Department of Electronic & Telecommunication Engineering

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Analog Heartbeat Sensor

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EN2091 – Laboratory Practice and Projects

Contents

1 Introduction and Functionality

Introduction

Heart rate is a vital physiological parameter widely used to evaluate a person's cardiovascular condition and overall health status. Measurement of heart rate accurately and non-invasively has become increasingly important in daily health monitoring, fitness assessment, and biomedical education. Among the various techniques available, optical pulse sensing using photoplethysmography (PPG) offers a simple, low-cost, and user-friendly method of detecting heartbeats.

This project presents the design of an analog heartbeat sensor that utilizes PPG to measure changes in blood volume at the fingertip. The sensing module consists of an infrared (IR) LED and a photodiode placed side-by-side in a reflective configuration. When a finger is placed over the sensor, the IR light penetrates the tissue and the amount of reflected light varies with each heartbeat as a result of rhythmic blood flow. These variations generate a small analog signal that corresponds to the user's pulse pattern.

An Arduino microcontroller is used to sample the conditioned signal and analyze the timing between pulse peaks to determine the heart rate in beats per minute (BPM). The calculated BPM value is then displayed on an OLED screen for easy real-time monitoring. The project provides an accessible and educational approach to understanding optical heartbeat sensing and basic physiological measurement techniques.

Functionality

The overall system is divided into four main functional blocks. The optical sensing block generates an analog signal based on the changes detected at the fingertip. This signal is then routed to the analog signal conditioning block, where the waveform is shaped and prepared for digital sampling. The conditioned signal is fed into the microcontroller processing block, where the Arduino measures the time interval between pulse peaks and calculates the heart rate. Finally, the display block presents the computed BPM value to the user on an OLED screen.

Data flow sequentially through these blocks in one direction, ensuring that each stage performs a dedicated task: sensing, conditioning, processing, and display. The block diagram demonstrates how each subsystem interacts and highlights the role of the Arduino as the central processing element that bridges the analog and digital domains. The result is a complete end-to-end system capable of converting fingertip pulse data into readable heart-rate output.

