EXPERIMENT 14

Final project: optical heart rate sensor

Due date: This experiment is to be completed over *two* lab sessions. The final demonstration and measurements are *due by the end of the second lab*.

14.1 Optical heart rate sensors

Optical heart rate sensors use a technique called photoplethysmography (PPG) to measure changes in reflected or transmitted light caused by blood flow. Typically, the light from a light emitting diode (LED) is shone through a finger and measured on the other side by either a phototransistor or a photodiode. A phototransistor is a device that turns on when the correct wavelength of light is shone onto the transistor. It can be operated as a switch or in the forward active[1] region depending on the application. In order to measure heart rate, it should be biased in the forward active region. The other device, a photodiode, is a diode that modulates the reverse bias current based on the amount of received light. Photodiodes are very similar to photocells used for solar energy harvesting.

(1) The forward active region is similar in behavior to the saturation region of a MOSFET.

We will use a IR204 and PT204-6B pair to measure heart rate. It is a LED and phototransistor pair that can shine infrared light out of the diode and measure the transmitted light using the phototransistor. When the transistor is biased correctly and the signal is amplified and filtered, the signal can measure blood flow and therefore pulse rate. We will use infrared light, but most commercial products use a combination of infrared, red, and green light to get a more accurate reading as well as measure the blood oxygen level.

14.2 System design

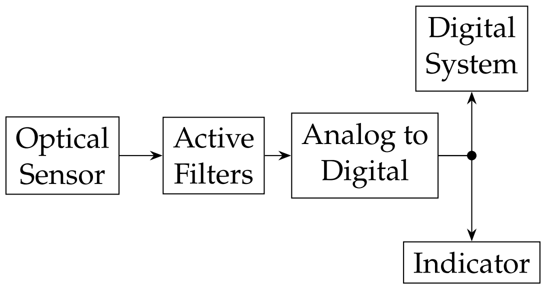

Figure 14.1: Heart rate sensor block diagram.

The basic layout of the desired design is shown in figure 14.1. The optical sensor shines infrared light through the user's finger and measures the transmitted light using a phototransistor. This output is then amplified and filtered using a set of active filters. Finally, the output waveform is converted to a digital 1 or 0 that will turn an indicator on or off. This output could also go directly to a digital system like a microcontroller to calculate the user's heart rate. For testing purposes, an oscilliscope will be used instead of the "digital system."

14.2.1 Optical system

The optical sensor requires an infrared photodiode and an infrared phototransistor.

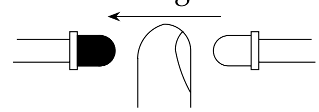

Figure 14.2: Optical sensor setup

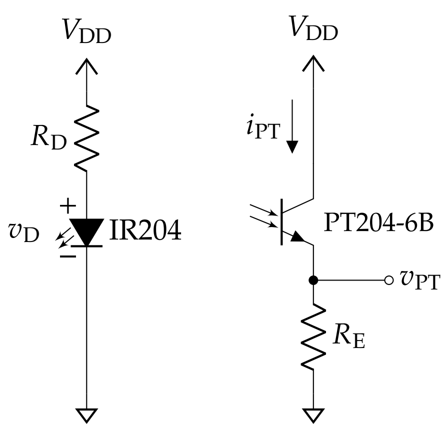

Figure 14.3: LED driver and receiver

The core design decisions in this system are the LED, the phototransistor, R_D, and R_E. The LED and phototransistor must be designed for the same wavelength, and it is usually best to pick an LED and phototransistor designed as a pair. Conveniently, the IR204 and PT204-6B are an infrared transmitter and receiver pair designed to work together.

Many PPG systems will use pulsed light using a circuit similar to the transmitter circuit from experiment 13. Pulsed LEDs can be driven at a higher current, so they will be much brighter than the DC driven LED. Additionally, pulsing the LED can allow for higher efficiencies.

Next, we must pick the resistors. R_D will determine the amount of current that flows through the LED, so it also determines the LED brightness. The current through the LED will be

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

For maximum brightness, the resistor should be picked based on the maximum I_D supported by the diode at the minimum V_D stated in the datasheet. This ensures that the LED current will not be exceeded during operation. You must also ensure that the power dissipated in R_D is less than its rated maximum power.[2]

[2] Most standard resistors are rated for 0.25 W or lower. Power resistors can be used when you need to dissipate more power.

