University of Sheffield

EEE228
Wearable Healthcare Sensor
Design Report

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Contents

Introduction

Wearable healthcare devices have become increasingly popular recently, with many people using them to monitor critical parameters such as heart rate, respiration, and peripheral oxygen saturation. By wirelessly collecting data, these devices can help create large health information databases, potentially revolutionising medical care. In this exercise, we will explore the technology behind wearable heart rate sensors and design and construct our device. The main objective is to create an accurate and reliable heart-monitoring wearable focusing on battery life and durability. The device will be judged based on its accuracy compared to existing products in the market and its robustness and wearability.

Theory

Photoplethysmography principles

Photoplethysmography (PPG) is a technique that uses optical methods to detect and measure changes in blood volume in peripheral tissues. It is a non-invasive way to gain valuable information about the cardiovascular system by measuring important parameters like heart rate, blood pressure, and oxygen saturation.PPG technology can be found in medical devices such as pulse oximeters and wearable fitness trackers. The Principle behind Photoplethysmography is based on the absorption and reflections of Light by the blood in the tissues. We can measure the spectrum of the Light after it has been passed through the blood, which contains haemoglobin (vivid red colour).

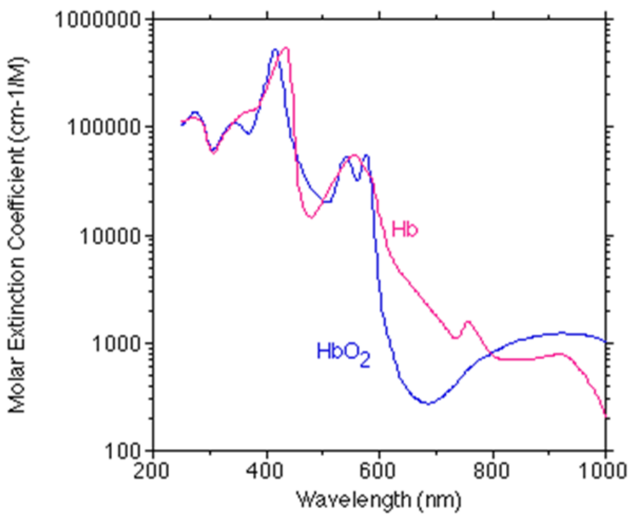

Figure 1 - specific extinction coefficient spectra of oxy and deoxyhaemoglobin. Note the logarithmic y axis.

The attenuation of light can be mathematically described using the Beer-Lambert equation.

$$log_{10}(I_0/I) = \epsilon\ .\ C\ .\ d$$

I_0 = incident light intensity
I = detected light intensity
d = the distance through the sample
C = the concentration
ϵ = The specific extinction coefficient

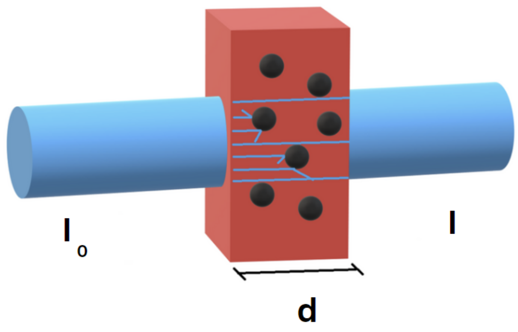

Figure 2 Beer- Lambert equation

Photoplethysmography is a technique that involves directing light into living biological tissue, such as the skin, muscle, or brain. One fundamental principle behind photoplethysmography is that when the heart beats, it propels blood into the arteries, resulting in a slight increase in the instantaneous concentration of haemoglobin, denoted as C. During a single cardiac cycle, the maximum detected light intensity is represented as Imax, and the minimum intensity is denoted as Imin. ΔC means the difference in concentrations between the time of occurrence of I_{max} and I_{min},
It can be derived based on the beer- Beer-Lambert equation.

$$log_{10}(I_{max}/I_{min}) = \epsilon\ .\ \Delta C\ .\ d$$

The relative signal can also be increased depending on several factors such as ϵ and d. We can control the relative signal by the distance between the emitter and detector and the choice of Phtotoemitter.