2 System Architecture

2.1 Functional Block Diagram

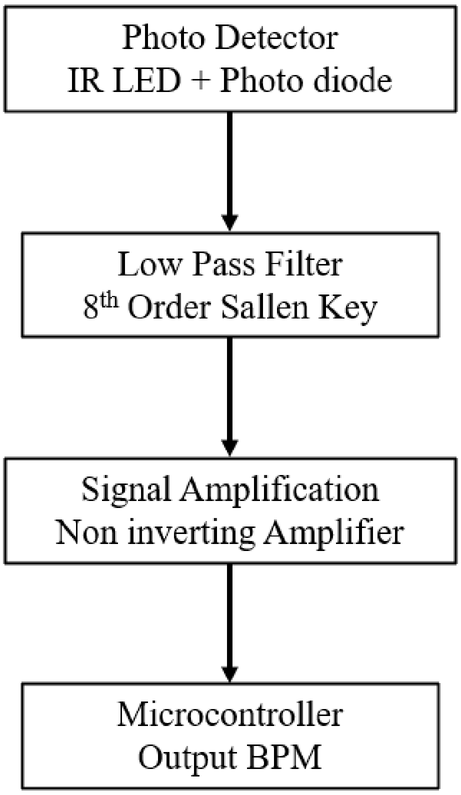


Figure 2.1: Block Diagram

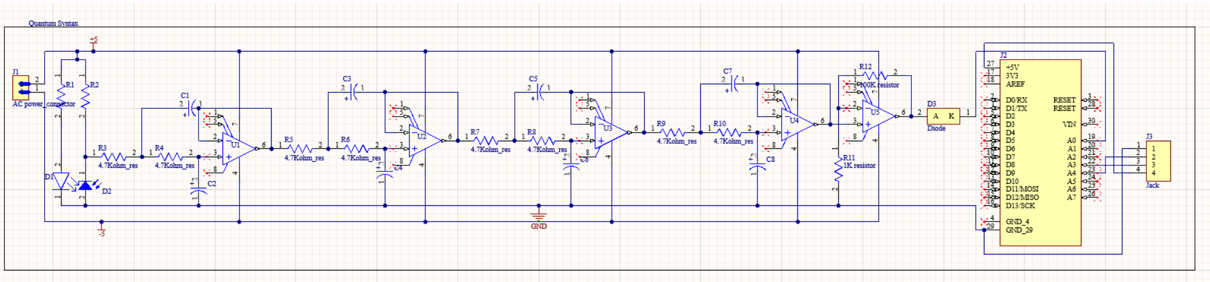


Figure 2.2: Schematic Diagram

2.2 Optical Sensing Module

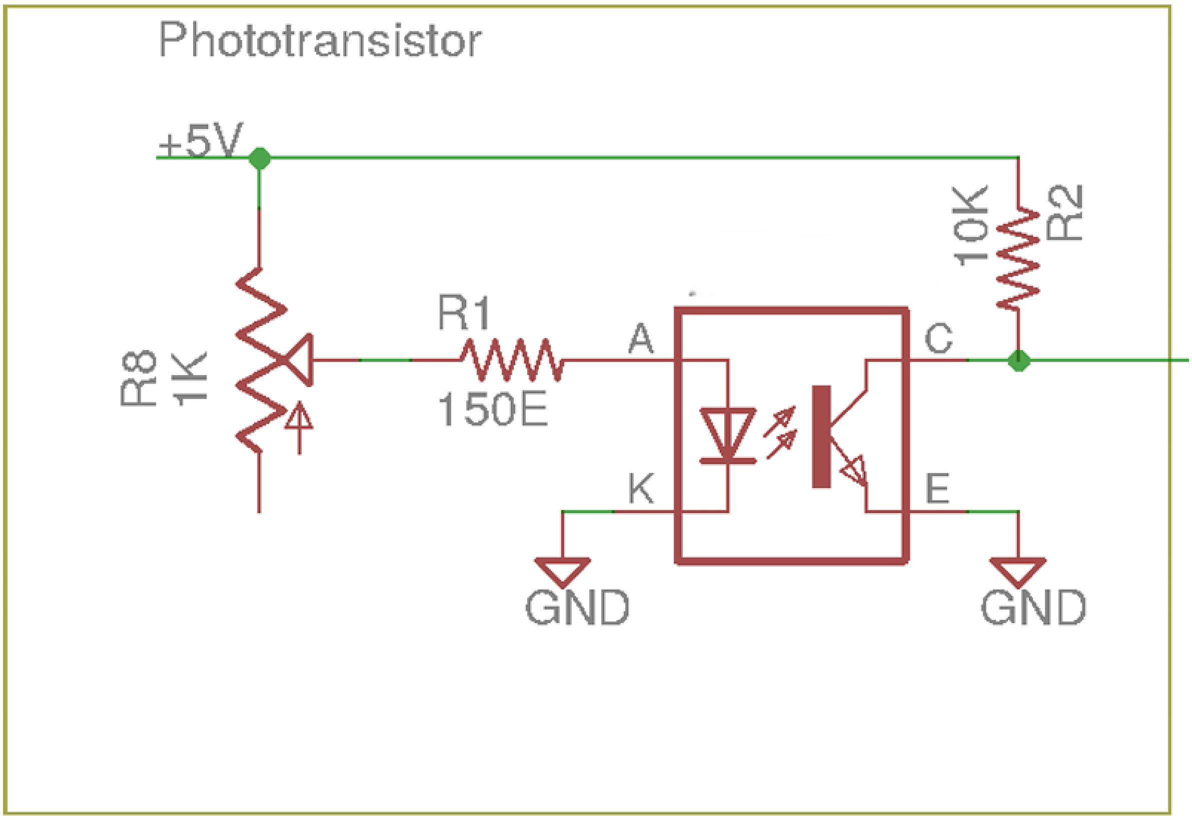


Figure 2.3: Photodetector Stage

The optical sensing stage uses an IR LED and a phototransistor to detect changes in blood volume in the fingertip. The infrared LED emits light into the skin and the phototransistor measures the reflected light. As the heart beats, changes in blood flow cause small variations in the reflected light, producing a weak electrical signal. This signal carries pulse information and is sent to the amplification and filtering stages to obtain a clear heartbeat waveform.

