Designing and building a circuit to measure heart rate

6.071 – Electronics, Signals and Measurement

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1 Objective

In this laboratory experiment, the goal was to design and test a circuit that is capable of measuring a human's heart rate. To be read by a LabVIEW program, the heart rate signal needed to be in the form of a square wave with high and low values of zero and five volts, respectively, with a tolerance of ±200mV. Additionally, the duty cycle for this wave must be between 35% and 65%, with a duty cycle close to 50% yielding the highest accuracy reading.

2 Background

The heart is responsible for delivering blood to all parts of the body by acting as a pump that causes blood to flow through the complex piping system of arteries and veins. From pump to pump, the volume of blood in these arteries fluctuates between a low and high value.

In this laboratory, we will take advantage of these fluctuations to measure the rate at which the heart beats. If an infrared light emitting diode is placed in front of a human finger and fed a constant current, the amount of IR light that is able to pass through the finger will depend directly on the volume of blood in the finger at the moment. This varying amount of light can be measured by an IR phototransistor placed directly across from the IR LED. This is the strategy that is used in this laboratory to obtain an input signal for the system that will then process the signal to meet the specifications required by the LabVIEW instrument.

The components used in the design of the circuit include resistors, capacitors, op amps, diodes, and transistors. All of the op amps in the circuit are LF356 op amps powered with ±15V, despite these connections not appearing in the schematics throughout the report.

3 Circuit Design

The circuit that was designed to process the incoming heart rate signal has several elements and stages, but these pieces can be represented as several basic processing stages, shown in the block diagram in Figure 1.

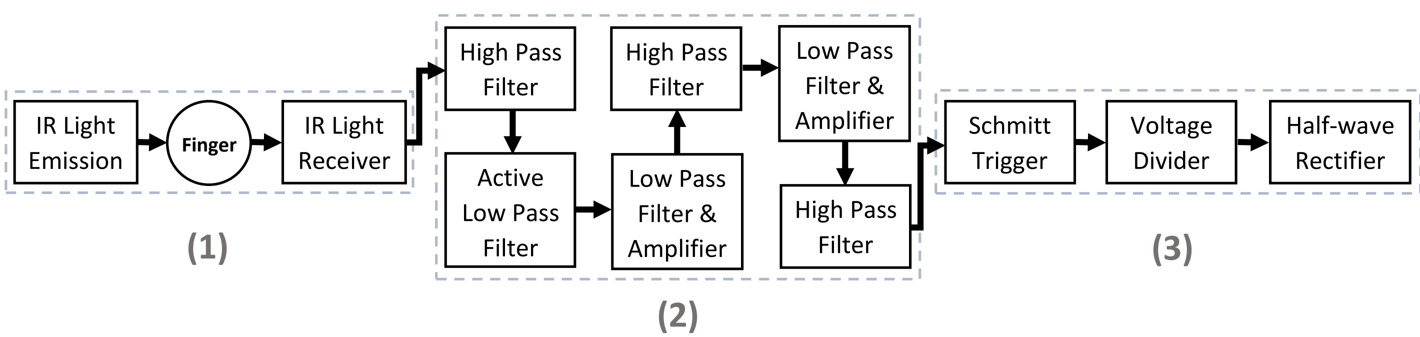

Figure 1: Block diagram of the full circuit, where each block represents a subcircuit and the larger groups represent a group of subcircuits that perform similar or related functions

Each of the individual blocks represents a single subcircuit that serves its own purpose, and the groups of blocks, identified by the grey dashed boxes, represent several subcircuits that perform similar or related functions. Group 1, as seen in Figure 1, is the aspect of the circuit that the user interacts with. This group of subcircuits emits and receives light as it passes through the user's finger. Group 2 includes all of the filtering and amplifying stages that allow the heart rate to be extracted from the noisy input signal. Group 3 takes in the filtered, amplified signal and turns it into a square wave with the specifications outlined in Section 1. Each of these subcircuits will be outlined in the following sections.

3.1 Group 1 Subcircuits

Group 1 consists of two separate circuits and the user's finger. The setup in this laboratory utilizes a tube structure that provides a fixed location for the LED and transistor elements and also gives the user a place to precisely position his finger. A diagram of the cross section of this structure is seen in Figure 2. This section will provide a description of the components in the two circuits and justify the component values chosen.

