Heart Rate Monitor Using PPG

Introduction

Heart rate monitoring is one of the cornerstones of modern healthcare. The evolution of monitoring technologies, from bulky electrocardiographs (ECG) to compact wearable devices like the Apple Watch and Fitbit, showcases the rapid adoption of photoplethysmography (PPG) in consumer health. Introduced in the 1930s, PPG has become essential in non-invasive, real-time monitoring due to its simplicity and reliability.

Motivation Behind the Project

With cardiovascular diseases causing approximately 18 million deaths annually worldwide (WHO, 2023), early detection and regular monitoring of heart rate are critical. A study conducted in 2022 highlighted how wearable heart rate monitors helped reduce emergency hospital admissions in hypertensive patients by 30%.

This project seeks to address such challenges by creating an affordable, accessible heart rate monitor. It also provides an excellent opportunity to deepen understanding of PPG technology, its applications, and its limitations.

What is PPG?

Photoplethysmography (PPG) is an optical technique that measures blood volume changes in the microvascular bed of tissue. It is based on the principle of light absorption and reflection:

Setup: A light source illuminates the skin, and a photodetector measures the intensity of reflected light.

Mechanism: Changes in blood volume during cardiac cycles modulate the intensity of the reflected light, creating a waveform corresponding to the heartbeat.

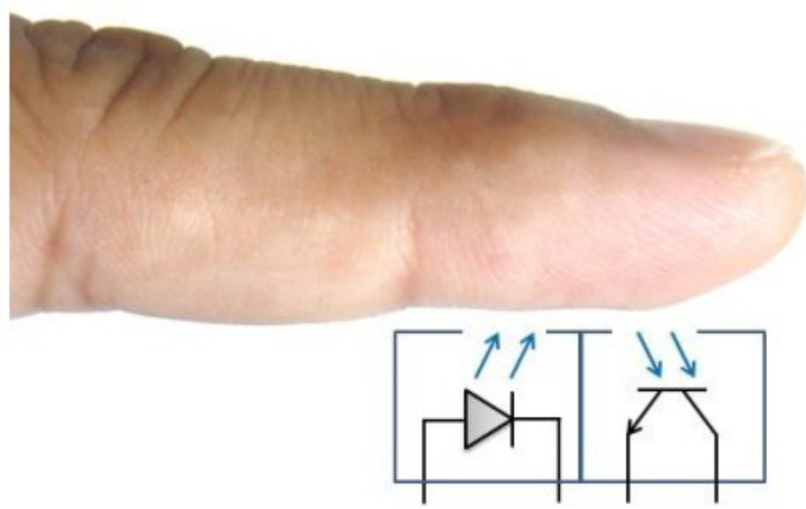


Fig10. Reflective photoplethysmography

PPG makes use of low-intensity infrared (IR) light. When light travels through biological tissues, it is absorbed by bones, skin pigments, and both venous and arterial blood.

Since light is more strongly absorbed by blood than the surrounding tissues, the changes in blood flow can be detected by PPG sensors as changes in the intensity of light.

The voltage signal from PPG is proportional to the quantity of blood flowing through the blood vessels. Even small changes in blood volume can be detected using this method, though it cannot be used to quantify the amount of blood.

A PPG signal has several components including volumetric changes in arterial blood, which is associated with cardiac activity, variations in venous blood volume which modulates the PPG signal, a DC component showing the tissues' optical property, and subtle energy changes in the body.