Finally, R_E needs to be selected. As the phototransistor receives more infrared light, it will pass more current through it. This current is then converted to an output voltage. The resulting relationship is given in equation (14.1). In order to select R_E, you need to find out the expected range of currents that will flow through the phototransistor during operation.

$$v_{PT} = i_{PT} R_E \tag{14.1}$$

The current i_{PT} is proportional to the amount of received light, but the amount of light will be transmitted through the user's finger is not an easily calculable quantity. Instead, you will need to experiment to find an adequate R_E.

14.2.2 Filters

In order to isolate the heart rate signal at the output of the sensor, we need to filter out any other signals. This requires a high pass and low pass filter cascaded in series. Additionally, each filter needs to provide gain as the signal at the phototransmistor output will be in the millivolt range.

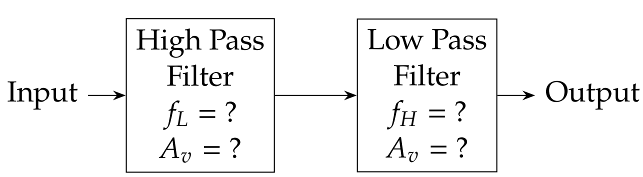

Figure 14.4: Filter system

We will choose a heartrate range from 40 beats per minute to 200 beats per minute. The high pass filter must allow through slow heart rates while the low pass filter allows through higher heart rates. Each filter must have the correct frequency selected as well as adequate gain.

While it may seem obvious that a very large gain should be selected, there is an upper limit on gain imposed by the input offset voltage of the amplifiers. If the gain is too high, the small difference in DC voltage between the inputs as well as the internal offset voltage will cause the output signal to saturate at either the upper or lower output limit. To combat this, you may need to add capacitors between different stages to isolate the DC voltages; however, every capacitor will act as a high pass circuit and must be designed to ensure that the slow heartbeat signal can make it through the system as a whole.

14.2.3 Analog to digital

The last subsystem needed is the analog to digital conversion. This system needs to take the output of the filters and convert it to a binary signal that indicates that a heartbeat is detected. The output of this system could then be used to drive an LED to indicate the heartbeat is detected as well as be read by a microcontroller to calculate the heart rate.

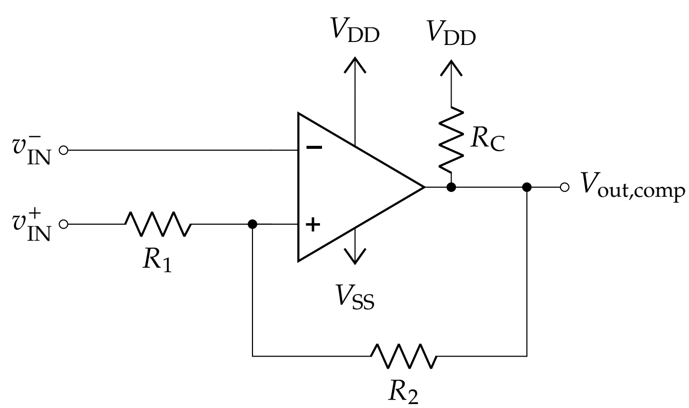

Figure 14.5: Comparator with hysteresis

Since we only need one bit of digital signal, we can make an analog to digital converter using just a comparator. The comparator threshold can be set based on the DC offset of the output of the filter system in order to detect the PPG signal.

In order to add noise immunity to the comparator system, it should be designed with hysteresis. The circuit in figure 14.5 implements a comparator with hysteresis. The amount of hysteresis is set by R_1 and R_2:

$$v_{\mathrm{hyst}} = (V_{\mathrm{DD}} - V_{\mathrm{SS}})\frac{R_1}{R_1 + R_2}$$

This value should be set to more than the amount of noise present on the signal but lower than the peak to peak of the complete input signal. Typically, R_1 and R_2 are chosen to be very large resistors ($> 100\,\mathrm{k\Omega}$) in order to maintain the high input impedance of the comparator.