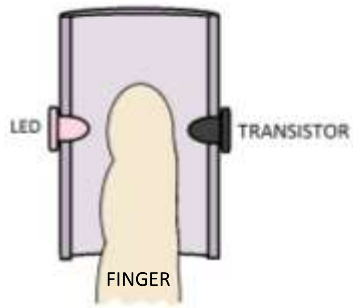

Figure 2: Cross sectional diagram of device that holds LED and transistor, with place for user to insert finger

3.1.1 IR Light Emission

The system begins with an infrared light source, which provides a means to probe the changing blood volume in the finger. The infrared light is emitted from a QED123 infrared light emitting diode, which is connected to a five volt power source at the positive terminal and to a 36Ω resistor at the negative terminal. The other end of the resistor then goes to ground. A schematic of this circuit can be seen in Figure 3, where $R_1 = 36\ \Omega$.

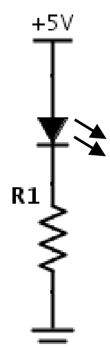

Figure 3: Schematic of circuit that powers QED123 infrared LED, where $R_1 = 36\ \Omega$

The value for resistor R_1 was chosen to maximize the power output by the diode, such that more light would be passing through the user's finger. The LED is rated[1] for a current of $I_{max} = 100mA$, so a resistor value that allowed approximately that much current to flow through the LED was chosen. Because the forward voltage drop across the LED is 1.7V, that means that $V_{drop} = 5V - 1.7V = 3.3V$ would be the voltage drop across whichever resistor was chosen. This means that the ideal resistor would be given by

$$R = \frac{V_{drop}}{I_{max}} = \frac{3.3V}{100mA} = 33\Omega\,.$$

The value $R_1 = 36\ \Omega$ was chosen because it was an easily accessible resistor value, and it is close to the ideal value such that it still provides high power output for the diode.

3.1.2 IR Light Receiver

The light that is emitted from the LED passes through the user's finger and then is received by a QSD123 infrared phototransistor. A phototransistor is characterized by taking in light as input to its base, which determines what happens at the emitter output. The transistor component is wired in a circuit that resembles that for the diode. The schematic for this subcircuit, shown in Figure 4, consists of a positive five volt power source connecting to the collector and a resistor $R_2 = 1k\Omega$ connected between the emitter and ground. Also connected at the emitter is the next component of the full circuit, described in Section 3.2.

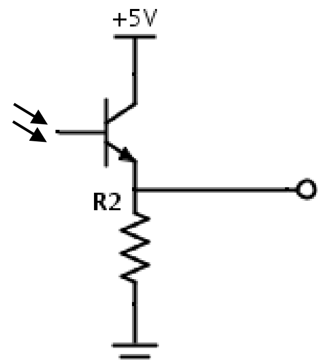

Figure 4: Schematic of infrared phototransistor circuit, where $R_2 = 1k\Omega$, and the node on the right is where the next stage of the circuit is connected.

The value of resistor R_2 was chosen to limit the current entering the op amp in a later stage of the circuit. In the actual circuit, the LED and the phototransistor must be placed directly facing each other, as shown in Figure 2, in order to effectively measure the light emitted from the diode without excessive loss. The output voltage at the emitter node is shown in the oscilloscope image in Figure 5, where the first trace (yellow) is the finalized heart beat signal and the second trace (blue) is the emitter node. The output signal at this node is not useful yet because there is high and low frequency noise that makes the underlying heart rate signal impossible to identify. Later stages of the circuit are designed to remove this noise in order to extract the desired signal.

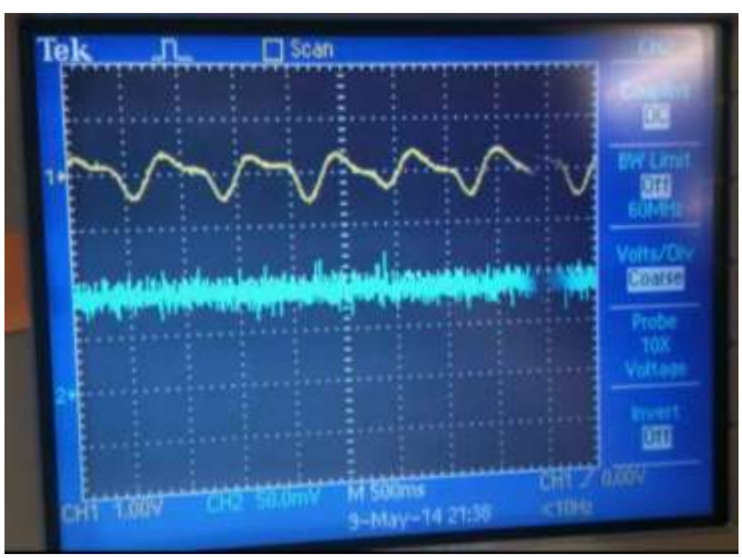

Figure 5: Voltage traces of filtered heart rate (yellow, trace 1) and phototransistor emitter output (blue, trace 2)