Applications of PPG in Healthcare

- Heart rate and rhythm monitoring

- Oxygen saturation (SpO_2) measurement

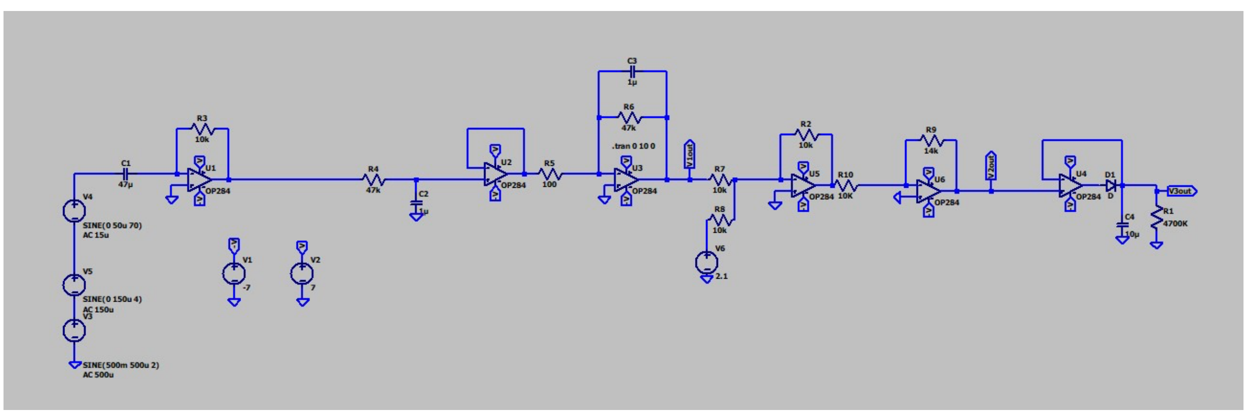
- Blood pressure estimation

- Stress and sleep monitoring

Comparison: PPG vs ECG

Feature	PPG	ECG
Technique	Measures blood volume changes	Measures electrical heart activity
Device Size	Compact	Bulky(requires electrodes)
Ease of Use	Non-invasive,simple setup	Requires placement of electrodes
Accuracy	Reliable for HR,less for rhythms	Highly accurate for heart rhythms
Cost	Low	Relatively Higher

Circuit Description



3.1 Circuit Overview

The project circuit consists of several key stages designed to extract a clean, readable heart rate signal:

1. **Pre-Amplifier:** Amplifies the weak PPG signal from the sensor.

2. **Low-Pass Filter:** Removes high-frequency noise.

3. **Voltage Follower:** Ensures impedance matching and prevents loading of the preceding stage.

4. **Non-Inverting Amplifier with Low-Pass Filter:** Further amplifies the signal while suppressing noise.

5. **Signal Conditioning:** Shifts and scales the signal to fit within the ADC-compatible range (0–3.3V).

6. **Peak Detection:** Extracts the envelope of the signal to detect individual heartbeats.

3.2 Component Values and Specifications

- ➢ **PPG Signal**:
  - ○ Combined waveform generated using three sine wave sources to simulate heart-like signals.
  - ○ Noise source added to mimic real-world interference.
- ➢ **Pre-Amplifier**:
  - ○ Op-Amp: OP284.
  - ○ Resistor: R3=10 kΩ
  - ○ Capacitor: C1=47 μF
- ➢ **Low-Pass Filter**:
  - ○ Resistor: R4=47 kΩ
  - ○ Capacitor: C2=1 μF
  - ○ Cutoff Frequency: fc=1/(2πR4C2)=3.39

➢**VoltagefollowerandActiveLowPassFilter:**

1. Op-Amp: OP284
2. R5=100Ω ,R6=47kΩ,C3=1μF

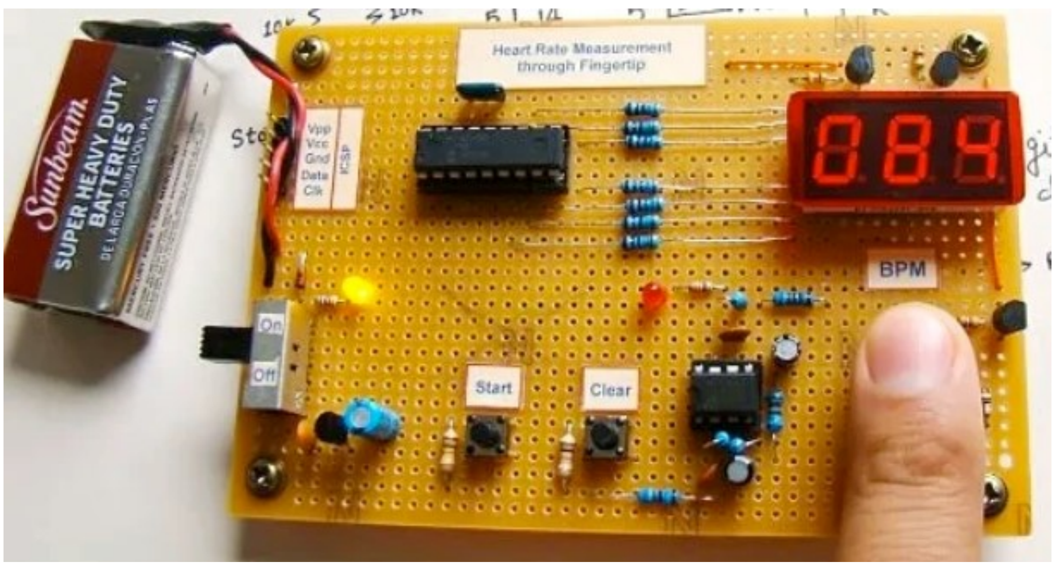
- ➢ **Signal Conditioning**:
  - ○ Bias Voltage: Vbias= 2.1V
  - ○ Resistors: R2=10 kΩ, R7=10kΩ, R8=10 kΩ, R9=14kΩ, R10=10kΩ ➢