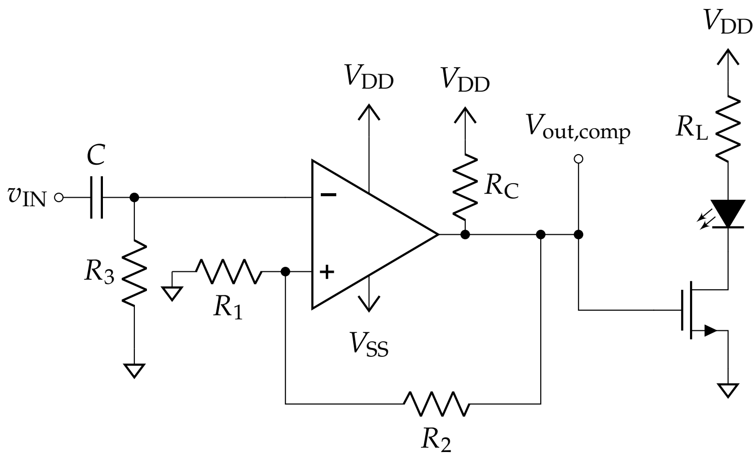

Figure 14.6: Comparator pulse detector with LED indicator

Since we are simply trying to detect sudden edges in the output signal corresponding to a heartbeat, we don't need the DC value of output of the filter and amplifier circuit. We can use the circuit in figure 14.6 to detect pulses on the input. This circuit still uses hysteresis. R_3 and C should be picked to have a cutoff frequency lower than 2 Hz.

14.3 Specifications

Specification	Requirement
Heart rate range	40BPM to 200BPM
Supply Voltage	±5 V
Output Voltage	−5 V to 5 V Digital Signal

14.4 Design of a PPG heart rate sensor

Your task is to design a heart rate sensor that provides a digital output as well as turns on an LED whenever a heartbeat is detected. The design must meet the specifications in section 14.3.

You should reference the following experiments for circuit inspiration

1. The inverter: experiment 1[3]
2. Op amp circuits: experiment 6
3. Nonideal op amp behavior: experiment 7
4. Active filters: experiment 13

[3] You may want to consider using the 74HC04 instead of the CD4007 if you need an inverter.

Task 14.4.1: Prelab questions

1. *Design* a circuit topology that would in principal meet the project specifications. While choosing component values and running simulations is highly recommended, it is not required.
2. A good starting point is:
   - A total gain between 100 and 1000 (Recall that gains in consecutive stages multiply)
   - A per-stage gain of less than 100
   - Set your high pass filter cutoff to be lower than 40BPM
   - Set your low pass filter cutoff to be higher than 200BPM

Extra Credit For 20% extra credit on the project score, design the system to work with only a single 5 V supply. The output digital signal should be 0 V to 5 V in this case.

Task 14.4.2: Tasks

1. *Finalize* your intended circuit topology. You are encouraged to get feedback on your design.
2. *Calculate* the required values and *verify* those components are available to you. You can use any components available from the ECE shop in EE162.
3. *Construct* and *test* each subsystem independently.
4. *Make* the following measurements
   a) A plot or plots that demonstrates the functionality of the optical sensor.[a]
   b) Frequency responses of all filters (individually and as a full chain).
   c) A plot or plots that demonstrate the analog to digital conversion.
5. *Integrate* the individual sub-systems.

6. *Generate* plots, table, and/or figures that proves your design meets all of the specifications given in section 14.3.

7. *Demonstrate* your fully integrated system to your TA by the end of your second lab.

[a] You are tasked with designing an acceptable plot.

You only need to submit one document to be graded for both the project and report grade. The project grade is focused on making correct measurements (measurement column) and getting the system working (accuracy column). The Formal report rubric focuses on the quality of your reporting.

Mini Project Grading Rubric			
	Measurement	Accuracy	Score
Design			
Full Schematic	12		
Filter Calculations	10		
Individual Subsystems			
Optical Sensor	8	4	
Low Pass Filter	8	4	
High Pass Filter	8	4	
Analog to Digital	8	4	
Fully Integrated Project			
Plots demonstrating functionality	10	5	
Project Demo			
Functionality Demo	10	5	
Total	100		

Formal Report Grading Rubric		
	Points	Score
Abstract	5	
Introduction		
Explains problem	5	
Briefly describes solution	5	
Theory		
Explains subsystem operation	10	
Derives relevant equations	10	
Design/Calculations		
Applies theory to calculate values used	10	
Results		
Final circuit diagram (quality/readability)	5	
Plots, images, and screen shots that demonstrate functionality	25	
Conclusion	5	
Overall organization and neatness	10	
Spelling/Grammar is acceptable	10	
Total	100	