3.2 Group 2 Subcircuits

This section of the full circuit is responsible for turning the noisy signal seen in Figure 5 to a clear wave that represents the change in blood volume in the user's finger. Because a typical human heart rate ranges from 60 to 180 beats per minute, the desired output frequency of the signal is between 1 to 3 Hertz. To achieve a clear signal, all frequencies above and below these limits must be filtered. Additionally, the phototransistor emitter voltage only has an amplitude of approximately 5mV, which is too small to effectively detect meaningful fluctuations. For this reason, the filtered signal must also be amplified in this group of subcircuits. The subcircuits in this section include an active low pass filter, three identical high pass filters, and two non-inverting amplifiers with low pass filtering.

3.2.1 High Pass Filters

Although the heart beat signal is at a low frequency, between 1 to 3 Hertz, there is still low frequency noise that pollutes the signal. In particular, the noise at zero frequency causes a DC offset that causes the signal to drift further from zero as it is amplified. To reduce this offset, high pass filters, seen in Figure 6, can be used to remove the majority of frequencies lower than 1Hz.

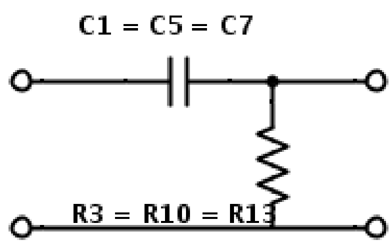

Figure 6: High pass filter subcircuit, occurring thrice within the full circuit to eliminate DC offset; $R_3 = 470k\Omega$ and $C_1 = 330nF$ to produce cutoff frequency of 1Hz

To achieve the cutoff frequency of 1Hz, the equation $\omega RC = 1$ must be satisfied for $\omega = 2\pi$. This constraint is satisfied when

$$RC = {}^{1}/_{2\pi}\,.$$

By choosing a capacitor value of 330nF, it is then dictated that the corresponding resistor must be

$$R = {}^{1}/_{2\pi C} = {}^{1}/_{2\pi(330nF)} = 482\ k\Omega\,.$$

To achieve approximately this value, a 200kΩ and a 270kΩ resistor are placed in series to achieve a resistance of 470kΩ. A slightly higher value is chosen instead of a slightly lower value because the cutoff is not ideal, and therefore the frequencies filtered will mostly be much less than the cutoff frequency. Achieving precisely 482kΩ in the circuit would require more complication than it would be worth to implement. The cutoff frequency actually achieved with these components is $f = {}^{1}/_{RC} = 1.03\ Hz$. Each of the low pass filter and amplification stages reintroduce a DC offset to the outgoing signal, so this high pass filter subcircuit is placed after the phototransistor subcircuit as well as after the two non-inverting amplifier filter subcircuits. Figure 7 shows an example of a signal before and after it passes through the high pass filter, where trace 2 (blue) is the signal of interest.

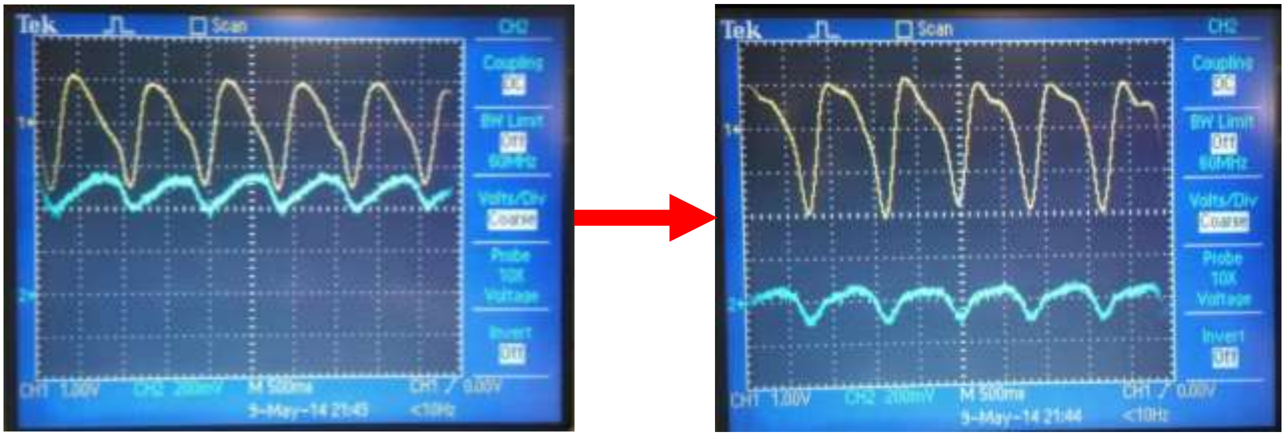

Figure 7: Comparison of DC offset before and after high pass filter stage (blue trace)