2.3 Analog Filtering and Amplification

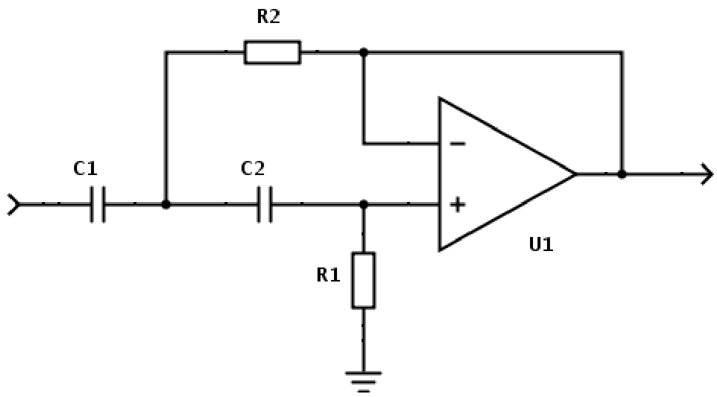


Figure 2.4: Sallenkey Low pass Filter

The filtering stage is a critical part of the analog pulse sensor, responsible for removing unwanted noise and extracting a clean heartbeat signal. The raw signal from the phototransistor is very weak and contains noise from various sources, including ambient light, electrical interference, and finger movement. To address this, an 8th-order low-pass Sallen-Key filter is used, implemented by cascading four 2nd-order sections. Each section uses precision resistors and capacitors to set a cutoff frequency around 3–4 Hz, which corresponds to the typical heartbeat range. By cascading multiple stages, the filter achieves a steep roll-off, effectively attenuating higher-frequency noise while preserving the pulse waveform. This multi-stage filtering produces a smooth and stable output signal, which can be used directly for monitoring or calculating the heart rate. The design ensures reliable performance for different users and environmental conditions.

Cutoff Frequency Calculation for Sallen-Key 2nd-Order Filter

The cutoff frequency of a second-order Sallen-Key low-pass filter is:

$$f_c = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}} \tag{2.1}$$

For equal components, $R_1 = R_2 = R$ and $C_1 = C_2 = C$:

$$f_c = \frac{1}{2\pi RC} \tag{2.2}$$

Substituting the values $R = 4.7\ \text{k}\Omega = 4700\ \Omega$ and $C = 10\ \mu\text{F} = 10 \times 10^{-6}\ \text{F}$:

$$RC = 4700 \times 10 \times 10^{-6} = 0.047 \tag{2.3}$$

$$f_c = \frac{1}{2\pi \times 0.047} \approx 3.39 \text{ Hz} \tag{2.4}$$

Therefore, the cutoff frequency for each second-order stage is approximately 3.4 Hz, which is suitable for isolating the heartbeat signal.

