Optimizing Wearable Performance: Real-time Algorithms for Heart Rate and Current Calibration on a Smart Ring

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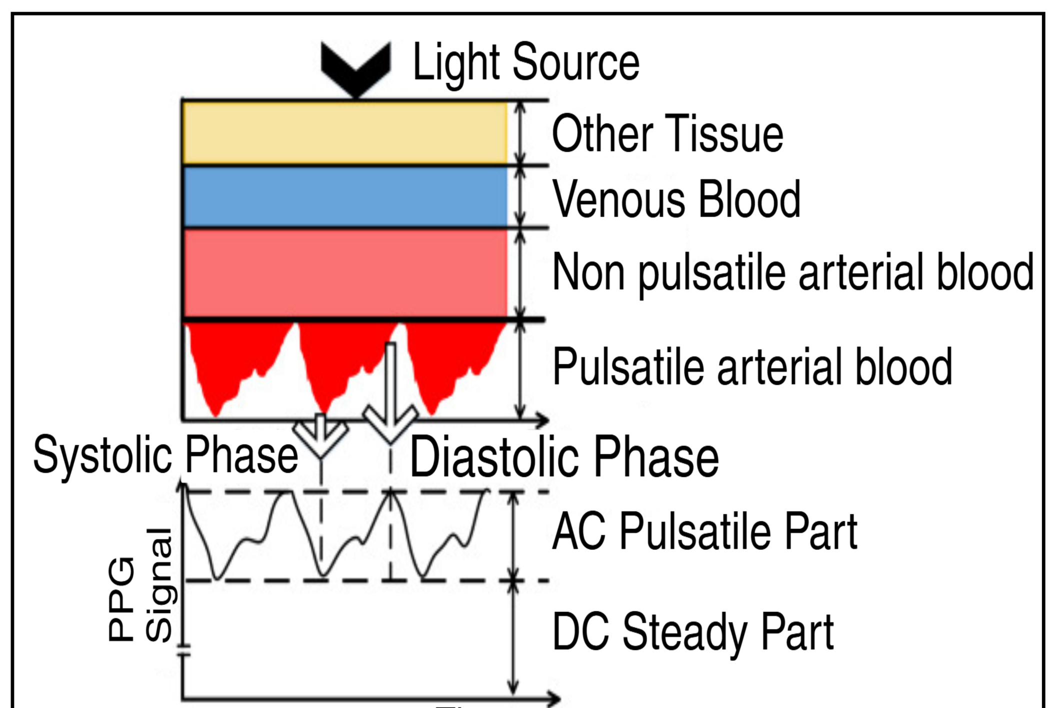
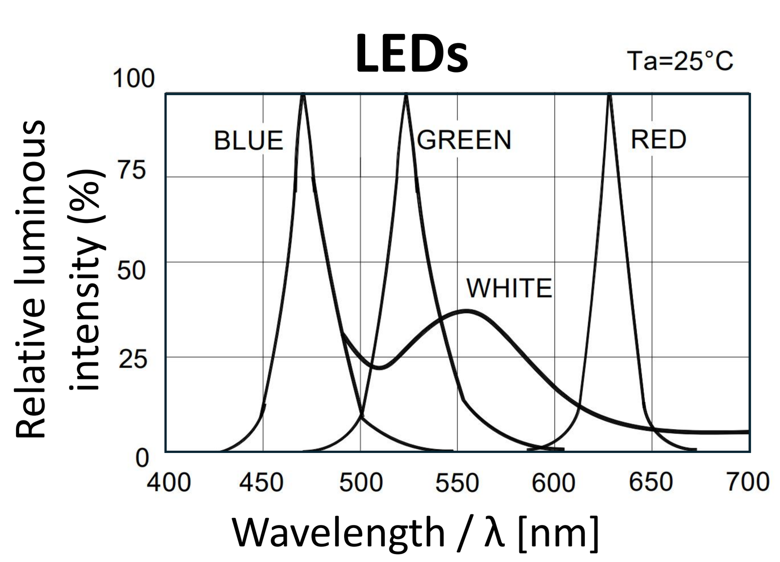
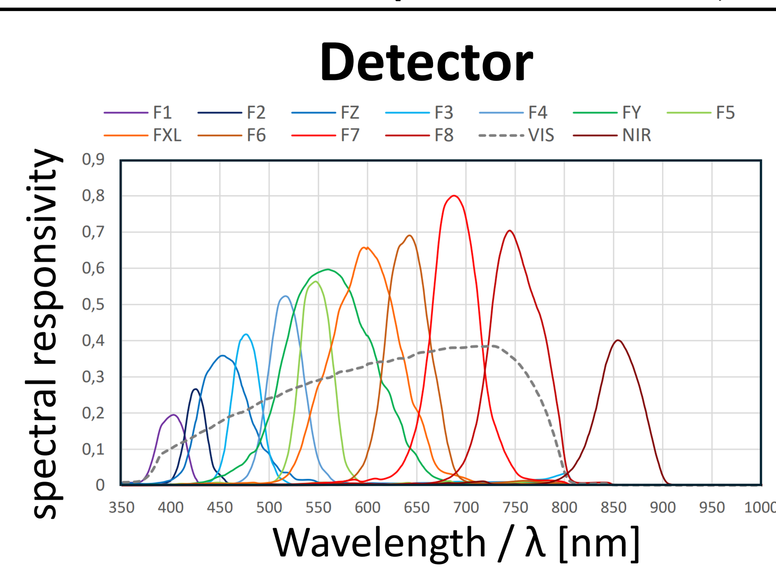
Abstract and Introduction