Photoemitter (Physical and Circuit Principles)

The Solid-state light emitters are either laser diodes or light-emitting diodes (LEDs) made from semiconductors such as gallium arsenide (GaAs) or gallium nitride (GaN). Based on the phenomenon of electroluminescence, the emission of light occurs when electrons recombine with electron holes in a semiconductor material.The colour of the light emitted is determined by the energy of the photons, which in turn is determined by the bandgap energy of the semiconductor material.

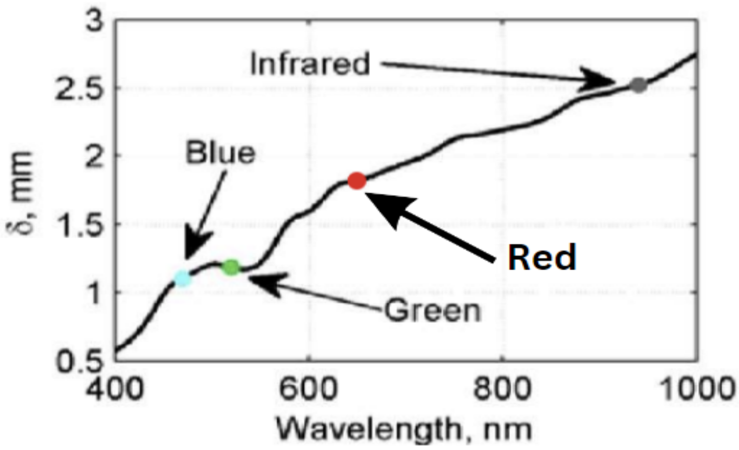

Figure 3 –Wavelengths of Green, Blue, Red and Infrared LED

LEDs are typically operated in a forward-biassed manner, similar to regular silicon diodes, where they exhibit an I-V characteristic (unlike usual diodes, the voltage drop is around 2V). To drive an LED, it is commonly connected in a circuit between the positive supply voltage, Vcc, and the ground (GND), with a series bias resistor. The value of the bias resistor is determined based on the desired drive current, I.

Photodetector (Physical and Circuit Principles)

When it comes to selecting photo emitters, there are several choices available. The two options we have are photodiodes and phototransistors. We will need to evaluate the advantages of each to determine which one is the best fit for our needs.

Photodiode Characteristics

The way a photodiode works is by utilising the internal photoelectric effect. When photons hit the material, they are absorbed and create electron-hole pairs in the depletion region of the junction. An electric field is present across the depletion region, and this causes the charge carriers to drift towards their respective electrodes, generating a current flow in the external circuit. The intensity of the light is directly proportional to the photocurrent, which is optimised by operating the photodiodes under reverse bias.

PhotoTransistor Characteristics

The principle of a phototransistor incorporates a base-collector junction that is sensitive to light. When properly biassed, the exposure to light causes a variation in the base-emitter current. This current variation is significant because the emitter-collector current is equal to the base-collector current multiplied by the current gain of the transistor. Consequently, the phototransistor is capable of generating a significantly larger photocurrent compared to a photodiode when exposed to the same amount of light.

Advantages and disadvantages between Photodiode and Phototransitor

	Photodiode	**PhotoTransistor**
Advantage	Fast response time	Higher gain
	High sensitivity	Higher output current
	Low noise	Compact design
	Simple circuitry	
Disadvantage	Lower output current	Higher noise
		Limited voltage gain
		Slower response time

Table 1- Table of Advantages and disadvantages between Photodiode and Phototransitor

Pulse Detection Algorithms

PPG uses various algorithms to detect the heart rate pulse, including peak detection, FFT, autocorrelation, time-frequency analysis, and machine learning. Peak detection identifies the peaks in the PPG waveform that correspond to each heartbeat. FFT transforms the PPG signal into the frequency domain, where the dominant frequency component represents the heart rate. Autocorrelation measures the similarity between the PPG waveform and its delayed versions to detect periodic patterns. Time-frequency analysis techniques analyze changes in the frequency content of the PPG signal over time. Machine learning algorithms, trained on labelled PPG datasets, can classify and predict heart rate patterns. The algorithm depends on accuracy requirements, computational resources, noise levels, and specific application needs.