3.2.2 Active Low Pass Filter

The signal that comes out of the first high pass filter has minimal DC offset but has a lot of high frequency noise that must be filtered. The first low pass filtering stage that the signal is subjected to is the active low pass filter, which provides two stages of filtering and then amplification with a gain of 2. To produce a cutoff frequency of 3Hz in the low pass filters, the equation $RC = {}^{1}/_{6\pi}$ must be satisfied. Again choosing a capacitor value $C_2 = C_3 = 330nF$, the required resistor value is $R_4 = R_5 = 161k\Omega$. In the circuit, two resistors with values 150kΩ and 10kΩ are placed in series to achieve a resistance of 160kΩ. The subcircuit, seen in Figure 8, has an inlet node that receives the signal from the first high pass filter and an output node that connects to the next stage of the circuit.

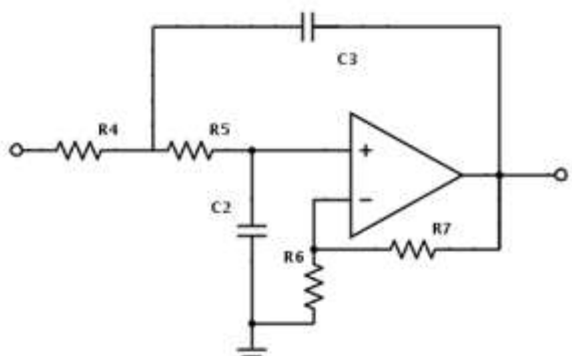

Figure 8: Active filter circuit, with resistance values $R_4 = R_5 = 161k\Omega$ and $R_6 = R_7 = 10k\Omega$, and capacitor values $C_2 = C_3 = 330nF$ to obtain low pass cutoff frequency of 3Hz and a gain of 2

The amplification function of the active filter provides a gain given by

$$\frac{V_o}{K} = \frac{R_f}{R_f + (1 + K)R_f}$$

where $R_f = R_6 = R_7$, K is the gain of the circuit, and V_o is the output voltage of the operational amplifier. The value $R_f = 10k\Omega$ was chosen for this circuit, such that the gain in this subcircuit is $K = 2$.

The effect of this subcircuit is seen in Figure 9, where the input and output signals are compared. The effect of the gain of 2 is easily visible in this comparison, as the amplitude of the noisy peaks has doubled and so has the small DC offset. However, the effect of the low pass filtering is not immediately noticeable.

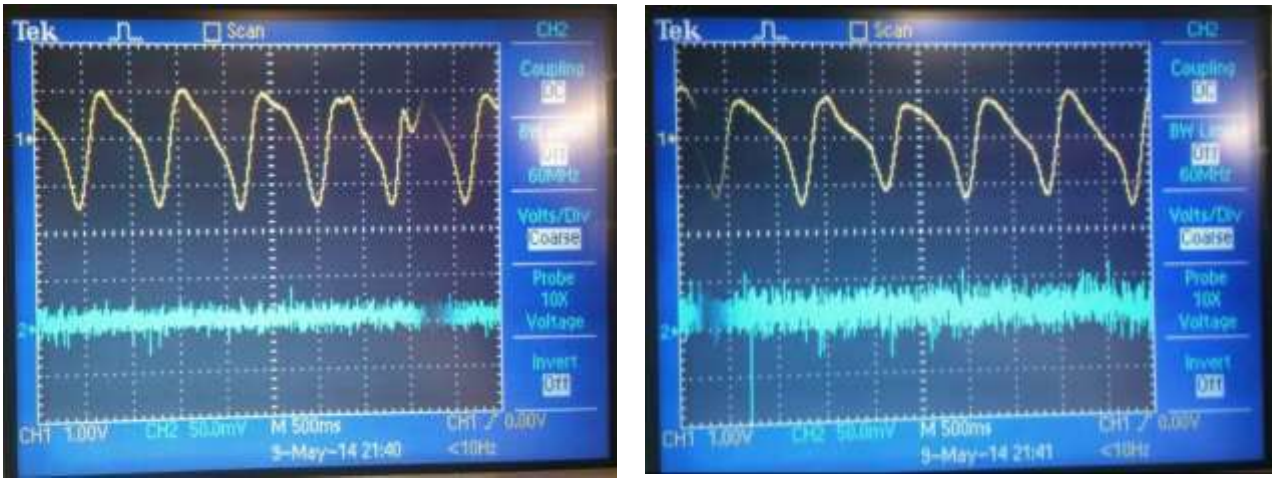

Figure 9: Comparison of signal before (left) and after (right) the low pass active filter

