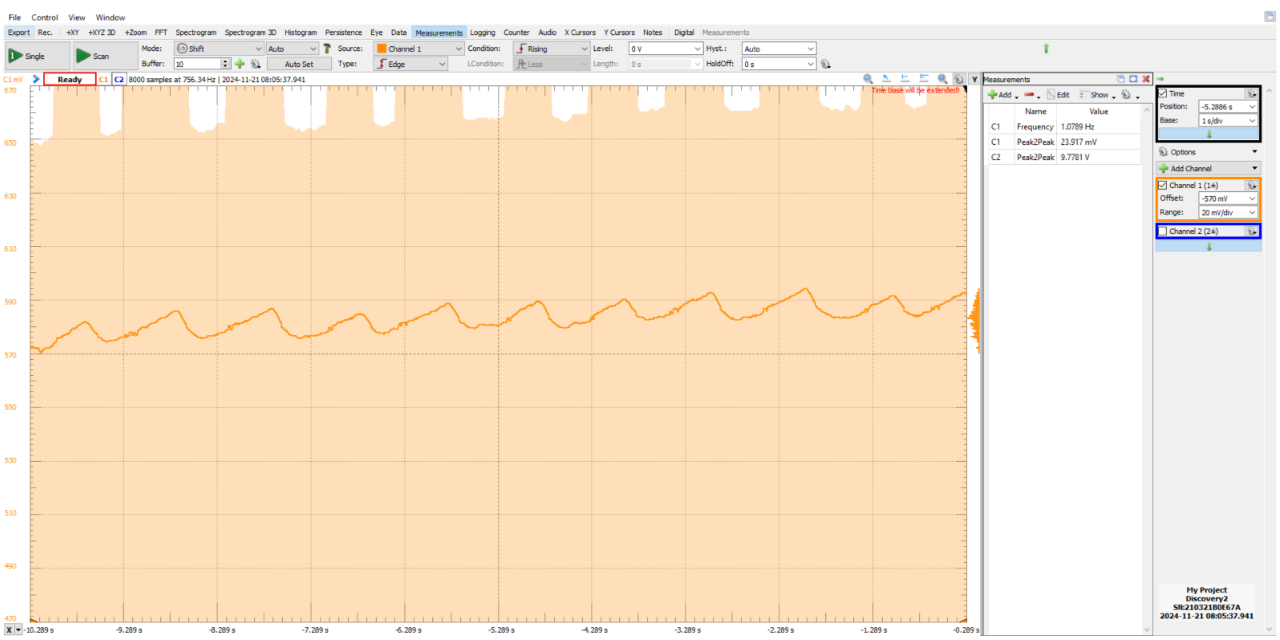
Sensor Measurement

The IR sensor and receiver successfully picked up a heartbeat signal when a finger was placed between them.