Amplification - Non inverting Amplifier

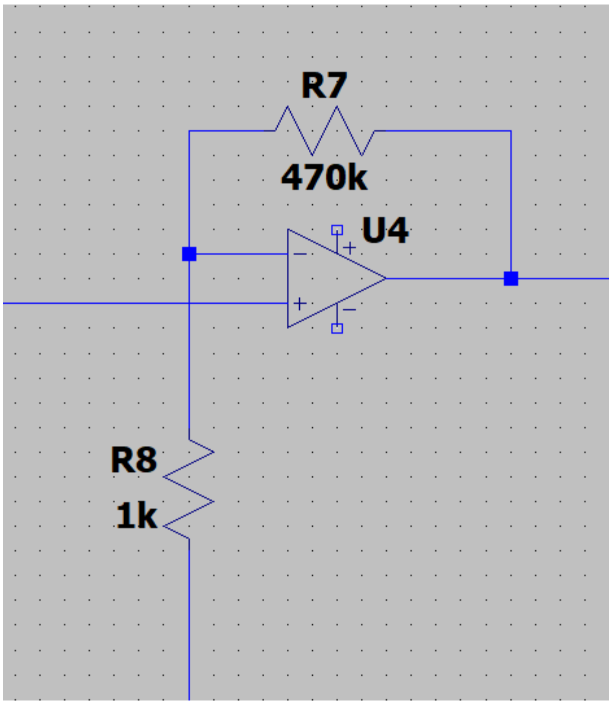


Figure 2.5: Amplification Stage

The final output to be processed by a microprocessor will have to be in a reasonable voltage range of 0 - 3.3V or 0 - 5V. For that we have added an inverting amplifier of 470x gain followed by a diode to rectify the negative voltages of the final waveform.

2.4 Digital Processing

The processing stage requires sampling the pulse waveform using an ADC and performing an FFT on enough samples to detect a peak in the 0.5–2 Hz frequency range. The accuracy of the FFT depends on the sampling duration. In our design, we have used a sampling frequency of $F_s = 16$ Hz and collected samples for $t_s = 16$ s, giving a total sample length of $N_s = F_s \times t_s = 256$ samples.

The frequency resolution of the FFT is given by:

$$\Delta f = \frac{F_s}{N_s} = \frac{F_s}{F_s t_s} = \frac{1}{t_s} = \frac{1}{16 \text{ s}} \approx 0.0625 \text{ Hz} \tag{2.5}$$

A larger sampling duration improves frequency resolution, which is important for accurately detecting low-frequency signals like heartbeats. It is common for heart-rate measurements to last between 15 and 30 seconds.

The algorithm is a simple 3-step process, looping continuously:

1. Collect N_s samples at a sampling frequency of F_s.
2. Compute the FFT of the samples and extract the values in the 0.5–2 Hz range.
3. Plot the FFT and mark the magnitude peak.

While better processing methods using dedicated FFT hardware or DSP processors could reduce computation time, for our prototype, an Arduino is sufficient.

3 Component Selection

Red LED

The red LED is used as the primary light source for illuminating the fingertip. Red light in the 600–700 nm range penetrates tissue effectively and produces noticeable variations in reflected intensity as the blood volume changes. It is cost-effective, stable, and suitable for basic optical heartbeat detection.

Photodiode

The photodiode is chosen for its high sensitivity and fast response to small changes in light intensity. It converts variations in reflected red light into a proportional electrical current. Its low noise characteristics and linear response make it ideal for detecting subtle optical changes caused by blood flow.

lm741 Op-Amp

The lm741 operational amplifier is used for signal amplification and filtering. It is inexpensive, widely available, and easy to integrate into analog circuits. Although older in design, it provides sufficient gain and stability for low-frequency biomedical signals such as heartbeats.

4.7 kΩ Resistors

The 4.7 kΩ resistors are used in the Sallen–Key low-pass filter sections. Together with the 10 μF capacitors, they set a cutoff frequency of approximately 3–4 Hz, appropriate for isolating the heartbeat signal (0.5–4 Hz range). Their value ensures effective noise suppression and stable filtering.

10 μF Capacitors

The 10 μF capacitors form the RC network in each 2nd-order filter stage. Their high capacitance helps achieve a low cutoff frequency suitable for slow biomedical signals. Using identical capacitor values also improves matching, stability, and predictable filter behavior.