Peak Detection:

- ○ Resistors: R1=4700kΩ
- ○ Capacitor: C4=10 μF
- ○ Diode: Ideal diode model for simulation.

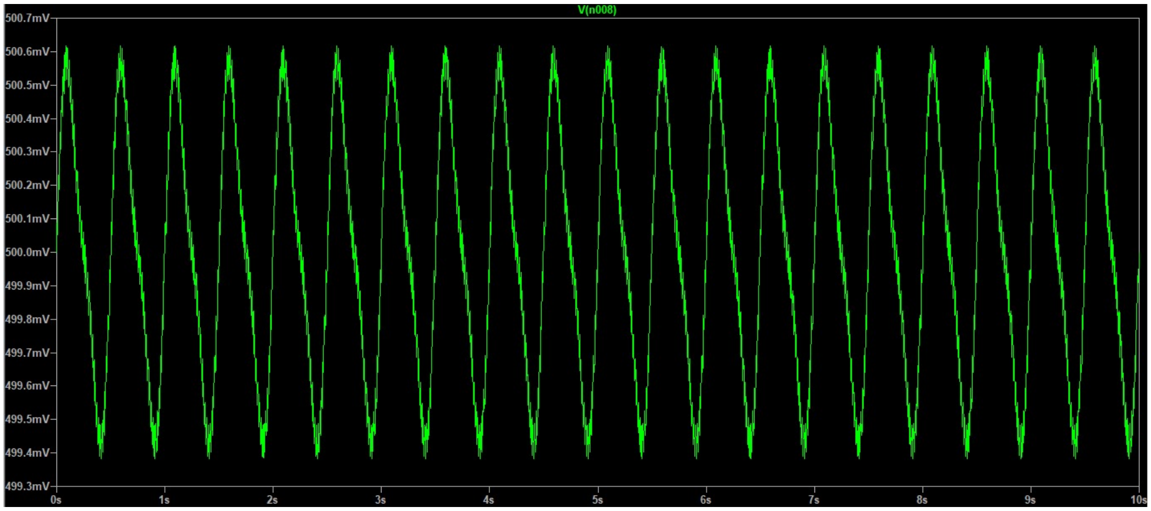
Working of the Circuit

1. **PPG Signal Generation**:
    - A synthetic signal is generated using two low-frequency sine waves (2 Hz and 4 Hz) to simulate heartbeats.
    - A higher frequency noise (70 Hz) is added to mimic real-world conditions.
2. **Pre-Amplification**:
    - The PPG signal is fed into the inverting terminal of an op-amp, amplifying it with a gain of 10 kΩ
3. **Low-Pass Filtering**:
    - A first-order low-pass filter is used to remove noise above 10 Hz.
4. **Voltage Follower**:
    - A buffer stage ensures isolation and prevents loading of the filter stage.
5. **Non-Inverting Amplifier**:
    - Provides additional amplification and a second-order filtering effect to smooth the signal further.
6. **Signal Conditioning**:
    - The signal is scaled and shifted to fit within a 0–3.3V range, suitable for ADCs.
7. **Peak Detection**:
    - Extracts the envelope of the signal, representing the peaks of heartbeats, which is the final output of the circuit.