3.2.3 Non-Inverting Amplifiers with Low Pass Filtering

The focus of these stages of the circuit is to amplify the signal to make fluctuations more visible and identifiable. However, there is still significant high frequency noise that must be eliminated before the heart rate signal may be unburied. Per these two requirements, two identical low pass filters are inserted into the circuit, with capacitors in the feedback loop to induce further filtering. Each subcircuit, shown in Figure 10, provides the same cutoff frequency ($f = 3Hz$) as the low pass stage described in Section 3.2.2 by utilizing resistor value $R_9 = R_{12} = 36k\Omega$ and capacitor value $C_4 = C_6 = 1.47\mu F$. This capacitor value is obtained by wiring a 470nF and a 1µF capacitor in parallel, such that their magnitudes add. In addition, this subcircuit provides a gain of 37, according to the equation

$$K = 1 + {}^{R_9}\!/_{R_8} = 1 + {}^{36k\Omega}\!/_{1k\Omega} = 37\,.$$

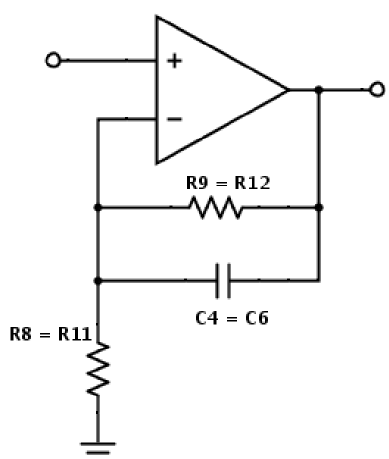

Figure 10: Non-inverting amplifier circuit ($K = 37$) with low pass filter, cutoff frequency 3Hz

Two of these amplifier subcircuits are included in the full circuit, separated only by a high pass filter as described in Section 3.2.1. Combined, the two amplifiers are expected to yield a gain of 1369 while eliminating most of the high frequency noise. Oscilloscope readings of the signals at the output of either subcircuit are found in Figure 11. As expected, the second amplifier stage yields a less noisy wave with a magnitude of approximately 0.4V compared to the noisier wave from the first amplifier, which has amplitude of about 0.02V. While this ratio is not quite 37, the amplitude measurements are only estimates and the input wave also varies in amplitude between the two measurements. It is also visible that the DC offset is reduced from the first to the second signal readings due to the high pass filter which acts in between the two.

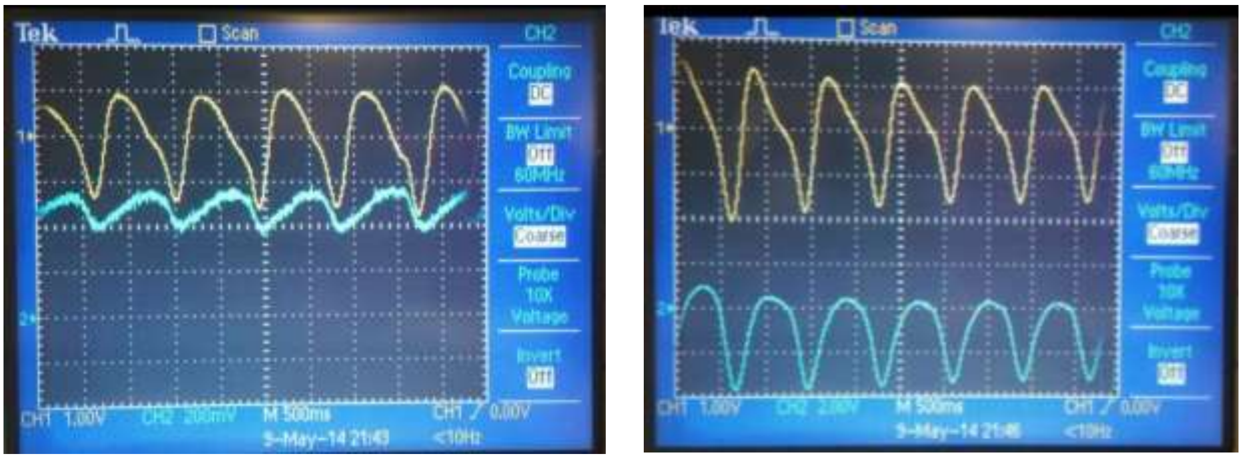

Figure 11: Output signals from first (left) and second (right) non-inverting amplifiers with low pass filtering

The reason for having two identical amplifiers in sequence instead of a single amplifier with gain of 1369 came from a process of trial and error. The conclusion drawn is that a single amplifier with huge gain would have high impedance that would cause the circuit to malfunction due to an overwhelmed op amp. For this reason, the two amplifiers are placed in series to produce the same effective gain. Another benefit to this setup is that it gives additional stages of filtering instead of just one.