Wearable Photoplethysmography (PPG) technology offers a non-invasive, real-time method for continuous monitoring of vital signs, aiding in early cardiovascular disease detection. The Franklin Research Laboratory is currently developing a multiwavelength smart ring that incorporates a greater number of photodiodes and LEDs to correct for skin tone related bias in pulse oximeters. However, the increased number of sensors and data channels poses challenges for automated, real-time, data processing and storage. This project presents two algorithms: 1) a current calibration algorithm that maximizes signal strength when used on different individuals and 2) an accurate real time heart rate (HR) monitoring algorithm that maintains efficient memory and processing speeds.



[Modified from F. Riaz et al, 2019]

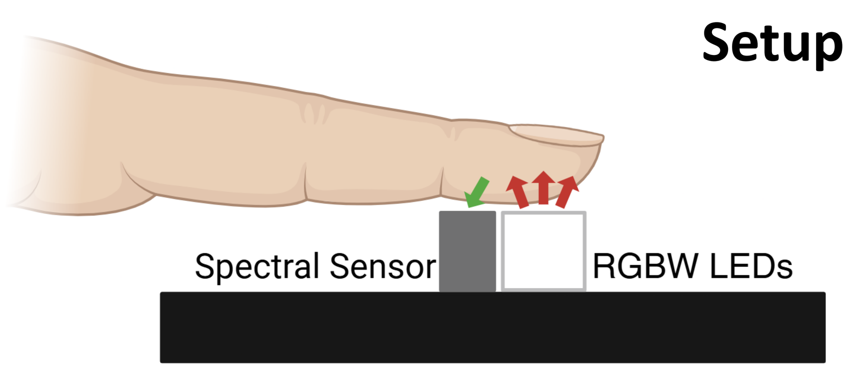


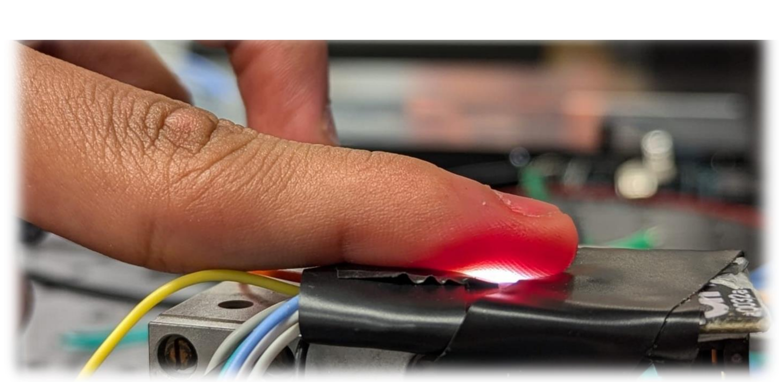


Current Calibration Methodology

Start → Interface with AS7352 Sensor → Set white, red, blue and green currents using linear extrapolation → Ramp up white, red, blue and green currents → End