Methodology

There are various critical steps that must be taken in order to monitor heart rate using Arduino Nano in terms of wearable devices. The first step is to choose a suitable photoplethysmography (PPG) sensor, such as LEDs or Photodetector kinds.After selecting a sensor network, it must be linked to the Arduino Nano using the pin connections provided in the datasheet. The next step is to install the Arduino IDE and write the code required to communicate with the sensor and process its readings. The Arduino's input pins are then utilised to acquire the sensor's output signal, which is subsequently filtered and extracted using signal processing techniques. To assess the processed signal and calculate the heart rate, algorithms are used. The outcomes are then shown on a 4 × 7 section screen. Finally, the Arduino-based heart rate monitoring system is put into operation for continuous monitoring or integration into other projects or applications. The methodology for building the heart rate monitoring device can be seen in the following Block diagram.

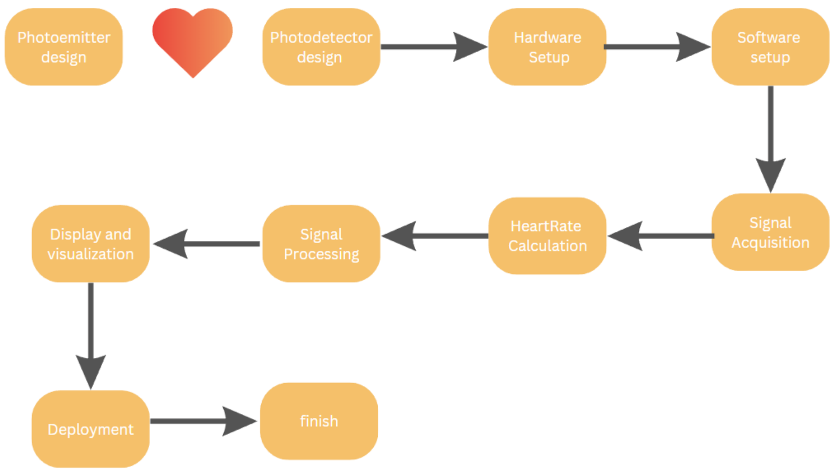

Figure 4 –Block diagram of building the heart monitoring device

Selection of Design for heart rate detection Circuit

Phototrasmitter (LED) Driver Circuit Design

When choosing a Phototransmitter, Infrared (IR) LEDs are chosen over other LEDs in oximeters for several reasons. IR light is absorbed differently by oxygenated and deoxygenated haemoglobin, making it suitable for accurate oxygen saturation measurements. Its longer wavelength allows it to penetrate deeper into tissue and measure oxygen levels in arterial blood. IR light is less affected by skin pigmentation and ambient light, ensuring reliable readings. It is compatible with photodetectors commonly used in oximeters and has become an industry standard. While some oximeters may use a combination of red and IR LEDs, IR LEDs alone are often sufficient for precise and consistent oxygen saturation measurements.

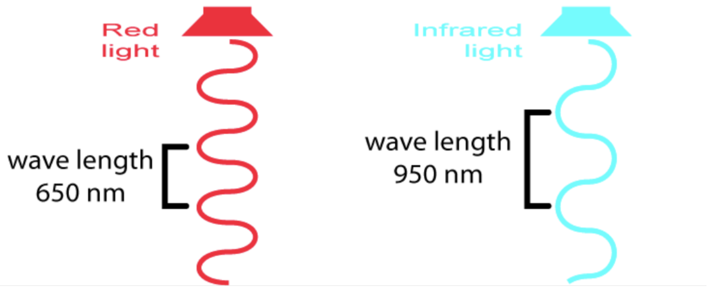

Figure 5 –Comparison between Wavelengths of, Red and Infrared LED

The Bias Resistor is calculated on the forward voltage of the Infrared LED, which is 1.2V and has a forward current of 20 mA.

