Final Exam: PPG Signal Acquisition and Analysis

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1. Introduction

Photoplethysmography (PPG) is a non-invasive optical technique widely used to detect blood volume changes in the microvascular bed of tissue. PPG sensors are commonly employed in wearable devices and medical equipment to estimate heart rate and monitor cardiovascular health. In this experiment, a transmissive PPG sensor was used to acquire real-time physiological signals through an Arduino Leonardo microcontroller. The collected analog voltage readings were transmitted to MATLAB for real-time plotting, filtering, and analysis.

The primary goal of this lab was **to develop a** system that captures raw PPG signals, applies appropriate preprocessing (normalization and low-pass filtering), and extracts key physiological features such as heart rate by detecting signal peaks. This process involved understanding analog data acquisition, basic digital signal processing techniques, and interpreting biological signals. The experiment not only reinforced fundamental engineering concepts such as sampling, noise reduction, and peak detection but also demonstrated how embedded systems can be integrated with software tools like MATLAB for biomedical applications.

Key concepts:

Light Attenuation: The gradual change in light intensity as it travels through a medium, such as air, water, glass, etc.

Blood Volume: Total amount of blood in circulation within the body's cardiovascular system.

Sensor: Device that detects and/ or measures physical properties.

2. Materials and Procedures

Materials:

- Arduino Leonardo Microcontroller
- Breadboard
- Computer with MATLAB Arduino Support Package
- LED (Ideally green)
- Jumper wires
- Resistors
- Photoresistor

Procedure:

1. Arduino and Sensor Setup:

- ❖ Connected the transmissive PPG sensor's analog output to the Arduino Leonardo's analog input pin A1.
- ❖ Powered the PPG sensor using the Arduino's 5V and GND pins.
- ❖ Connected a digital pin (D12) to an LED for basic Arduino communication testing.

2. MATLAB Initialization:

- Established communication with the Arduino using MATLAB's arduino() function, specifying the COM port and board type.
- Defined key parameters such as sampling frequency (200 Hz) and acquisition duration (30 seconds).

3. Data Acquisition Loop:

- Started a timer using MATLAB's tic function.
- Read analog voltage values from the PPG sensor inside a for-loop at a sampling rate of 200 samples per second.
- Plotted the raw voltage data in real-time during acquisition using dynamic plot updates.

4. Signal Preprocessing:

- Normalized the collected signal by subtracting its mean and dividing by its standard deviation.
- Applied a 4 Hz low-pass Butterworth filter to remove high-frequency noise from the normalized data.

5. Peak Detection and Heart Rate Calculation:

- Used MATLAB's findpeaks function to identify peaks corresponding to heartbeats in the filtered signal.
- Calculated the average time between consecutive peaks to estimate heart rate in beats per minute (BPM).

6. Data Saving and Visualization:

- Saved the collected raw time and voltage data into a .mat file for later analysis.
- Generated a final plot of the filtered signal with detected peaks highlighted, along with the calculated heart rate displayed in the title.