3.3 Group 3 Subcircuits

After the non-inverting amplifiers described in Section 3.2.3, the signal is passed through a final high pass filter to eliminate any lingering DC offset. The next segment of the circuit is responsible for turning the noise-free wave into a square wave signal that triggers whenever the input wave reaches a certain nonzero value. In this final section of the circuit, the square wave will be manipulated until it becomes the zero to five volt wave that is required by the LabVIEW instrument.

3.3.1 Schmitt Trigger

The purpose of the Schmitt trigger is to take the oscillatory input signal and trigger high and low values of a square wave, with the trigger points being governed by the equation

$$V_{-} = \frac{R_{14}}{R_{14} + R_{15}} V_o$$

where V_- is the value given to the op amp from the previous stage of the circuit, and V_o is the ±15V output by the op amp. The desired trigger voltage is 0.04V because the signal provided to the trigger consistently has peaks beyond this value, but the amplitude of the remaining noise is much less than 0.04V. To achieve the desired trigger voltage, the equation is solved to obtain a relationship between R_{14} and R_{15} which requires that $R_{15} = 309R_{14}$. Resistor values $R_{14} = 220\Omega$ and $R_{15} = 68k\Omega$ are used to satisfy this condition. A schematic of the circuit is seen in Figure 12.

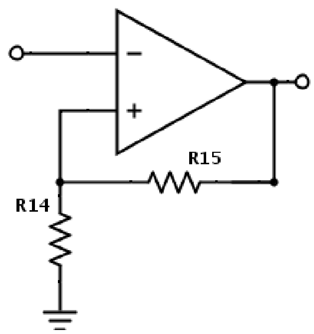

Figure 12: Schmitt trigger subcircuit with trigger voltage 0.04V and resistor values $R_{14} = 220\Omega$ and $R_{15} = 68k\Omega$

Due to the setup of this subcircuit, it is expected that the trigger will output a square wave which triggers whenever the incoming signal reaches a value of 0.04V. Figure 13 verifies that this is indeed what happens in the circuit when built and tested.

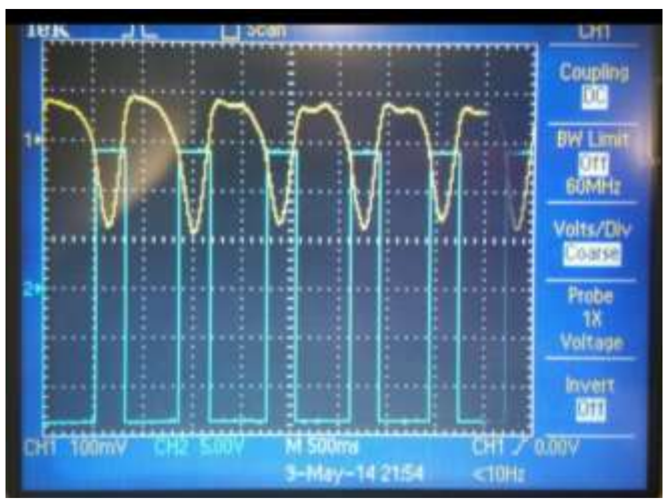

Figure 12: Oscilloscope trace of Schmitt trigger output (blue) with respect to incoming signal (yellow)

Though the circuit works, it appears to invert the wave by reaching a high value when the input dips to its low value, and vice versa. This could be caused by a negative connection or a sign error in calculation, but it yields the same result when trying to determine heart rate.

3.3.2 Voltage Divider

The signal output by the Schmitt trigger has high and low values at approximately positive and negative 13V, respectively. While this is the expected behavior, it does not provide the LabVIEW instrument with the proper range of voltage values. To obtain the correct range, the 13V peaks must be reduced to 5V peaks, and then the negative values must be eliminated. The voltage divider subcircuit stage, seen in Figure 13, provides the reduction in voltage through the equation

$$V_o = \frac{R_{17}}{R_{17} + R_{16}} V_{in} \,.$$

This equation determines that the relationship between the two resistors must be $R_{17} = 0.6R_{16}$. The values used in the circuit are $R_{17} = 1.8k\Omega$ and $R_{16} = 3k\Omega$.