Setup

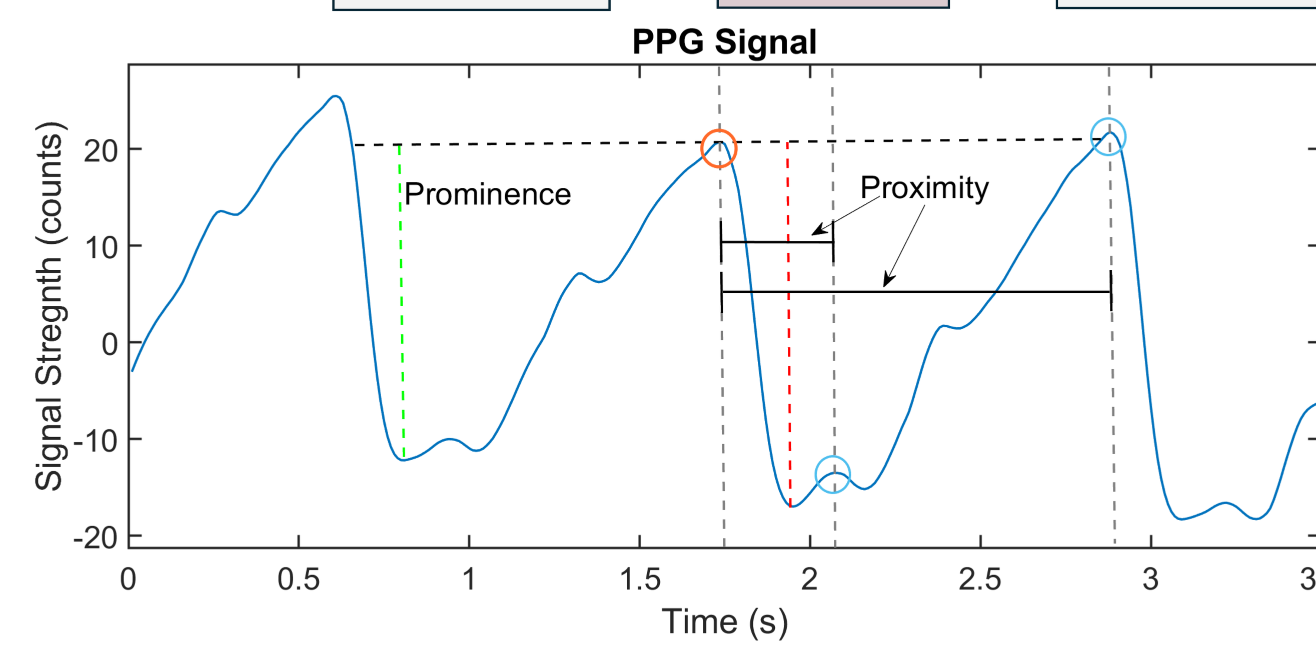




- **Skin Thickness & Tone:** darker skin tones absorb more light, both reducing signal strength.
- **Algorithm Requirements:**
  - Signal strength should be above 2000 counts for affected channels.
  - Complete calibration within 15 seconds to reduce power consumption.

Heart Rate Algorithm Methodology

Start → Filter Incoming Data → Find Peaks → Filter Peaks by Prominence and Proximity → Calculate HR → End