3. Results

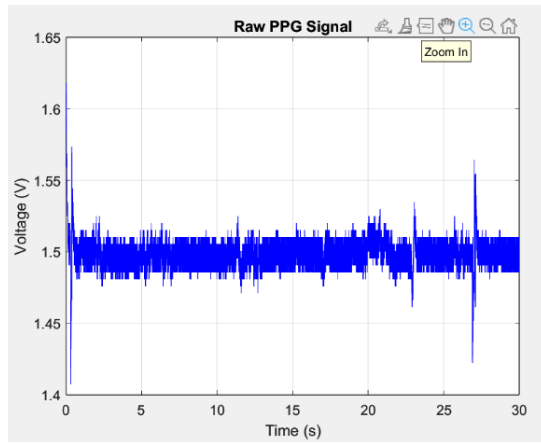

Figure 1 – Noisy raw PPG signal

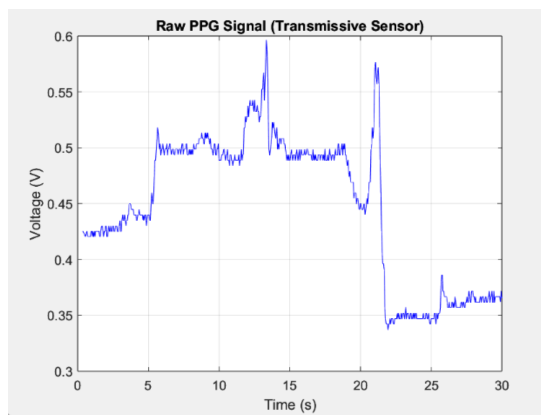

Figure 2 – Raw PPG with sharp decline

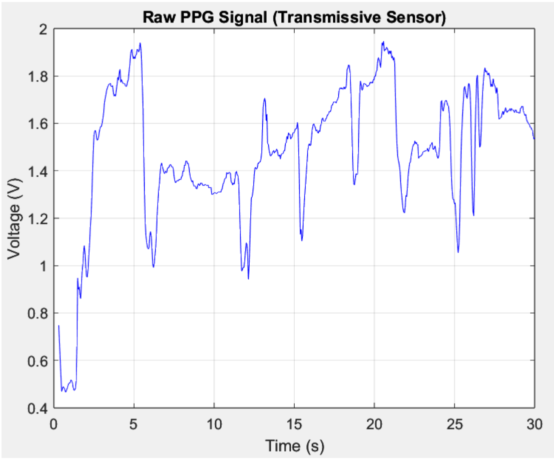

Figure 3 – Raw PPG more or so resembling a heartbeat monitor

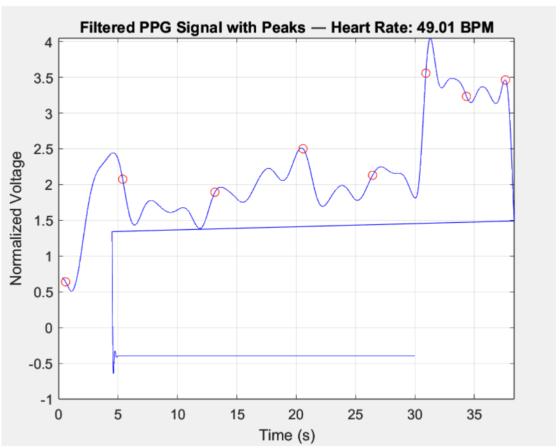

Figure 4 - Filtered data of figure 3

Data acquisition was attempted several dozen times using a transmissive PPG sensor, resulting in signals of varying quality. Our group decided to present our three best signals each from distinct trials with each showcasing a signal better than its predecessor. Figure 1 depicts the first signal, which produced a highly noisy signal with minimal identifiable features, primarily consisting of random fluctuations that did not resemble typical cardiac activity. This was likely due to the external factors like ambient lighting conditions from the university's library, as the photoresistor is very sensitive to external light and movement. Figure 2 demonstrated partial improvement, exhibiting some discernible waveform patterns; however, a pronounced signal drop occurred approximately 20 seconds into the recording, likely due to sensor misalignment or equipment quality. Figure 3 yielded the most usable dataset, characterized by multiple distinguishable peaks and a quasi-periodic structure that more closely approximated the morphology of a typical PPG waveform. Nevertheless, despite using different subjects during data collection in order to determine if it influenced data collection, the measured heart rate consistently remained in the mid to high 40s beats per minute (lower than physiologically expected) across many of the trials. This discrepancy suggests that the low-cost PPG sensor and acquisition setup may have introduced systematic errors, likely due to low signal sensitivity, improper peak detection, or missed beats within the noisy data. Throughout the data collection process, several challenges were encountered, including motion artifacts, external light interference, and limitations associated with the sensitivity and stability of the low-cost sensor used. Based on overall signal quality and the ability to extract meaningful physiological information, figure 3 was selected for subsequent analysis.

As evidenced in figure 4, despite applying several preprocessing techniques, including signal normalization, moving average filtering, and flat-line removal based on moving variance, we were unable to fully eliminate the flat-line artifacts in the recorded PPG signal. The cause of these persistent flat lines is likely due to limitations in the sensor's performance or incorrect sensor placement during data collection, leading to poor optical contact and weak signal acquisition. This issue may have been exacerbated by external factors, such as ambient light interference or poor sensor calibration.

4. Discussion

Although the results did not clearly demonstrate what was intended, our group was able to learn the nuances of PPG capturing and the difficulties that come with collecting accurate sensor data. In addition to outside influences, equipment and posture play a crucial role in data acquisition, and failing to remain stationary would oftentimes skew the results greatly.

Our group encountered several issues during the experiment:

1. **Obtaining Clear and Reliable Data**: Obtaining a clear and reliable PPG waveform proved to be a significant challenge throughout the experiment. Despite numerous attempts and using different subjects, it was difficult to capture a signal that resembled a typical heart rate graph, with most trials producing either noisy or unstable waveforms. Even when the signal appeared more structured, the calculated heart rate consistently measured in the mid to high 40s beats per minute, significantly lower than expected for healthy individuals. These difficulties were likely due to limitations of the low-cost sensor, external lighting interference, and signal noise. Overall, the results reflect the challenges of achieving accurate physiological measurements with basic equipment and highlighting the need for more robust data acquisition methods.
2. **Inaccurate BPM Readings**: During initial testing, the sensor consistently measured heart rates between 70 and 90 BPM. However, in later trials, the readings dropped unexpectedly to the mid-40s. Despite several troubleshooting efforts, including switching from a reflective PPG sensor setup to a transmissive one, the issue persisted.
3. **Protruding Baseline Artifacts**: As shown in Figure 4, the filtered PPG signal revealed persistent low-level baseline lines beneath the primary waveform. Various signal processing methods and advanced MATLAB techniques were applied to eliminate these artifacts, but they remained visible. While this issue emphasizes the importance of high-quality sensors and equipment for optimal signal acquisition, it also provided a valuable learning opportunity to practice real-world data cleaning and analysis strategies within a lab environment.

5. References

[1] Allen, J. (2007). Photoplethysmography and its application in clinical physiological measurement. *Physiological Measurement, 28*(3), R1–R39. https://doi.org/10.1088/0967-3334/28/3/R01

[2] Castaneda, D., Esparza, A., Ghamari, M., Soltanpur, C., & Nazeran, H. (2018).

A review on wearable photoplethysmography sensors and their potential future applications in health care. *International Journal of Biosensors & Bioelectronics*, *4*(4), 195–202. https://doi.org/10.15406/ijbsbe.2018.04.00125

[3] Elgendi, M. (2012). On the analysis of fingertip photoplethysmogram signals. *Current Cardiology Reviews*, *8*(1), 14–25. https://doi.org/10.2174/157340312801215782

[4] MathWorks. (2024). *MATLAB (Version R2024a) [Software]*. The MathWorks, Inc. https://www.mathworks.com/

https://youtu.be/CdKni9vaA9g?si=jFStgqYfVwPvslmh