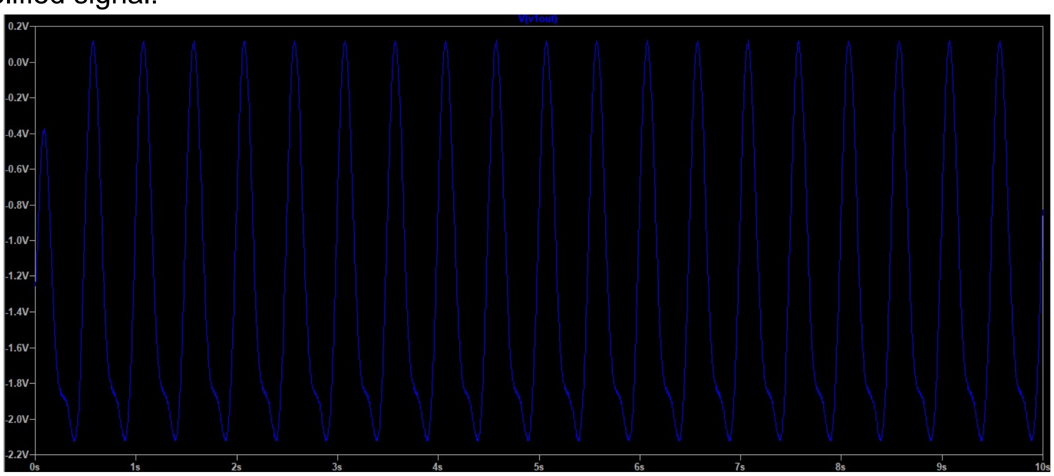


Simulation Results

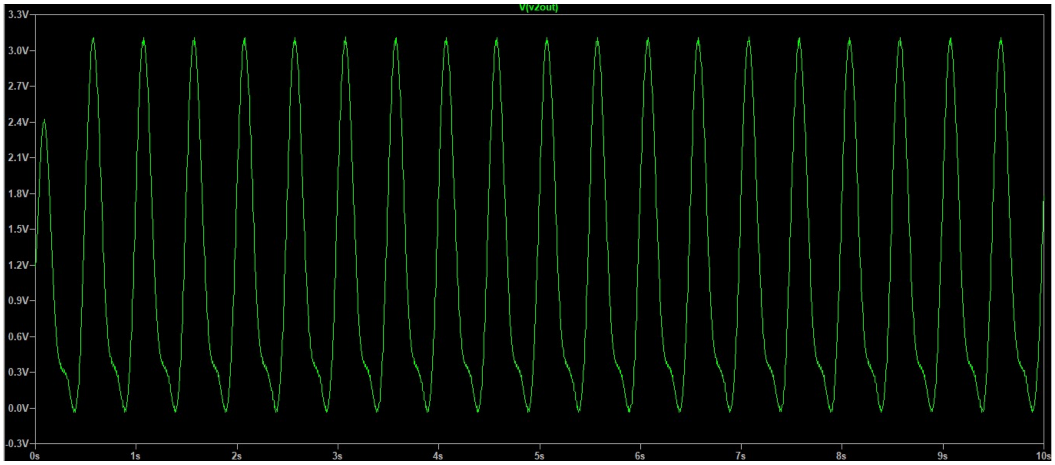
1. **Input Signal:**



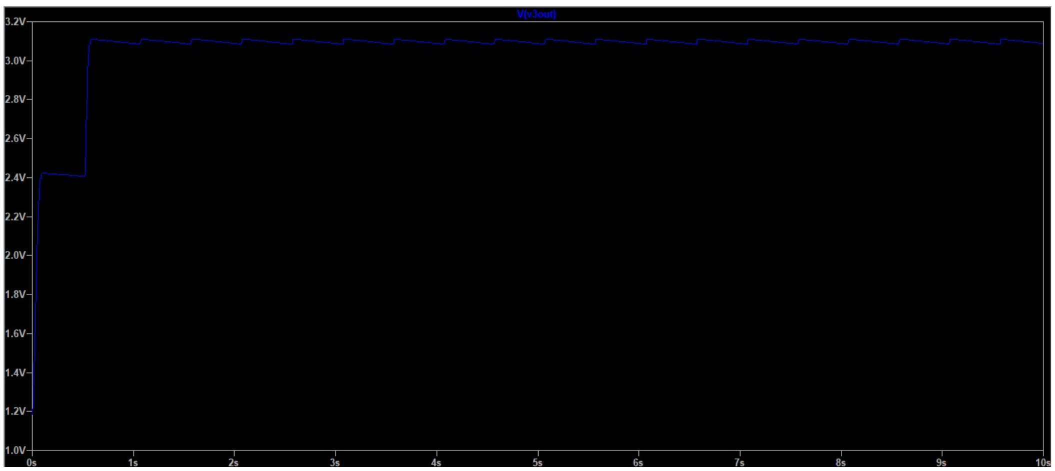
2. **Signal Before Conditioning (V1out):** ○ Noise-free amplified signal.