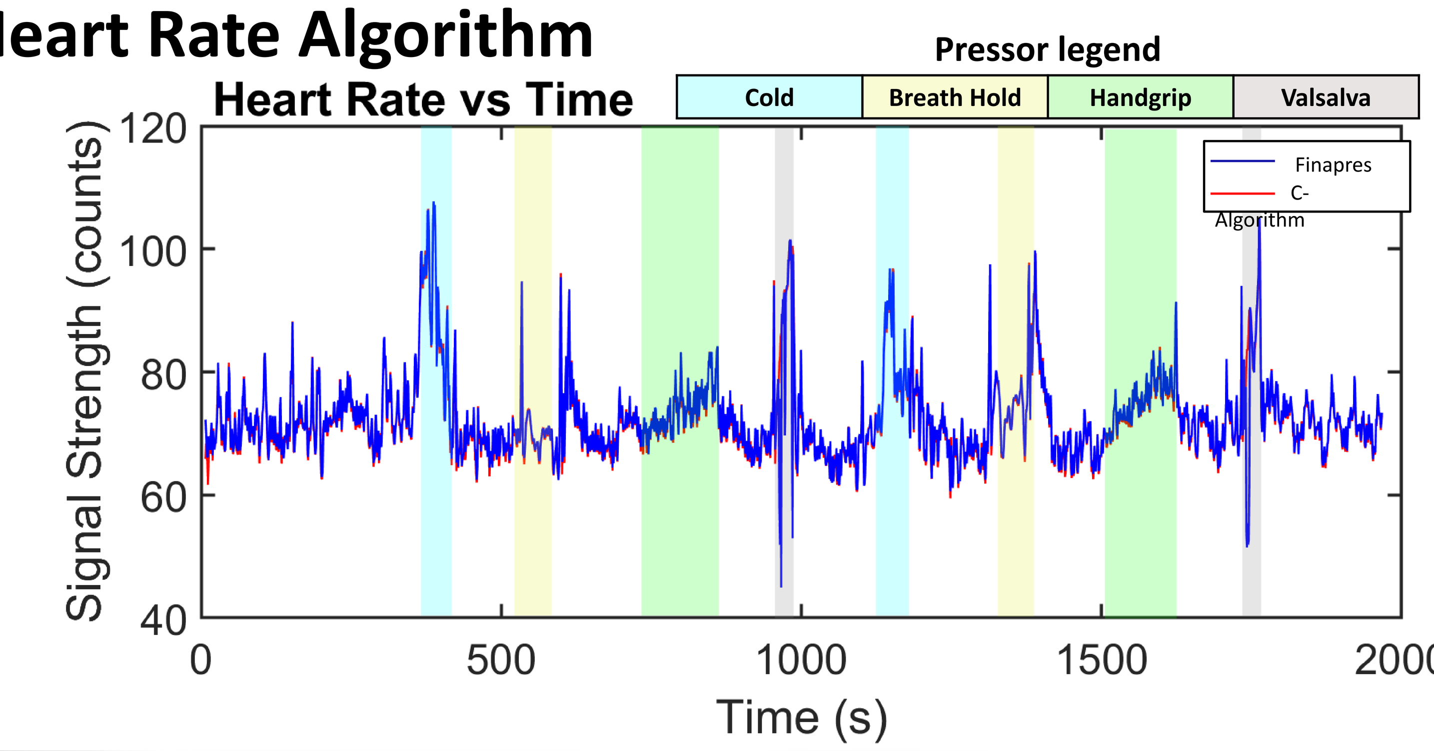


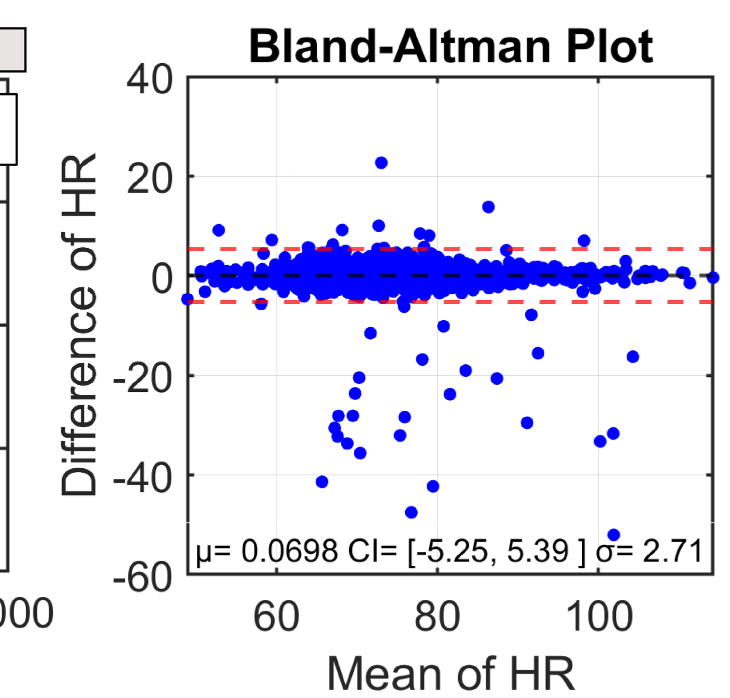
Objective: Develop a real-time heart rate algorithm optimized for processing speed and memory usage, while maintaining accuracy.

- **Algorithm Requirements:**
  - Maximum memory used by the algorithm is 120kb.
  - Maximum time to process each incoming 1008-byte data set is 30 milliseconds.

Results

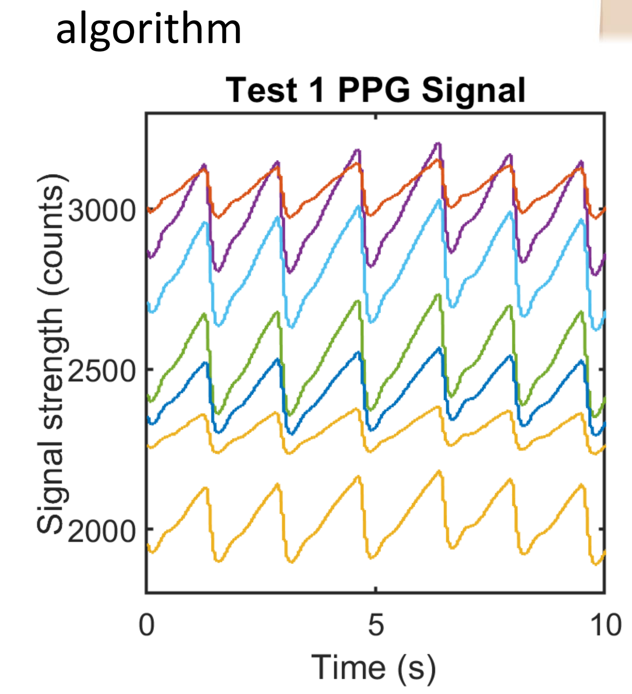
Heart Rate Algorithm





Current Calibration Algorithm

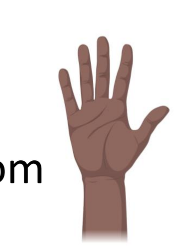
Test : 1
- Paler skinned subject
- Current calibrated using algorithm