Plot



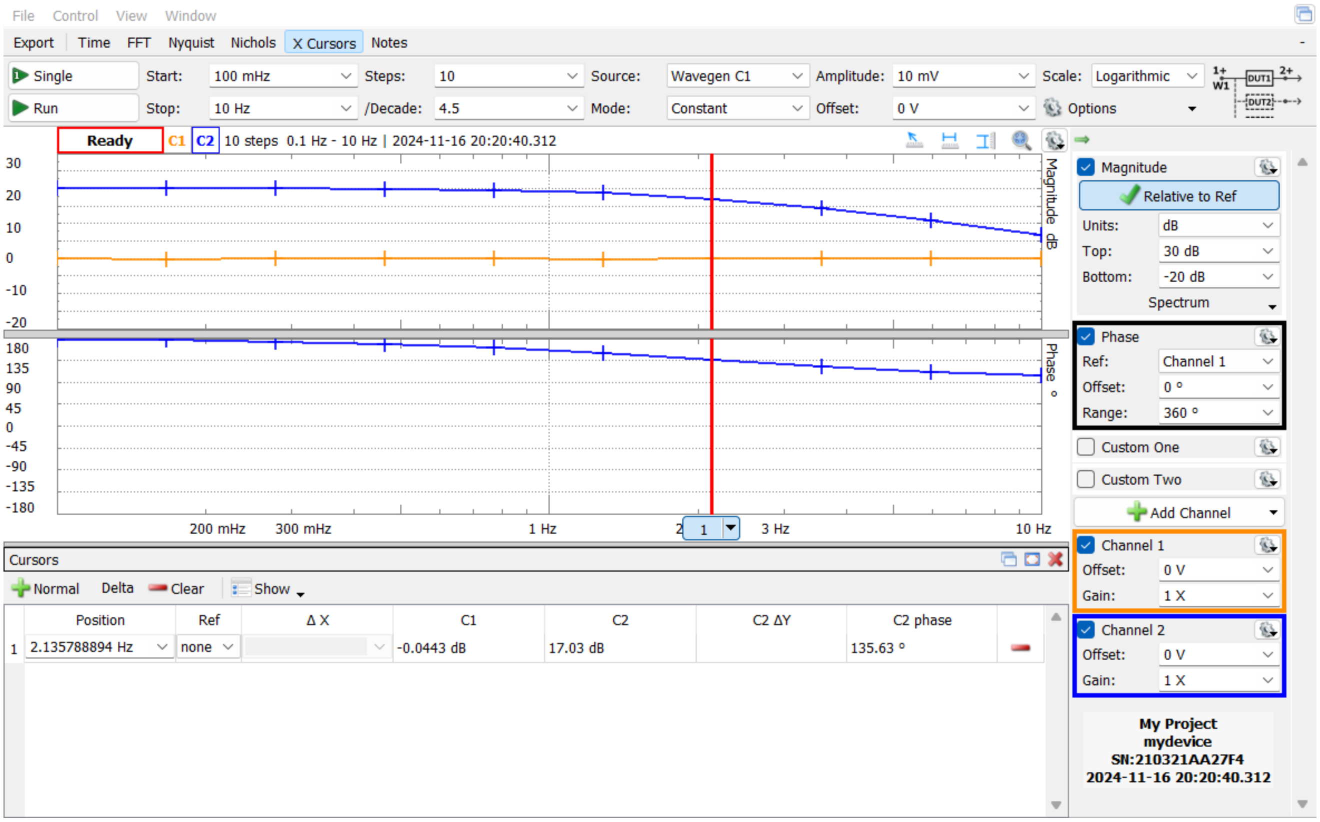
Optical sensor with thumb in sensor



Optical Sensor with pointer in sensor

LPF Measurement

Plot



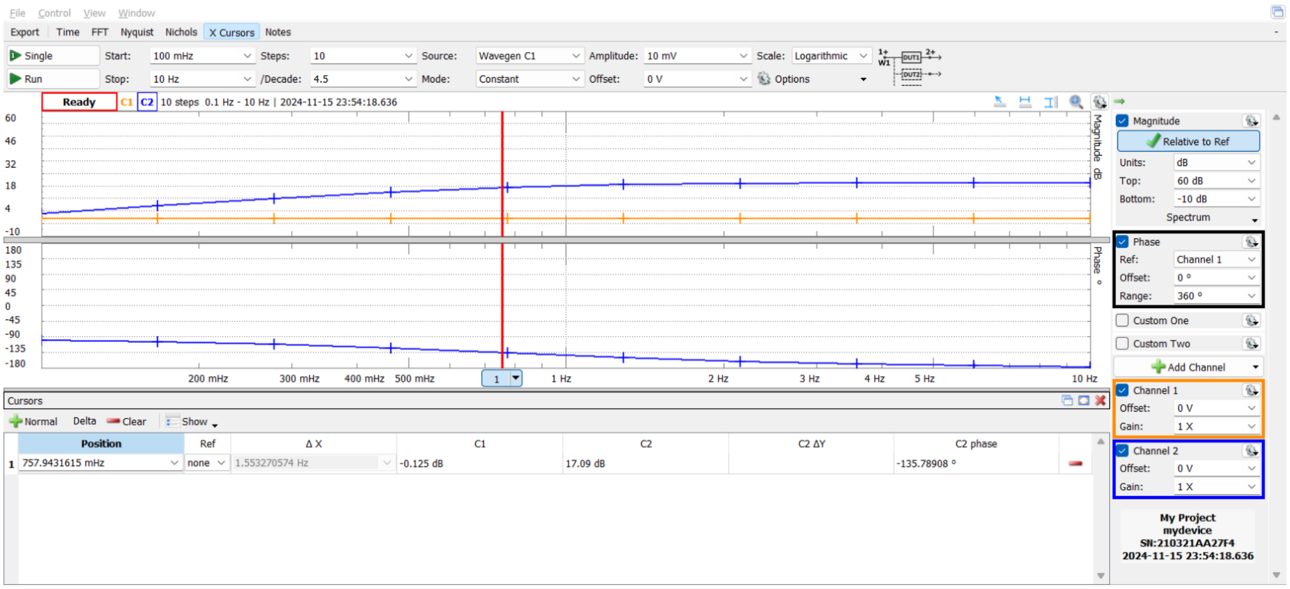
Low Pass Filter FRA

$$f_{0_{LPF}} = 2.136Hz$$

This is a lower cutoff frequency than expected, but when the circuits are combined together, the filter works as intended.