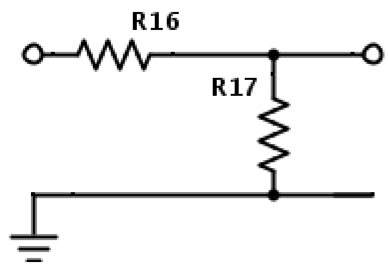

Figure 13: Voltage divider subcircuit, which reduces 13V Schmitt output to 5V

The only expected behavior out of this circuit is a reduction in the voltage amplitude, such that the output voltage is approximately ±5V. Figure 14 shows that this is the case.

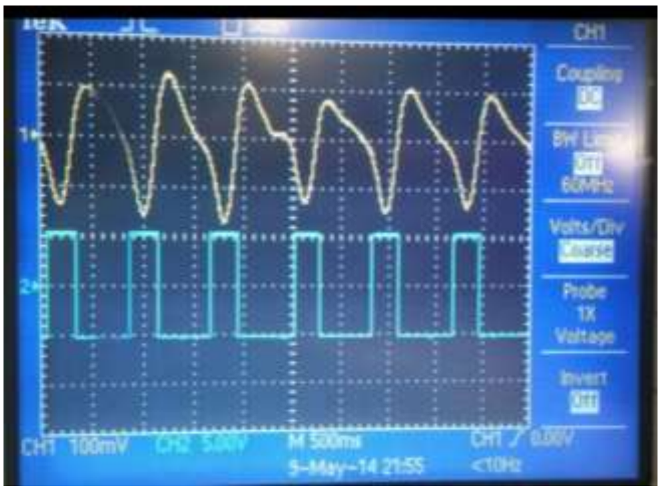

Figure 14: Oscilloscope view of voltage divider output (blue), with peaks at ±5V

3.3.3 Half-Wave Rectifier

The final process that the wave must undergo is the elimination of the negative values, such that the high voltage is 5V and the low voltage is 0V. This action can be accomplished with a half-wave rectifier, which is simply a forward-biased diode, seen in Figure 15.

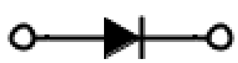

Figure 15: Half-wave rectifier subcircuit, which consists of a single 1N4007 diode

As seen in Figure 16, and as expected, this circuit element only allows forward voltage to pass, so it corrects all negative input voltage to 0V. At this point, the signal is finally ready to enter the LabVIEW program.

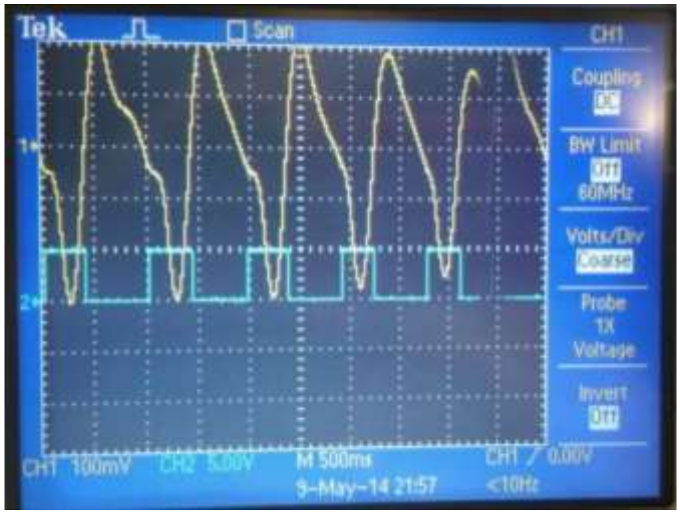

Figure 16: Oscilloscope view of rectified signal (blue) that has had its negative voltage moved to 0V

4 Results & Conclusion

The signal, after being processed through the entire circuit seen in Figure 17 as a complete schematic, was fed into the LabVIEW program which interpreted it into heart rate readings.