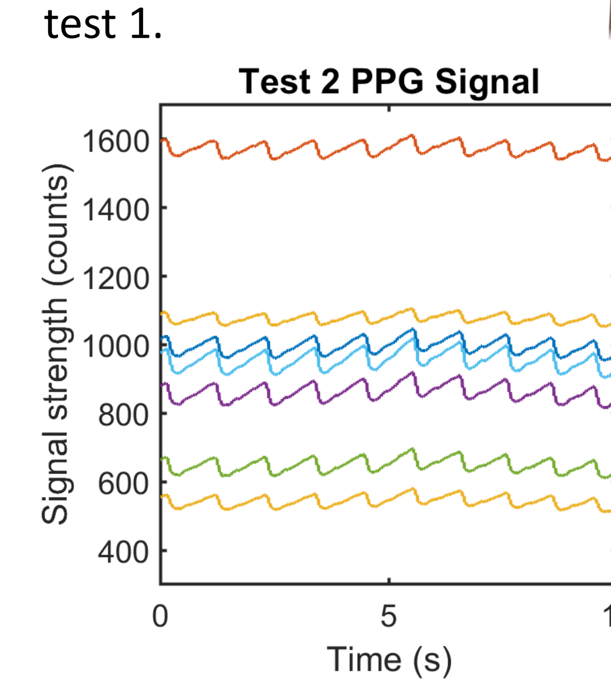


Blue	Green	Red	White
6mA	2mA	5mA	10mA

Average Channel SNR: 20.13
Average Channel reading: 2586

Test : 2
- Darker skinned subject
- Using current settings from test 1.

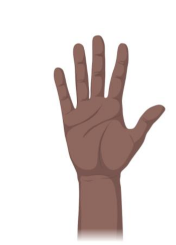


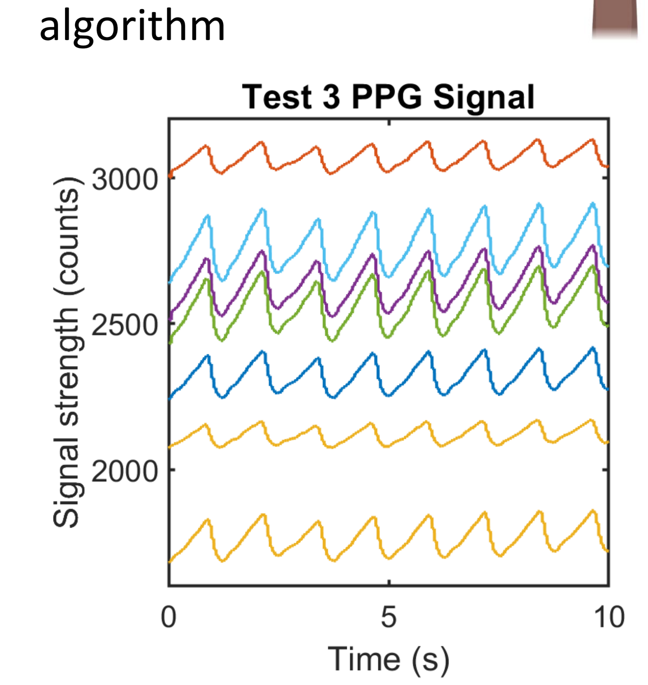


Blue	Green	Red	White
6mA	2mA	5mA	10mA

Average Channel SNR: 17.79
Average Channel reading: 980

Test : 3
- Darker skinned subject
- Current calibrated using algorithm





Blue	Green	Red	White
10mA	10mA	10mA	10mA

Average Channel SNR: 19.62
Average Channel reading: 2396

Conclusion

- Signal strength greatly increased for darker skin tones between tests, but the change in SNR remained low, possibly due to exclusive use of reflective PPG.
- HR algorithm exhibits 5 BPM confidence intervals, with most inaccuracy stemming from Valsalva maneuver artifacts due to a noisier signal.

Current calibration metric	Average of 15 runs
Calibration time	11.5 (s)
No. Channels above 2000 counts	6/7

HR Algorithm metric	Result
Memory	69kb
Processing time per 1008 bytes of data	7ms

Next Steps

- Further development is required for the HR algorithm using noisier signals and more extreme conditions (e.g. motion artifacts).
- Testing the current calibration algorithm on the ring which will include both transmissive and reflective PPG.
- High-pass filter C implementation requires improvement to match MATLAB frequency response as this will allow us to collect more accurate SPO2 and perfusion data.