HPF Measurement

Plot

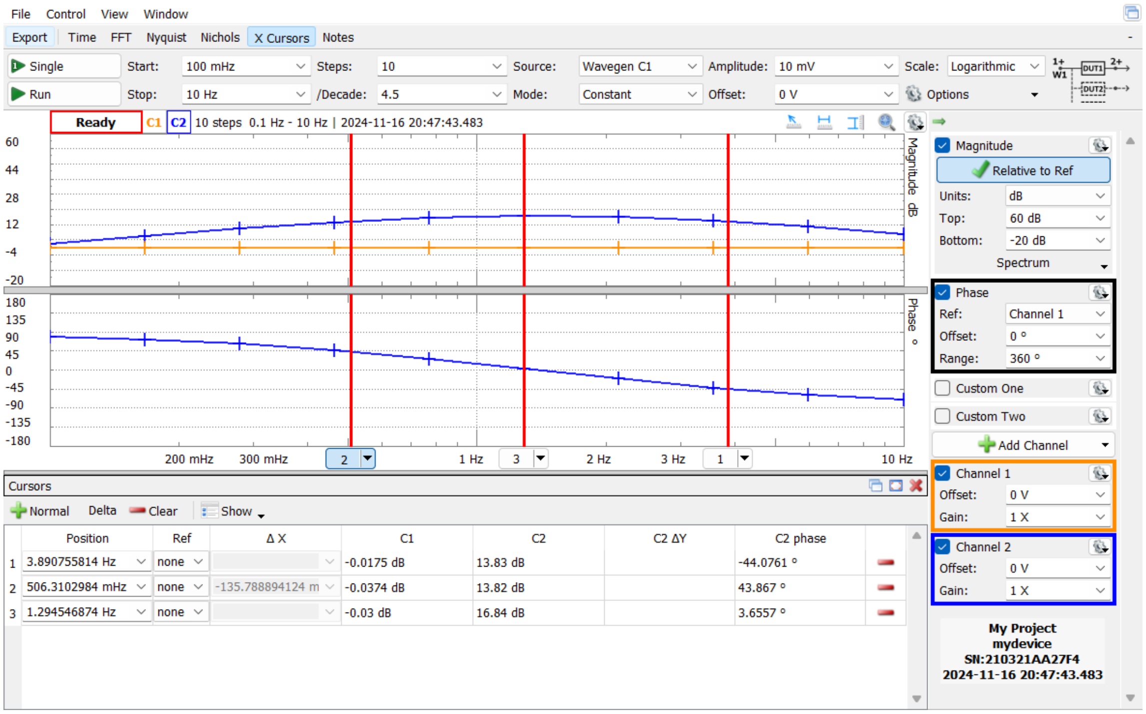


High Pass filter FRA

$$f_{0_{HPF}} = .758\ Hz$$

Filter Output

Plots

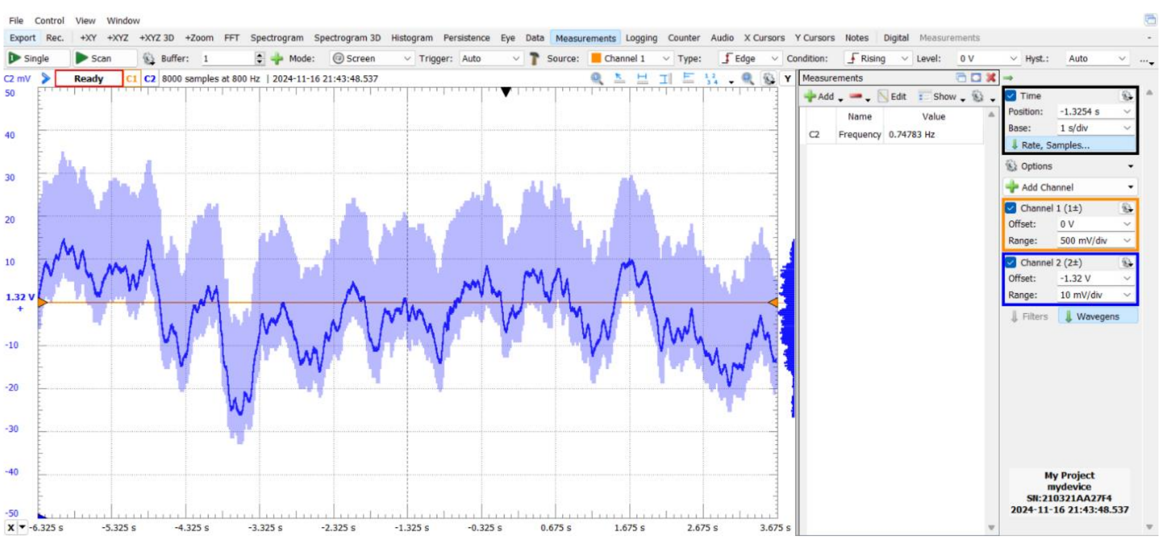