Therefore we can be calculated by the following formula :

$$I_f = \frac{V_p - V_f}{R}$$

$$R = \frac{5V - 1.2V}{20mA}$$

$$= 190\ \Omega$$

$$\simeq 220\ \Omega$$

However, due to E12 series resistors, we have to choose to nearest 220Ω.

Circuit diagram of Photoemitter (LED driver) used in our Project

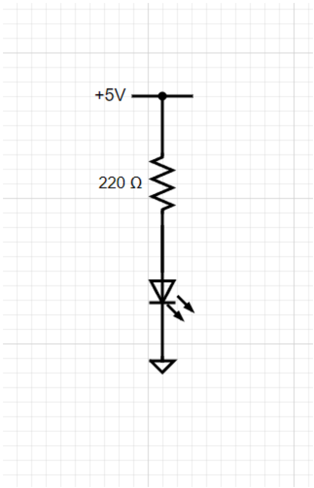

Figure 6 -Schematic diagram of LED driver circuit

Phototrasmitter (LED) Driver Circuit Design

Photodiodes are preferred for detecting heart rate in photodetector circuits due to their high sensitivity to light, faster response time, linear response to light, lower noise levels, and small size. They are effective in measuring changes in blood volume with each heartbeat, allowing for real-time heart rate monitoring.

We choose Hamamatsu S1223 as our photodiode, which offers High sensitivity in visible to near-infrared range, High reliability and High-Speed response.

Figure 7 –Hamamatsu S1223

With some essential specifications about Hamamatsu S1223:
Isc =6.3A
I d =0.1nA

Ct = 10 pF

Circuit diagram of Photodetector used in our Project

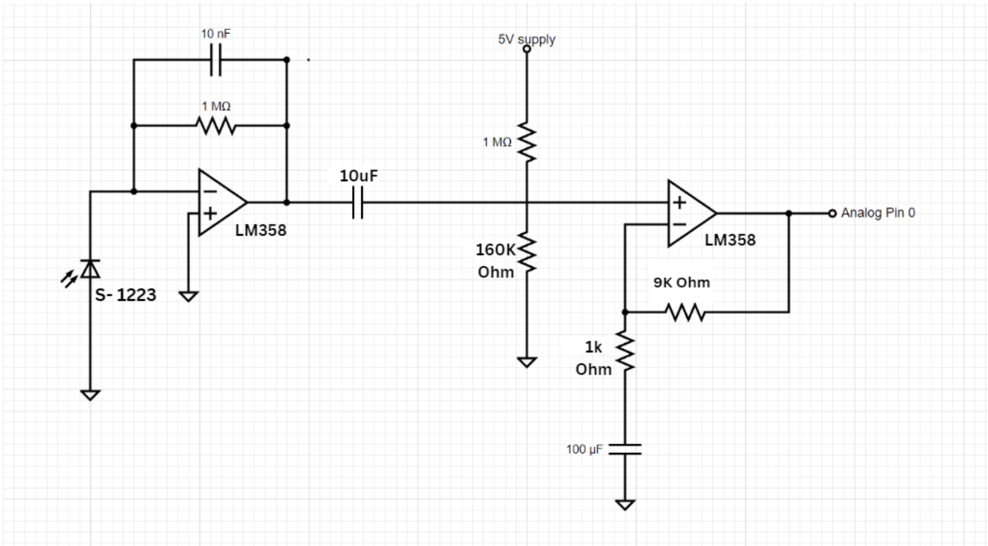

Figure 8 - Schematic diagram of Photodiode Amplifier detection circuit

In order to detect the current and amplify the signal, we have chosen LM358 as our operational amplifier to perform in our detecting Heart rate signal.