3. **Signal After Conditioning (V2out):**
    ○ Shifted and scaled signal with a 0–3.3V range, suitable for ADC input.



4. **Signal After Peak Detection (V3out):**
    ○ Smooth envelope signal representing the heartbeat peaks.



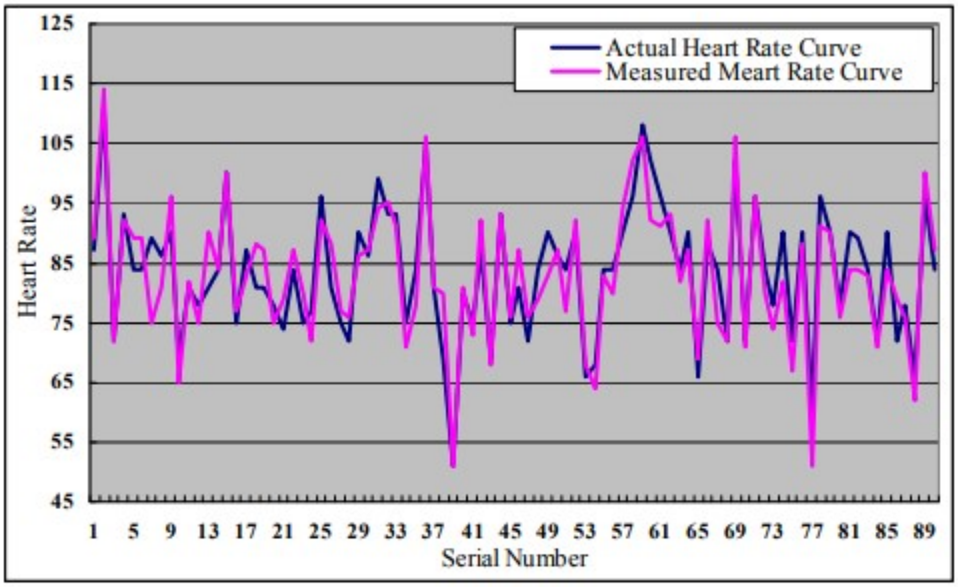


Figure 11. Difference between original heartbeat and measured heartbeat

Societal Impact

Heart rate monitors, especially those built on PPG technology, have the potential to bridge the gap between resource-rich and low-resource settings:

Accessibility: This project demonstrates a low-cost, simple-to-implement solution, making it ideal for rural and underserved areas.

Preventive Healthcare: Regular monitoring enables early detection of anomalies, reducing hospital admissions.

Global Health Equity: As wearable health devices become affordable, PPG-based systems can democratize access to essential diagnostics globally.

Global Trends and Numbers

Wearable Adoption: By 2025, over 1.1 billion wearable devices are expected to be in use worldwide (Statista, 2023).

Healthcare Innovations: The global wearable medical devices market, valued at $29 billion in 2023, is projected to grow at a CAGR of 20% over the next decade.

Impact: Studies show a 25% increase in fitness tracking adoption among at-risk populations, enhancing health outcomes.

Challenges Faced During the Project

This section highlights the technical, practical, and design challenges encountered during the development of the heart rate monitor using PPG and how they were resolved:

1. **Signal Noise and Interference**

Issue: The raw PPG signal was heavily influenced by noise, including power line interference and high-frequency artifacts, which masked the actual heart rate signal.

Solution: A low-pass filter was incorporated to eliminate high-frequency noise, and careful tuning of the cutoff frequency was performed to retain the desired signal while suppressing noise.

2. Simulation Constraints in LTspice

Issue: LTspice simulations with components like diodes in the precision rectifier stage significantly slowed down the simulation, sometimes taking hours to produce results.

Solution: Diodes were replaced with simpler circuits, diode-free circuit configurations such as a non-inverting amplifier stage for signal conditioning. This improved simulation speed and maintained performance.