Band Pass filter FRA (combined LPF and HPF)

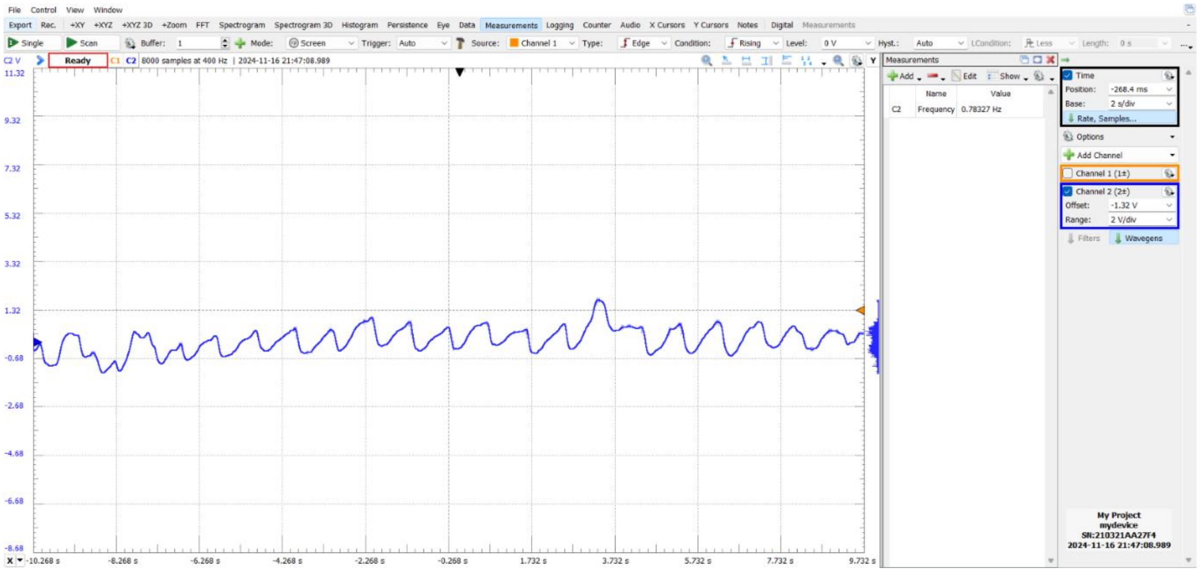
$$f_H = 0.506Hz$$

$$f_c = 1.295Hz$$

$$f_L = 3.891Hz$$



Filter input (Receiver output)