4 PCB Design

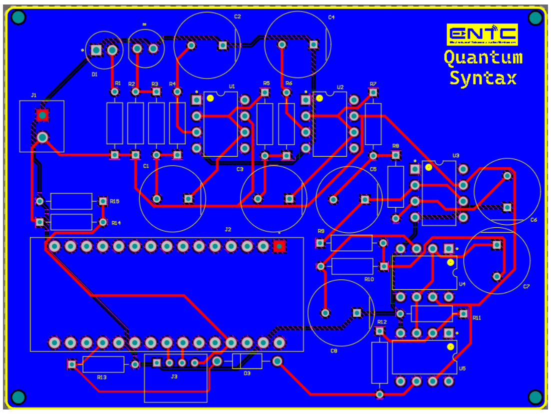


Figure 4.1: PCB Desig

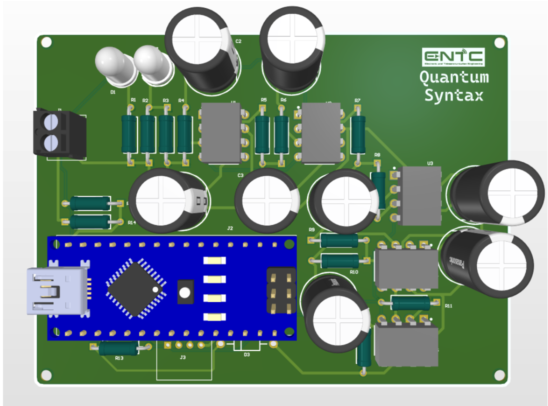


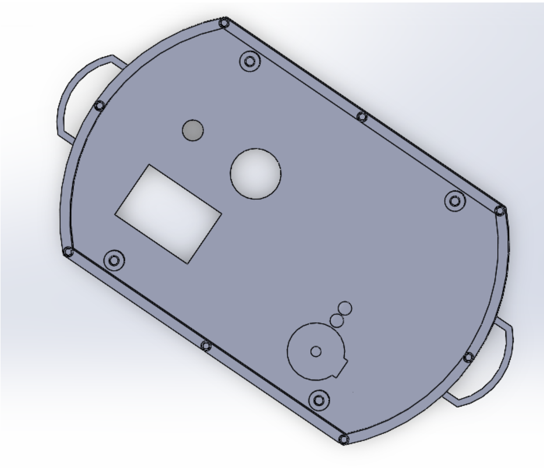
Figure 4.2: PCB 3D View

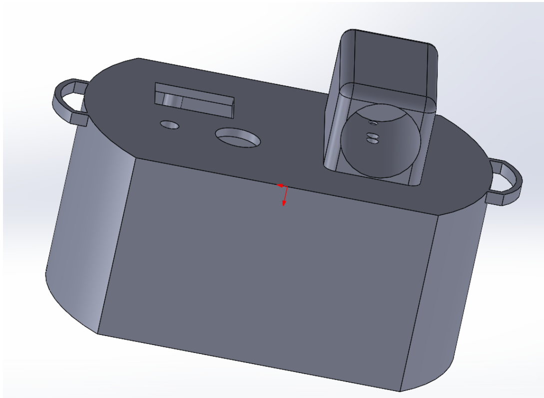
For the analog heartbeat sensor, we designed a compact 75 x 78mm printed circuit board (PCB) using Altium. The PCB, a two-layered structure, was manufactured in Sri Lanka. Traces of the lines are 0.254mm width. The drill hole size in the PCB is 3mm. We placed the components in such a way to overcome the complexity in the routing and thermal heating issues.

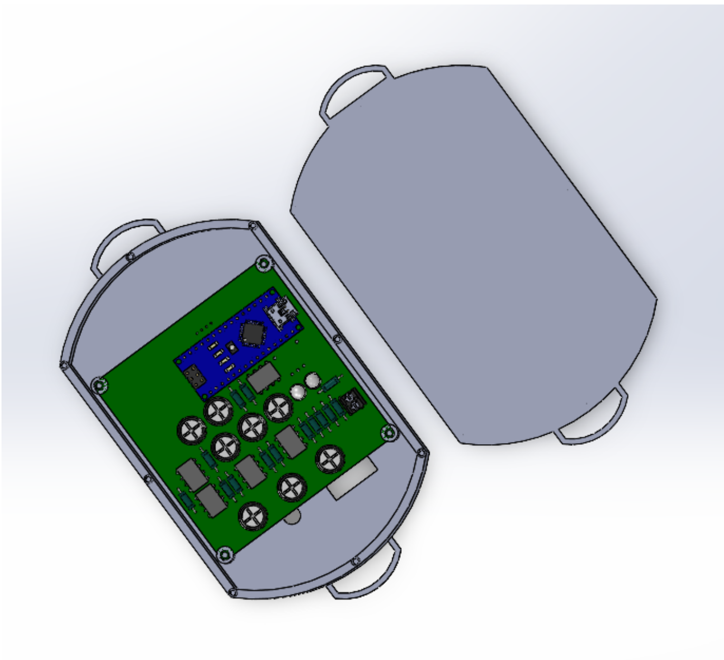
PCB Design Files: `https://dms.uom.lk/s/frMMk7ygro2RwP8`