3. Design Convergence Problems

Issue: LTspice often struggled with convergence in complex circuits, particularly when multiple active elements were present.

Solution: Simulation parameters were fine-tuned.Simplified versions of certain sub-circuits were tested in isolation before integration.

4. Component Value Selection

Issue: Determining optimal resistor and capacitor values for different stages, especially for filters, was challenging as improper values could lead to distortion or signal attenuation.

Solution: A systematic approach of calculating values based on theoretical formulas, followed by iterative adjustments during simulation, was used to achieve the desired frequency response.

5. Trade-offs in Circuit Complexity

Issue: While adding more features and stages would enhance the circuit's functionality, the complexity also made simulation slower and harder to debug.

Solution: A balance was struck by including essential features (e.g., signal conditioning and peak detection) while documenting additional enhancements in the report for potential future work.

6. Limited Hardware Validation

Issue: The project relied solely on simulations due to the lack of time and knowledge for hardware implementation. This limited the ability to test the circuit in real-world conditions.

Solution: Theoretical analysis and simulation results were thoroughly validated

7. Amplification Challenges

Issue: Ensuring the amplified signal remained within a suitable voltage range for subsequent stages, without clipping or introducing distortion, was tricky.

Solution: Proper gain design in the pre-amplifier and subsequent stages, along with voltage offset adjustments, ensured the output signal was clean and within the desired range.

8. **Learning Curve for LTspice**

Issue: As students, learning the nuances of LTspice for complex simulations was initially time-intensive.

Solution: Extensive self-study, online resources, and iterative testing helped overcome this challenge, leading to a better understanding of circuit design and simulation.

9. Data Interpretation and Validation

Issue: Validating the output waveform to ensure it accurately represents a PPG signal was challenging due to the absence of real-time comparison with physical data.

Solution: Literature on PPG signal characteristics was studied to match the simulated waveform's amplitude and frequency to typical PPG signals, ensuring realistic outcomes.

10. Visualization Limitations

Issue: LTspice lacked advanced visualization options to present the results in a user-friendly manner.

Solution: Simulated waveforms were manually analyzed.

11. Time Constraints

Issue: The project had to be completed within a tight timeline, which limited the scope for iterative design improvements.

Solution: A well-structured timeline with specific milestones was followed to ensure timely completion of all major stages, including simulations and report writing.

These challenges not only made the project demanding but also enriched the learning experience, fostering a deeper understanding of practical circuit design, simulation, and problem-solving skills.

Future Scope

1. AI Integration:

Machine learning algorithms can be used to classify PPG waveforms for detecting arrhythmias or other cardiac conditions.

2. IoT Connectivity:

Real-time heart rate data can be transmitted to mobile apps or cloud platforms for remote monitoring.

3. Hardware Development:

Transitioning the design from simulation to a physical prototype would enable real-world testing.

4. Extended Biometrics:

Expanding the device to measure SpO_2 and estimate blood pressure using PPG signals.

Conclusion

This project demonstrates the potential of PPG technology in heart rate monitoring, paving the way for cost-effective, non-invasive, and accessible health diagnostics. By addressing design challenges and emphasizing practicality, the work contributes to advancing wearable healthcare and preventive medicine. The journey reflects not only technical achievements but also the importance of perseverance and adaptability in engineering design.

References

1. World Health Organization (WHO). "Cardiovascular Diseases." 2023.

2. Statista. "Wearable Device Market Forecast." 2023.

3. Allen, J. "Photoplethysmography and its application in clinical physiological measurement." Physiological Measurement, 2007.

4. Medical Journal Reports. "Impact of Wearable HR Monitors on Hypertensive Patients." 2022.

5.Heart Rate Monitoring System using Finger Tip through Arduino and Processing Software,International Journal of Engineering Research & Technology (IJERT),ISSN: 2278-0181 ,NCESC - 2018 Conference Proceedings

6.Design and Development of a Heart Rate Measuring Device using Fingertip M.M.A. Hashem1 , Rushdi Shams2 , Md. Abdul Kader3 , and Md. Abu Sayed4 Department of Computer Science and Engineering Khulna University of Engineering & Technology (KUET) Khulna 9203, Bangladesh

7.Introduction to Measurement system: Tarea 3 Heartbeat Measurement Circuit LA-CoNGA physics