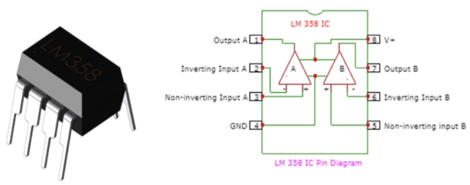

Figure 9 - Schematic diagram of Photodiode Amplifier detection circuit

Some important features and specifications of LM358 IC are as follows:

- Integrated with two operational amplifiers in a single package
- A wider range of power Supply, e.
    - 3V to 32V in a single power supply
    - ±1.5V to ±16V in a Dual power supply
- The large voltage gain is around 100 dB
- Wider bandwidth in 1 MHz
- The low supply current is 700µA
- The output voltage swing is high

Photodiodes produce a leakage current that is directly proportional to the intensity of light.in order to measure the light intensity,we have to use A current to Voltage converter or (transimpedance amplifier) to convert the photodiode current to a voltage. Since we use reverse biassing mode ,its capacitance is decreased and so it can respond faster. However ,the current produced by photodiode is relatively small .So we need a large resistor such as 1 MΩ

as gain- setting resistor.We add the capacitor in the feedback loop to give the stability and act as active-low pass filter to reduce the high- frequency noise.
Let's consider cut off frequency as 20 Hz ,(it mean any signal f > 20Hz will be smother)

$f_c = \frac{1}{2\pi RC}$

$C = \frac{1}{2\pi R f_c}$

$C = \frac{1}{2\pi \times 1M \times 20}$

C =7.95nF

Let's use the nearest value of capacitor as 10 nF

Cut off Frequency will become 15.91Hz

Next step we should design an amplification process, where gain of 11 at f = 1Hz is set. We should have high pass filter to remove low-frequency signals.In this case, we can consider as we are removing signals that are lower than normal pulse signal.we choose 160 kΩ and 10μF to get approximately around f_c =1 Hz.
After that, we use a non-inverting op amp to produce AC gain value 11.A noninverting op amp amplifies and input voltage in accordance with the equation.

Gain = $1+\frac{R_2}{R_1}$

Where R_2= the resistor in Feedback loop and
R_1= the resistor connected to the ground.
We use 10 k Ohm and 1 k Ohm to create 11 gain value.

= $1+\frac{10k\Omega}{1k\Omega}$

=1+10

=11

We add a capacitor to Block the DC bias signal and only allow the ACc signal to pass it.This means only AC signal which is our pulse rate gets amplified. Finally the AC signal has been fed into the analog pin of the arduino and processes the signal.

Data Acquisition and Processing System & Heart Rate Algorithm

When Processing the raw Signal that can be collected straight from the photodetector circuit, instead of processing via the matlab, we use the Arduino platform to process the Signal directly.

Firstly, we study the raw Signal, which is unfiltered by software. As we can see, there is much noise in the Signal.

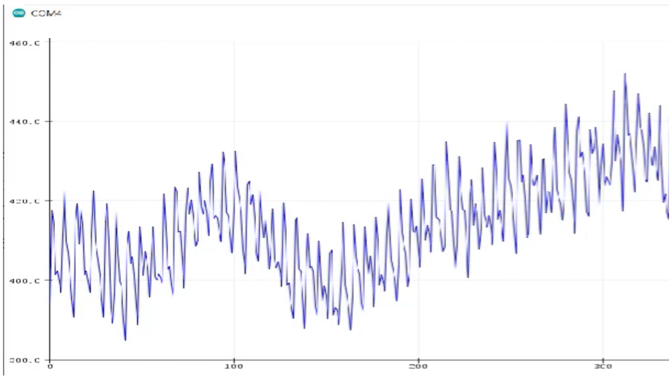

Figure 10 - Raw Data collected from the photodiode

Smoothing the Signal

To get a smoother output, we take an average of 25 readings from the sensor (determine Constant). To update the readings, we calculate the difference between the oldest and newest readings and then add the new reading to the sum. As for the array, we swap out the oldest reading with the most recent one.By doing this, the Signal becomes clear to detect the rising and falling slope.