5 Enclosure Design

We have designed an enclosure using SolidWorks. The enclosure measures 10cm x 20cm and is designed to be user-friendly. During the design process, we paid special attention to the power supply. The enclosure has 2 banana connectors to connect to the laboratory power supply and a barrel jack connector to connect to the 10V power supply. The user can use either one of them.







Enclosure design Files: `https://dms.uom.lk/s/JsinTobMC27JrpA`

6 Software Simulation and Hardware Testing

We used LT Spice software to simulate the circuit that we created. It gave the voltage outputs very accurately and we confirmed that the selected components are suitable for the implementation.

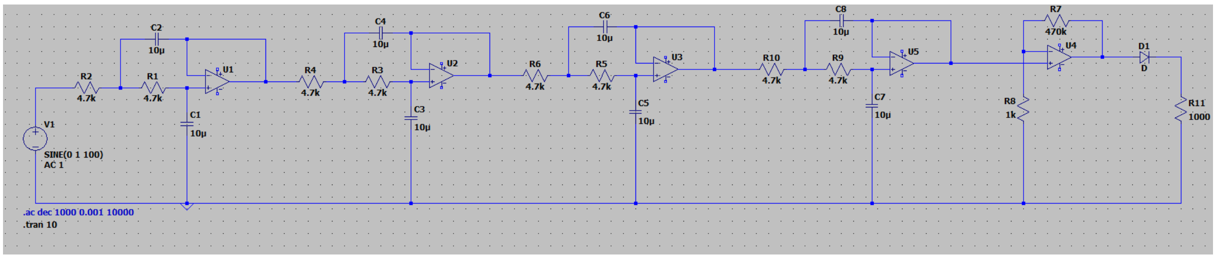


Figure 6.1: LT Spice circuit

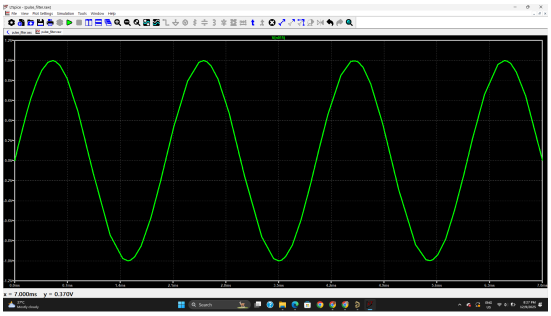


Figure 6.2: Input waveform

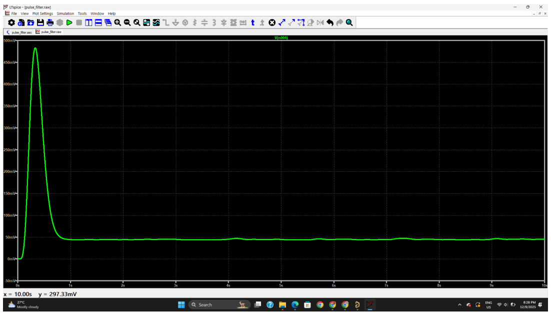


Figure 6.3: Output waveform

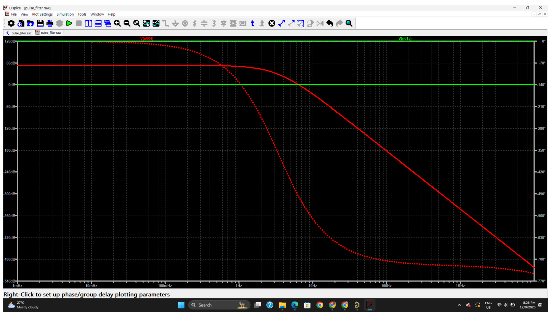


Figure 6.4: Filter Cutoff Frequency

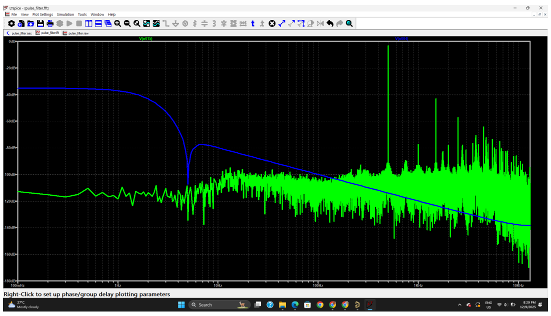


Figure 6.5: Frequency Response

Simulation Files: `https://dms.uom.lk/s/Lk2Px2HpGSfST6s`

7 Conclusion and Future Work

The experimental results demonstrate that heart-rate measurement can be reliably achieved even at very low IR LED drive currents. A clear linear relationship was observed between the LED current and the corresponding output signal amplitude, enabling predictable control of signal strength through appropriate current selection. A minor dependence of reflected signal amplitude on skin pigmentation was also noted; however, this effect becomes less significant when operating at lower LED currents.

Additionally, the FFT-based analysis indicates that the accuracy of heart-rate estimation improves with increased sampling duration, emphasizing the importance of longer measurement intervals for enhanced precision.

During practical implementation, variations in applied finger pressure introduced fluctuations in the output amplitude. For future product-level designs, it is therefore essential to ensure that the sensor maintains a light, consistent contact with the finger, preserves a fixed optical distance, and is mechanically isolated from finger movements to achieve stable and repeatable measurements.