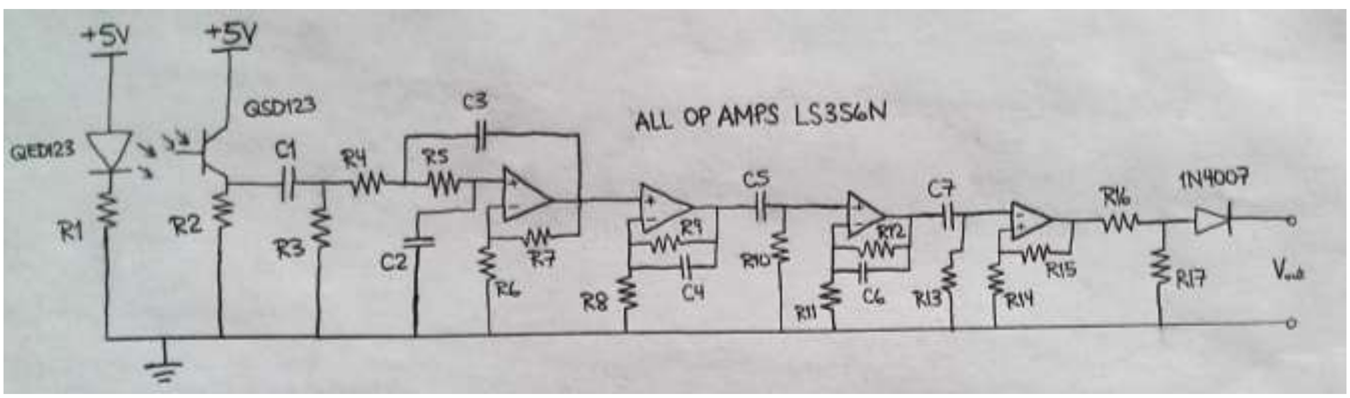

Figure 17: Full schematic of circuit design, where user finger is placed between IR LED and phototransistor; V_{out} is the signal that is sent to LabVIEW

The LabView interface is shown in Figure 18, where the input signal is causing a reading of 83 beats per minute. This value is reasonable because the user had been anxiously awaiting the reading and also laughing quite hard; these are factors which would cause the user's usual resting heart rate of about 65 beats per minute to be elevated. One fault in the circuit output was that the duty cycle was always quite low, never reaching close to 50% and instead lingering between 35% to 45%. Had the higher frequencies associated with the beat been filtered out, the duty cycle would be much closer to 50%, and the readings subsequently may have been more accurate.

Future iterations of this design should include final low pass filtering to reduce the "harmonics" of the beat captured in the reading. Additionally, some of the filter and amplification stages could potentially be condensed by finding the optimal resistor values that would provide the same filtering and amplification but would require fewer stages without overloading any of the elements.

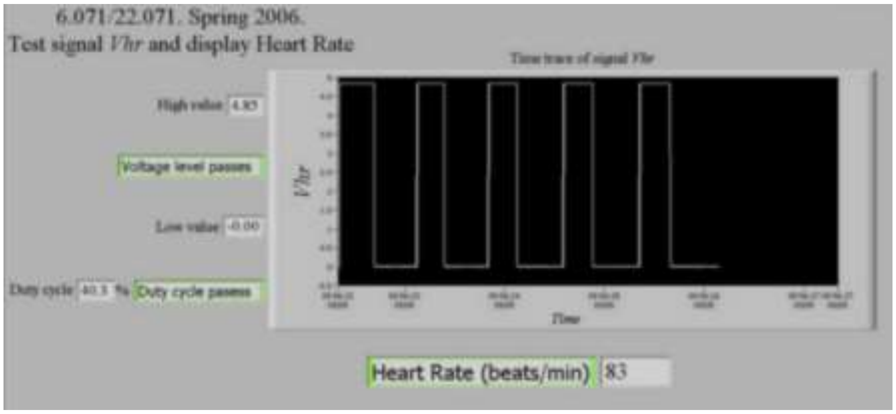

Figure 18: LabVIEW interface while signal is being translated into beats per minute

Overall, the circuit design presented in this report was successful in detecting heart beats and converting those beats into a consistent square wave with the specified amplitude and a near-50% duty cycle. The summary of elements used in the circuit is found in Table 1.

Element Type	Value / Part No.	Quantity
Diode	QED123 (IR LED)	1
	1N4007	1
Transistor	QSD123 (IR Phototransistor)	1
Operational Amplifier	LS356N	4
Capacitor	330 nF	3
	1.470 µF	2
Resistor	36 Ω	1
	220 Ω	1
	1 kΩ	3
	1.8 kΩ	1
	3 kΩ	1
	10 kΩ	4
	36 kΩ	2
	68 kΩ	1
	150 kΩ	2
	200 kΩ	2
	270 kΩ	2

Table 1: Complete list of elements used in circuit

References

1. QED123 spec sheet, Fairchild Semiconductor, https://stellar.mit.edu/S/course/22/sp14/22.071/courseMaterial/topics/topic2/resource/qed123/qed123.pdf