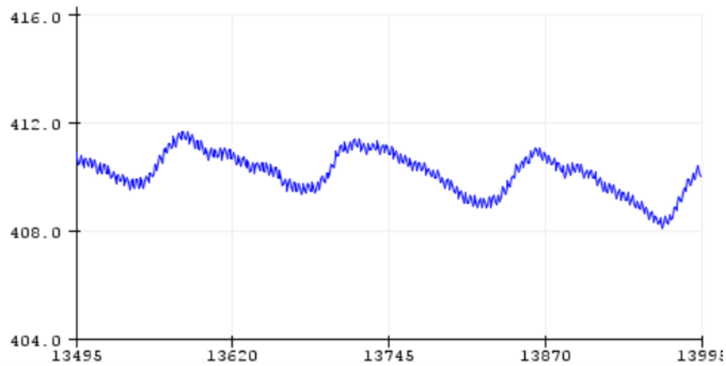

Figure 11 -Pulse Rate data After smoothing

Determine the Algorithm for Peak Detection

Therefore, We can use the peak detection method to get heart rate from the ADC signal. After that, we find the threshold value based on the data we have collected so far to be able to detect the high peak so far.

Signal Processing

The ADC sample's signal processing involves checking if the reading is above the threshold, comparing the new reading to the average value, and comparing the peak value to the average value. If the ratio is above a certain threshold, it is considered a signal peak or a heartbeat detection..

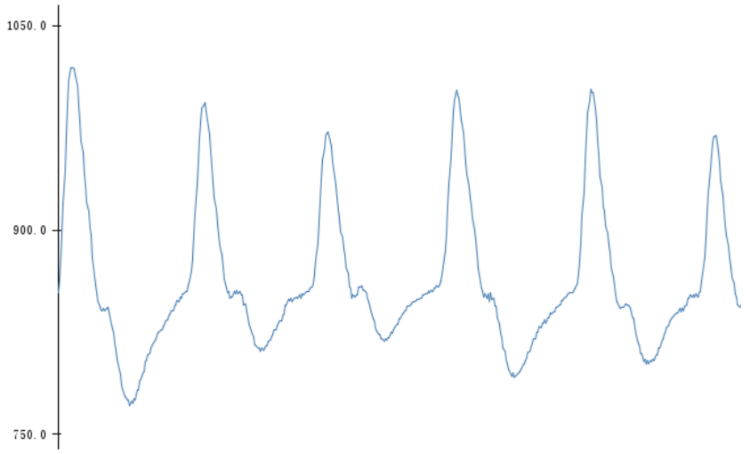

Figure 12- Pulse Rate data after processing

Heart rate Algorithm

After determining the peak, we collect the time that occurs and waits for the next consecutive heartbeat. Can be done by measuring the time elapsed between the rising edges of the peaks. We must divide 60 by the time duration between two consecutive signal peaks to get the Pulse rate. It will give the number of Heartbeats that occur in one minute. We use the millis() function in arduino to determine the time the peaks occur. To get more accuracy; we can divide the 60 by the average of time duration in more than two two consecutive signal peaks.

BPM = 60 / (the current peak time - the last Peak time)

Demonstration of Safety

The safety of a heart rate sensor using an IR LED and photodetector circuit requires adhering to the IEC 62471 standard. This standard provides guidelines for assessing the potential hazards of optical radiation emitted by such devices. The device design includes shielding and insulation to prevent direct exposure to the IR LED and electrical components. By following the standard and conducting safety assessments, the heart rate wearable device can provide reliable and safe measurements without compromising user well-being.

Construction

We tested our prototype using a breadboard in the early phase, but wanted to move to a stripboard to provide more permanent support and secure the connection between components. Although it may not provide flexibility, it can make our project more wearable than a breadboard due to its robustness.