This project fulfills almost all the requirements, but there are some constraints we couldn't overcome. The main problem we faced was providing power to the op-amps. After some research, we were able to find a solution and design our own power supply, which can directly plug into the wall and the sensor. However, we couldn't print the PCB, so we had to use a dual channel power supply in the laboratory.

Future Developments

- **PCB Implementation for the Optimized Power Supply**
  Finalize the in-house power supply for the voltmeter by developing a printed circuit board (PCB) for the designed power supply to enhance reliability and streamline the manufacturing process.

- **Making a mobile app for monitoring Heart Beat**
  We are making a mobile app for monitoring heart rate. In the future, we plan to make it an IoT wearable device. By connecting the device to the mobile app, users will be able to monitor their heart rate through the app

- **Add a simple UI**
  The device can include a simple user interface with selectable modes such as BPM only, BPM with waveform, and average BPM over a chosen time period. The device can also offer adjustable LED brightness and different filter modes to improve usability and customization.

8 Bill of Materials

Component	Qty	Cost (Rs.)
IR LED 940nm	1	10
Photodiode	1	10
LM741 Op-Amp	5	150
Capacitors	8	24
Resistors	14	28
Arduino Nano	1	900
OLED Display	1	590
Diode	1	10
PCB	1	700
Enclosure	1	6400

9 Contribution of Group Members

- Abishek L. — Enclosure Designing and Assembling
- Santhosh S. - Breadboard Implementation and Soldering
- Saruka U. - PCB Designing and Circuit Building

10 References

1. LM741 Datasheet: `https://www.alldatasheet.com`
2. Heart Rate Measuring using PPG: `https://www.ee.iitb.ac.in/~stallur/wp-content/uploads/2017/02/Heart-Rate-Measurement-using-PPG1.pdf`
3. Sedra, A. S., & Smith, K. C. (2014). Microelectronic Circuits (7th ed.). Oxford University Press
4. Arduino Documentation: `https://docs.arduino.cc/`