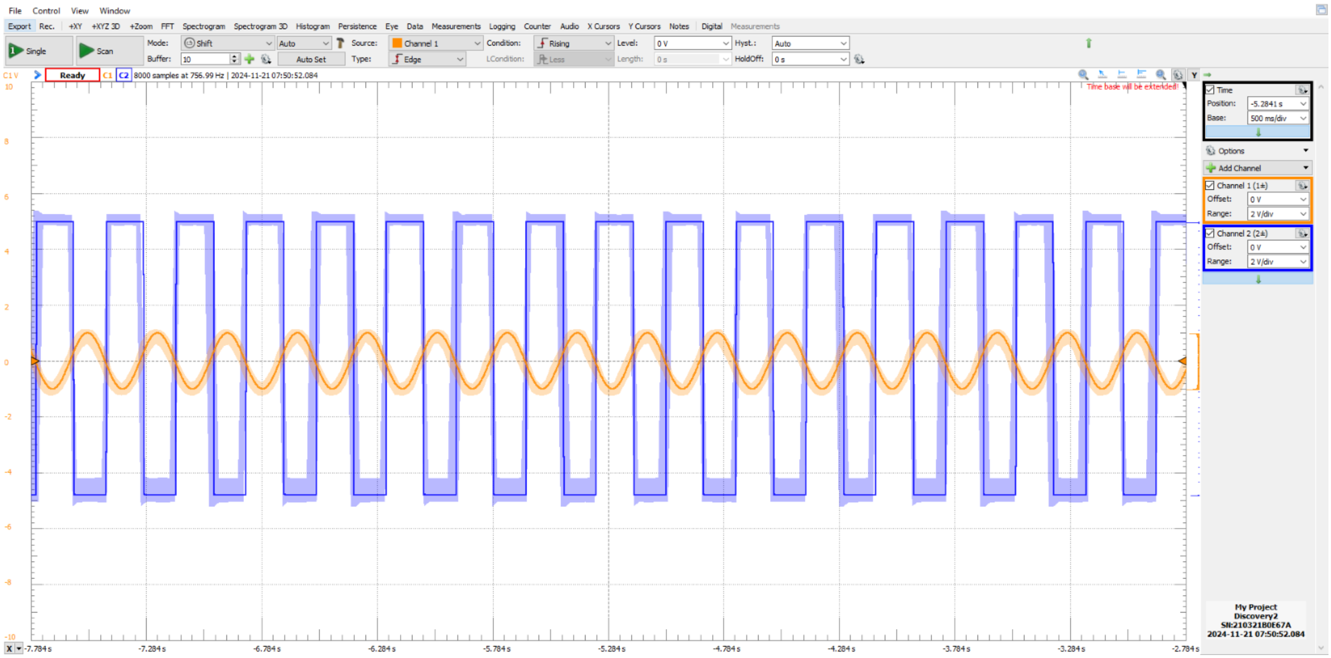


Filter output (ADC input)

ADC Measurement

To test the ADC circuit, a 1V 1Hz sin wave was applied to the v_{in} where the filter output would have gone. This test showed the ADC worked, as shown below:

Plot

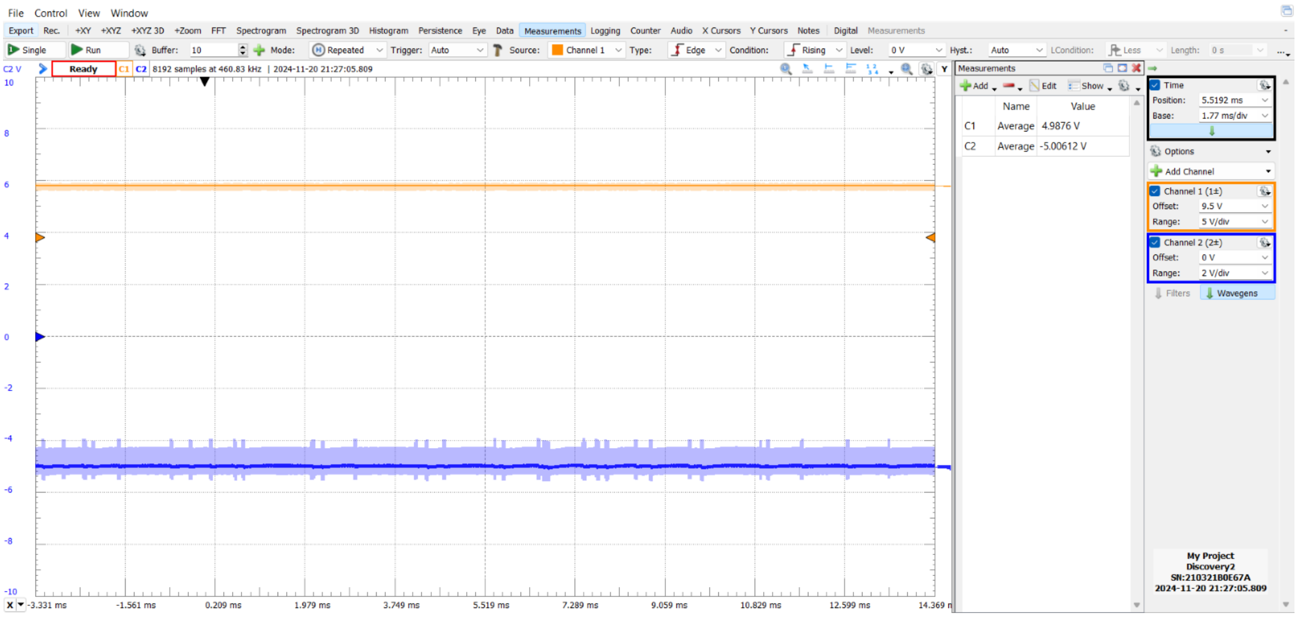


Isolated ADC measurement with input signal

-5v Supply

As shown below the +5v rail successfully powered the inverted boost converter to produce -5v.