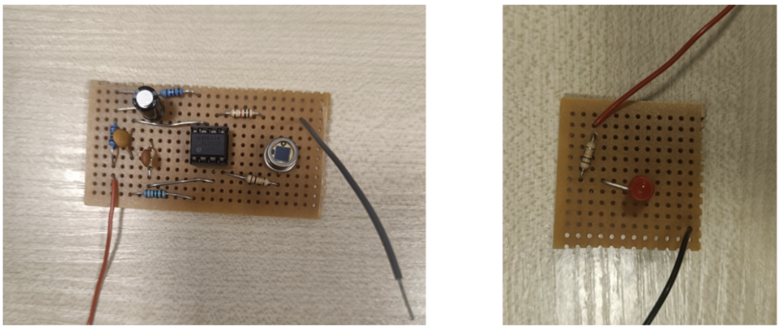

Figure 13 - Building the circuit on the stripeboard

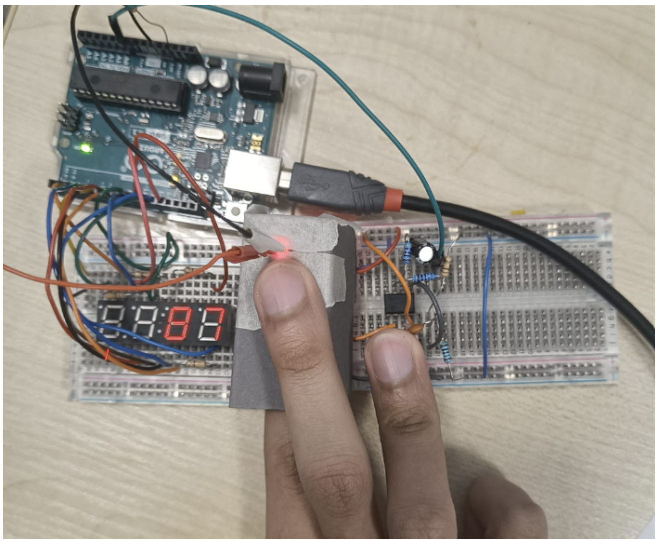

Figure 14 - Building the circuit on the Breadboard

Transmittance mode is the best choice for Photoplethysmography detection, as it captures light by placing the light emitter and photodetector opposite each other.

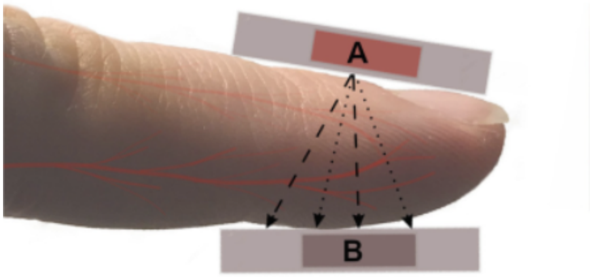

Figure 15 -Transmittance Mode

The light emitted by the LED passes through the body part and is modulated by changes in blood volume and flow, resulting in a PPG waveform. This waveform is then processed and analysed to extract relevant physiological information. Our product focuses on a traditional design to achieve accuracy close to the market.

Results

In this section, we will discuss what external factors influence our wearable device's accuracy.
According to the research, some factors can affect heart rate readings:

- Fingernail polish or artificial nails
- Skin temperature: A skin temperature of about 91.4°F is recommended
- Altitude
- Intravenous dyes: These are used to colour blood serum for surgical or diagnostic purposes and can affect light absorption
- Poor circulation
- Skin thickness
- Tobacco use
- Skin pigmentation

Response when transilluminating tissue

Transilluminating tissue refers to transmitting light through body tissues to visualize or examine structures beneath the surface. We can get small signals by detecting how much light gets through the tissue. Since heart rate sensors are very vulnerable to motion, they significantly differ in the readings. Nail polish and Intravenous dyes can also prevent photo-emitters from transmitting the light through the finger. Another issue is that since humans have a diverse range of skin tones, Readings may differ from commercialised products.