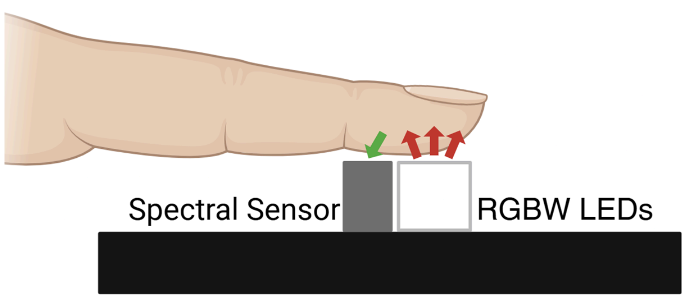
References

1. F. Riaz, M. A. Azad, J. Arshad, M. Imran, A. Hassan, and S. Rehman, "Pervasive blood pressure monitoring using Photoplethysmogram (PPG) sensor," *Future Generation Computer Systems*, vol. 98, pp. 120-130, Sept. 2019, Fig. 2.
2. Ž. Pirnar, M. Finžgar, and P. Podržaj, "Performance Evaluation of rPPG Approaches with and without the Region-of-Interest Localization Step," *Appl. Sci.*, vol. 11, no. 8, p. 3467, Apr. 2021. https://doi.org/10.3390/app11083467.
3. B. Bent, B. A. Goldstein, W. A. Kibbe, and J. P. Dunn, "Investigating sources of inaccuracy in wearable optical heart rate sensors," *NPJ Digit. Med.*, vol. 3, p. 18, Feb. 2020. https://doi.org/10.1038/s41746-020-0226-6.

Summer: Heart Rate and Blood Oxygenation (SPO2) algorithms.

Background: Over the summer, I worked at the Ted Rogers Centre for Heart Research, where I developed Heart Rate and SpO_2 algorithms for a next-generation smart ring device. Unlike most commercial options, such as the Oura Ring, this device featured an innovative design with significantly more LEDs capable of absorbing wavelengths across the entire light spectrum.

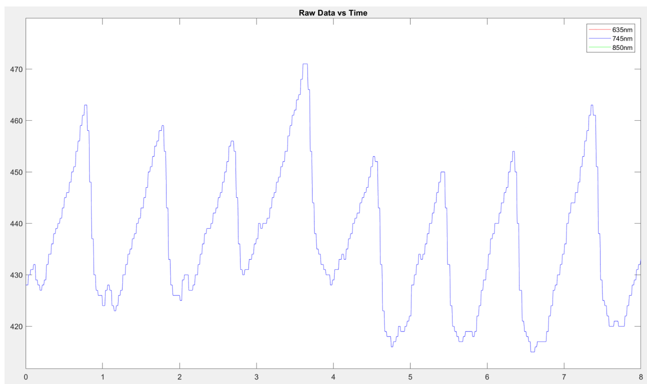
Photoplethysmography (PPG):



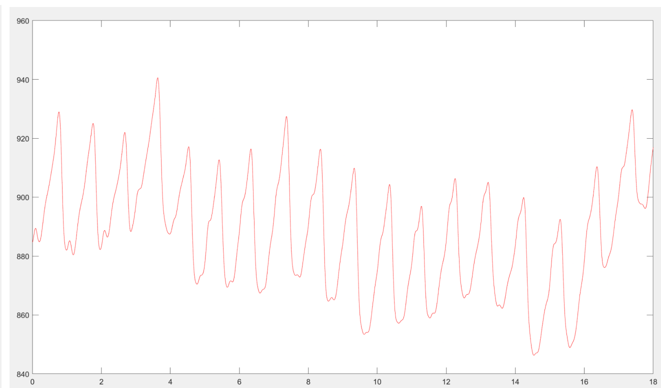
The smart ring captures cardiac signals using PPG technology by shining light into the finger. When the heart contracts, arteries narrow, absorbing less light and causing more to be reflected or transmitted to the photodiode, creating a peak in the signal. Conversely, during dilation, arteries expand, absorbing more light and reducing the signal. These fluctuations form the basis for extracting heart rate and SpO_2 data.

Digital Signal Processing:

Unfiltered Signal



Filtered Signal



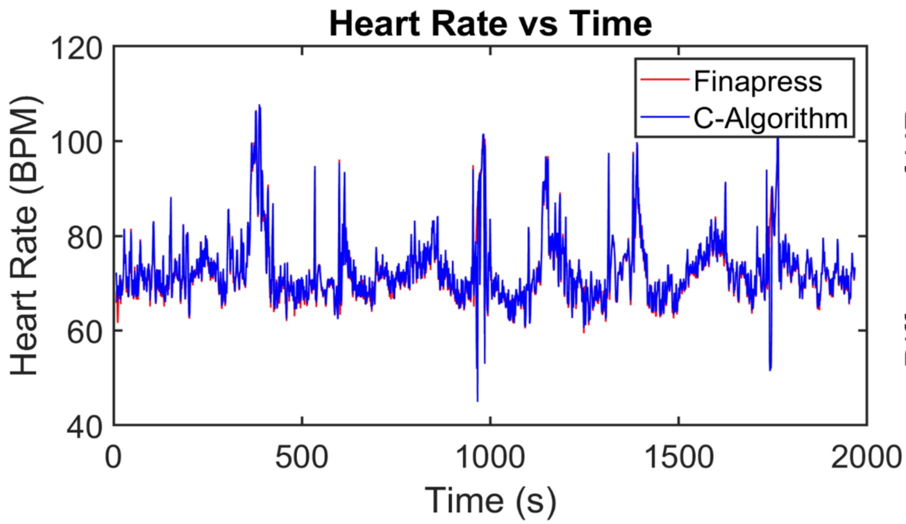
PPG signals are inherently noisy, and since we are only concerned with frequencies in the range of 0.5–5 Hz, filtering was essential. To address this, I developed several algorithms to implement high-pass, low-pass, and band-pass filters of varying orders (1st and 2nd order) and types, including Butterworth and Chebyshev designs. I then conducted a comprehensive signal-to-noise ratio (SNR) analysis to evaluate the performance of each filter and identify the optimal configuration for noise reduction and signal clarity.

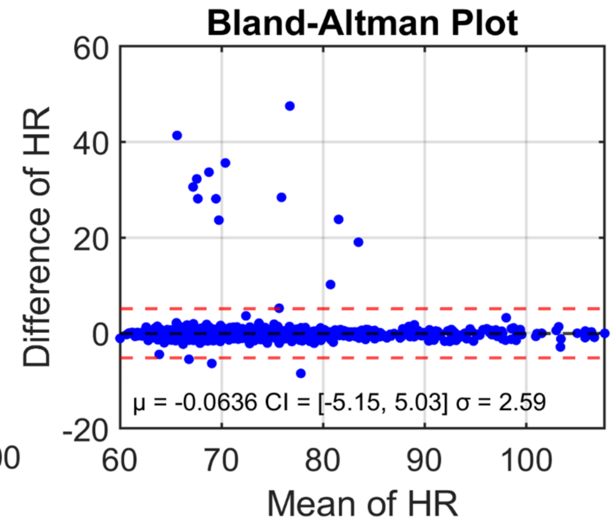
I also wrote a filter analysis report here.

Digital Signal Processing challenge:

When the PPG signal is collected by the ring's sensors, it is processed in discrete chunks. However, applying the filter to each chunk introduces a settling period of 50–75 samples, during which the filter adjusts to the signal. This caused the filtering process to reset with each new chunk, disrupting signal continuity. To address this, I implemented overlapping chunks and ensured the filter state was preserved by storing the filter coefficients and sample indices from the previous chunk. This approach seamlessly maintained signal integrity across chunks and eliminated the need for reinitializing the filter.

Heart Rate Algorithm





We validated the heart rate algorithm against the Finapres Nova, a gold-standard device, using stress tests like handgrips and cold baths to assess robustness during abrupt heart rate changes. A Bland-Altman plot shows that 95% of measurements differ by less than 5 BPM, demonstrating high accuracy. Additionally, the algorithm achieved a lower standard deviation than many industry devices, highlighting its reliability and precision.

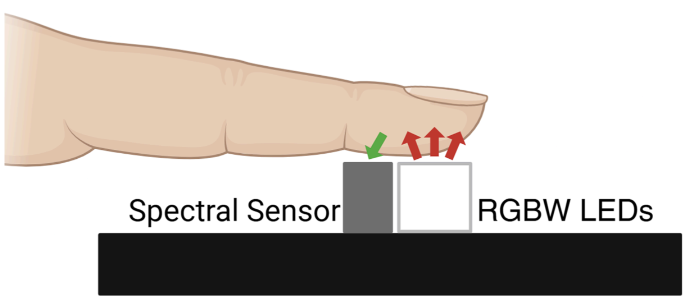
Blood Oxygenation Algorithm

Blood oxygenation or SPO2 is calculated using a ratio of ratios equation, wherein we divide the AC/DC components of an PPG signal from a Near infrared wavelength and a Red wavelength. While this algorithm was developed, it was unable to be tested due to lack of PPG reference data.

Summer: Current Calibration Algorithm.

Background: PPG signals face significant challenges with darker skin tones due to melanin, which absorbs more light and weakens the reflected signal. This results in wearable devices often producing inaccurate data for individuals with higher melanin levels. To address this, the Franklin Research Laboratory is developing a smart ring equipped with five LEDs (red, green, blue, white, and infrared) and 13 photodiodes capable of detecting multiple wavelengths of light. By using diverse wavelengths that penetrate the skin and interact with melanin differently, the ring enhances signal quality and ensures improved accuracy across all skin tones.