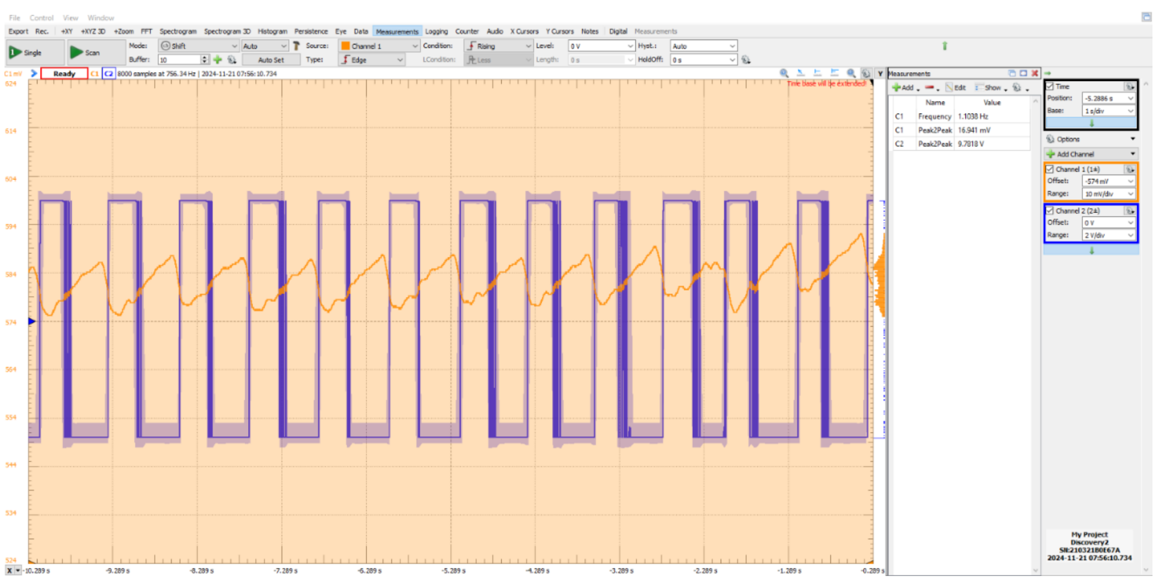
Plot



+5v and -5v rail measurements

Fully Integrated Project

Plot



Full circuit test (CH1: V_{pt}, CH2: $V_{out\ DC}$)

Conclusion

This project successfully displayed a heart rate on the LED. Each subsystem worked independently – the sensor successfully detected change in infrared light, the filters successfully removed unnecessary signals, the ADC successfully turned the AC signal into a clean DC signal, and the display successfully showed the heartbeat. The inverted boost converter also created a -5v DC signal without the use of the AD2's second voltage rail. The sensor worked very well with still hands.

The sensor was sensitive to movements, but this could be easily fixed by properly mounting the emitter and transmitters. When the hand was removed, the signal also self oscillated. This did not affect the use of the filter, but it was not intended. This could be prevented by fixing the random capacitances within the large 2 breadboards that were used. The components used were cheap and there were a lot of connections, so overall it did not matter much because it detected the heartbeat well before the hand was removed.

References

Texas Instruments. (n.d.). *LM324 low power quad operational amplifier* [Data sheet]. Retrieved December 7, 2024, from https://www.ti.com/lit/ds/symlink/lm324.pdf

Texas Instruments. (n.d.). *LM339-N low power quad comparator* [Data sheet]. Retrieved December 7, 2024, from https://www.ti.com/lit/ds/symlink/lm339-n.pdf

Texas Instruments. (n.d.). *NE555 precision timer* [Data sheet]. Retrieved December 7, 2024, from https://www.ti.com/lit/ds/symlink/ne555.pdf

Lite-On. (n.d.). *LTV-2751 optocoupler* [Data sheet]. Retrieved December 7, 2024, from https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/3837/1239779737_2751.pdf

Everlight. (n.d.). *PT204-6B phototransistor* [Data sheet]. Retrieved December 7, 2024, from https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/4819/PT204-6B.pdf