Response to both dark and very bright conditions

When utilizing an IR LED and photodiode circuit to measure heart rate, the accuracy of the readings can be impacted by the response to dark and very bright conditions. In dark environments, the lack of ambient light can weaken the signal, necessitating higher LED intensity and increasing the signal to Noise ratio. On the other hand, in very bright conditions, the photodiode can become saturated with excessive light, causing distorted signals. Methods like light shielding, filters, and signal processing algorithms should be utilized to overcome these situations.
Another way to solve this is by calibrating the device in varying lighting conditions and finding references to eliminate the noises. By implementing appropriate measures and considering the specific challenges of each condition, the heart rate measurement can provide accurate readings across a wide range of lighting environments.

Comparisons Between Our Wearable Heart Rate Monitoring Device and Braun YK-81CEU And Result Accuracy

Table show the comparison BPM recorded from our Heart rate monitor device and BRAUN YK -81CEU

	Our wearable Heart Rate Monitoring Device	Braun YK-81CEU
1	73	76
2	71	73
3	72	72
4	80	84
5	78	78
6	76	76
7	92	90

Table 2 -he comparison BPM recorded from our Heart rate monitor device and BRAUN YK -81CEU

Result Accuracy

The values measured from our prototype are compared to the standard heart rate that have been obtained by the Braun YK-81CEU.

Average heart rate BPM values measured from the our prototype = 77.4

Average heart rate BPM values measured from the our prototype = 79.42

Percentage error % $= \frac{Standard\ value - experimental\ value}{Standard\ value}$ x 100

Percentage error = 2.42%

System Accuracy = 97.58%

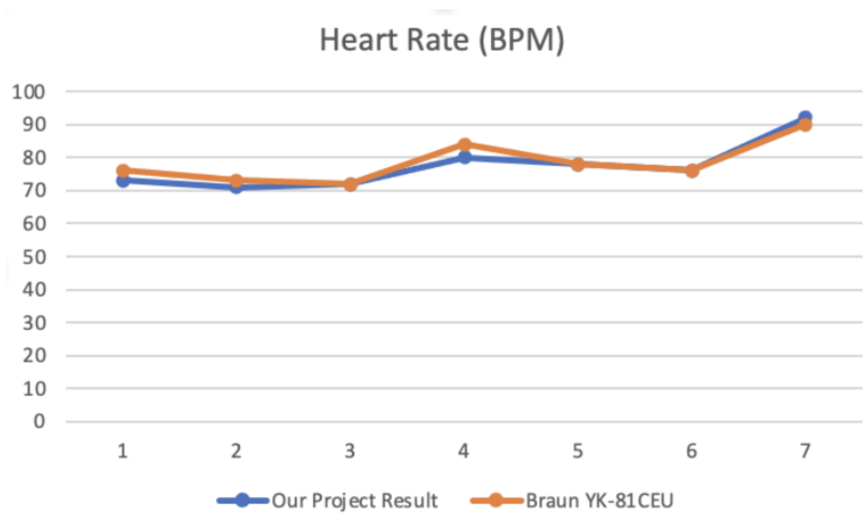

Figure 16 - Line Graph show the difference between our Heart rate monitor device and BRAUN YK -81CEU

Discussion

What I learnt in this design exercise is that the RED LED should be used as a photo emitter to provide a fair reading value compared to an Infrared LED, and that Green LEDs have become the best option to detect the pulse rate in darker skin tones. Additionally, the circuit should be constructed on a stripe board or PCB board instead of the breadboard, and the photodiode should be chosen based on temperature, circuit analysis, battery life, and robustness. Finally, the design of probes that attach to human skin should be considered to ensure stability when measuring the pulse rate.

Conclusion

The most important details in this report are that building a heart rate monitoring sensor using an IR LED and a photodiode is an effective and non-invasive method for measuring heart rate through transilluminating tissue. It is important to consider the response to different lighting conditions, such as dark and bright environments, as they can impact the accuracy of the sensor's readings. Additionally, if granted additional time, the project could incorporate cloud connectivity to enhance data storage, analysis, and accessibility. Finally, the project could explore the possibility of fabricating a 3D printed casing for the heart rate monitoring sensor, optimized for wearability and user comfort.

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