Photoplethysmography (PPG):



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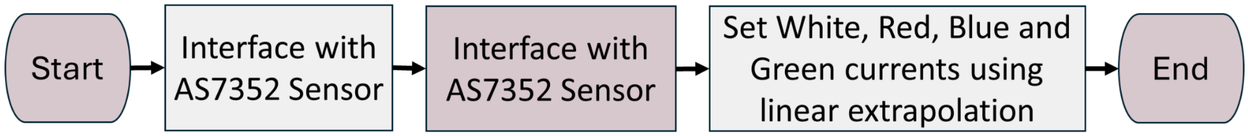
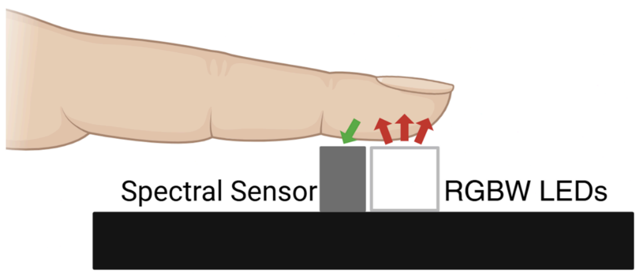
Current Calibration Algorithm:

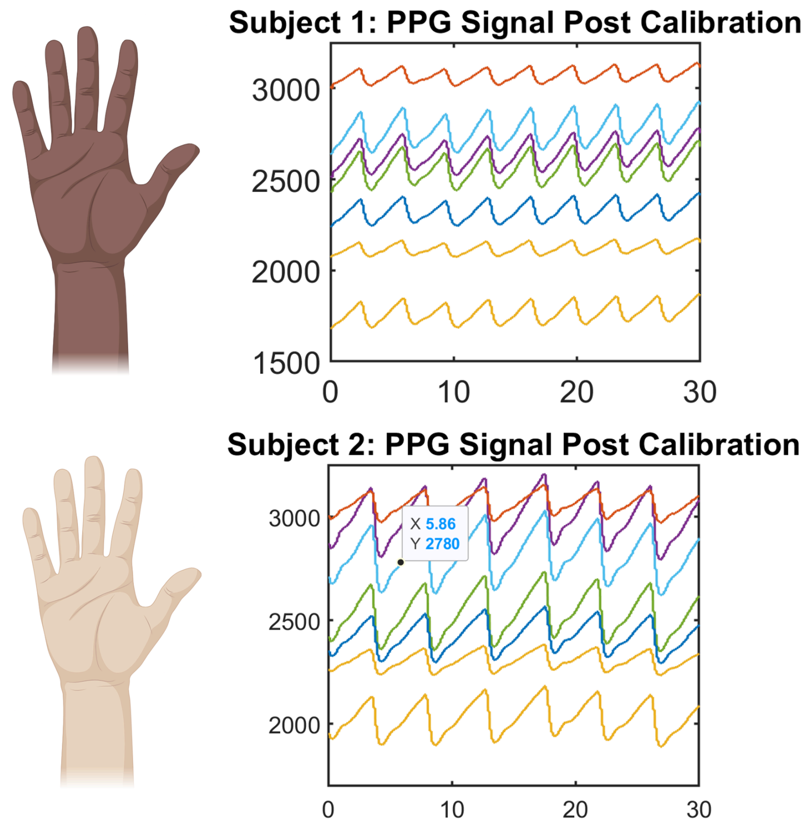




To address the issue of weaker PPG signals across varying skin tones, the algorithm adjusts the current sent to the LEDs, making the light stronger at specific wavelengths based on the user's skin tone. This enhances the signal strength, improving the ratio of the desired heart rate signal to unwanted noise, resulting in clearer readings.

The algorithm is designed to calibrate quickly—within 15 seconds—so it can adapt to the user’s skin tone and provide accurate readings immediately. Additionally, it maximizes the signal strength from the sensors, ensuring that as many readings as possible exceed a threshold, improving overall accuracy.

Results:



In **Test 1**, with a paler-skinned subject, the algorithm successfully calibrated the current, ensuring that all channels reached the target of 2000 counts, resulting in strong and accurate readings.

In **Test 2**, we used the same calibration settings from the paler-skinned subject for a darker-skinned individual. However, this did not work as well—the calibration failed to reach the 2000 counts target for any of the channels, and there was a significant drop in the signal-to-noise ratio (SNR), leading to less accurate data.

In **Test 3**, we adjusted the calibration specifically for the darker-skinned subject. With these settings, 6 out of 7 channels met the 2000 counts target, showing a substantial improvement in signal strength and accuracy compared to Test 2.