

ECE 445
Project Proposal
Smart Pulse Oximeter

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1. Introduction

1.1 Problem

The problem at hand is the inaccuracy of pulse oximeters in individuals with darker skin tones due to the way these devices interpret oxygen saturation levels. Pulse oximeters function by emitting light through the skin and measuring how much is absorbed to determine oxygen levels in the blood. However, higher concentrations of melanin absorb more light, leading to less accurate readings and potential overestimation of oxygen saturation in individuals with darker skin tones. This discrepancy can lead to delayed treatment or underestimation of how severe a patient's condition is. Addressing this problem is essential to improving equitable healthcare outcomes. A more inclusive and reliable pulse oximetry technology is needed—one that accounts for diverse skin tones and ensures accurate readings for all individuals.

1.2 Solution

This project aims to develop an adaptive pulse oximeter that adjusts the number of wavelengths used based on the user's skin tone (melanin concentration). Traditional pulse oximeters often produce inaccurate readings for individuals with darker skin tones due to increased melanin absorption, which interferes with light-based oxygen saturation measurements. Many modern devices attempt to address this by using multiple wavelengths, but this approach increases power consumption. Our solution integrates a camera and computer vision algorithms to determine skin tone and a wavelength-switching mechanism to optimize accuracy while conserving power. The device will also measure heart rate using the same optical components, making it a multifunctional health monitoring tool. All collected data will be displayed digitally for real-time user feedback.

1.3 Visual Aid:

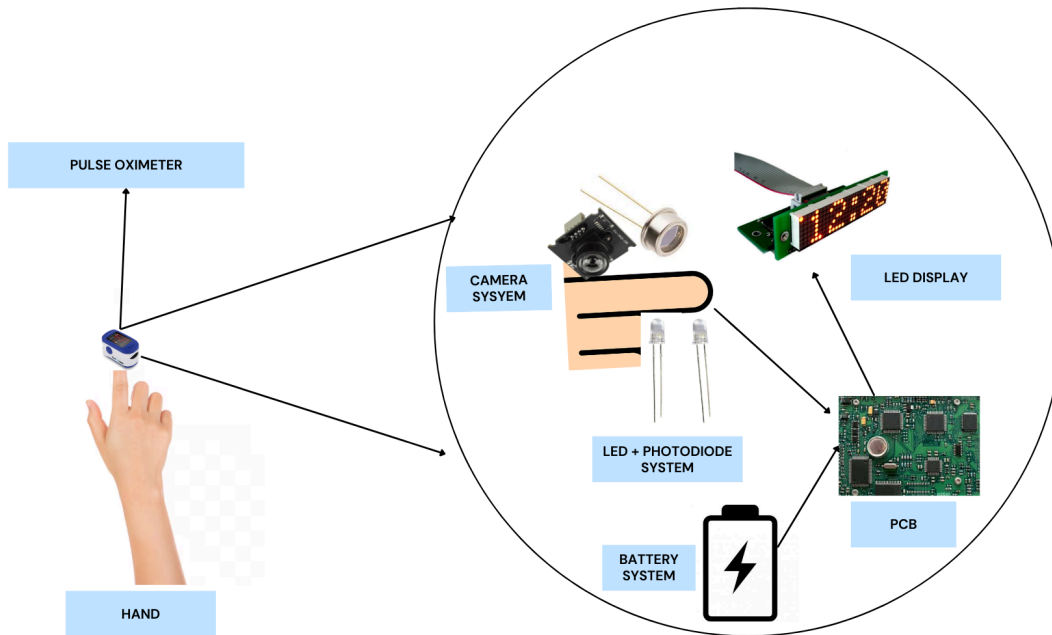


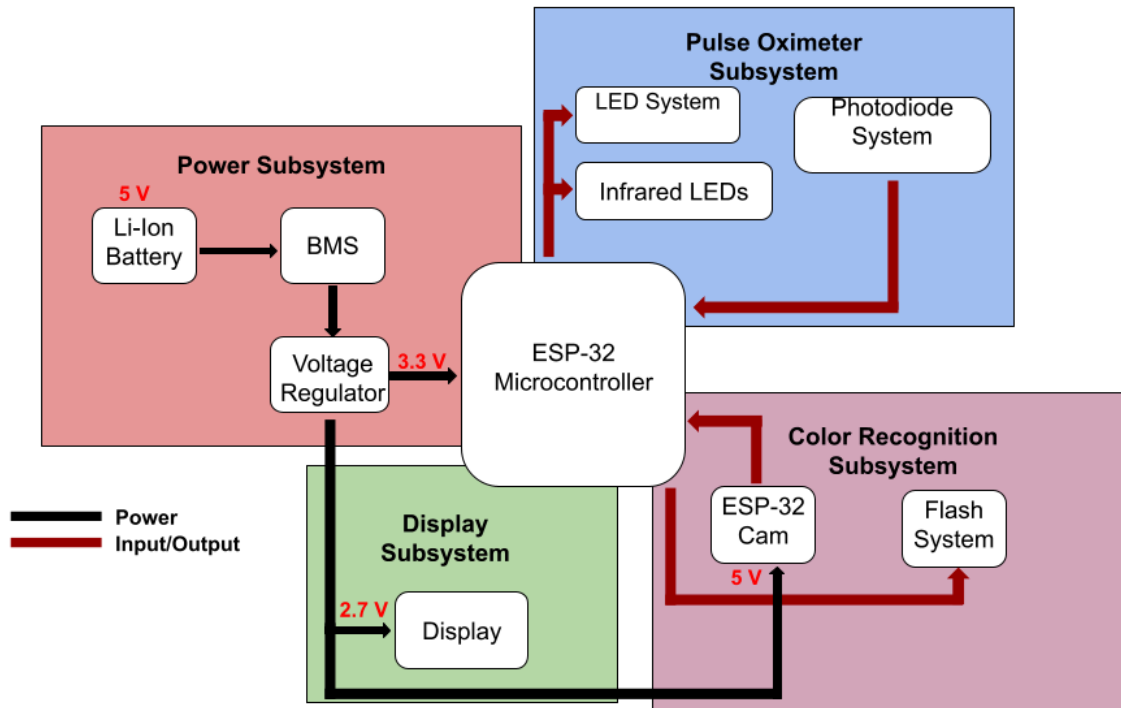
Fig. 1: Visual Aid

1.4 High-level Requirements

1. All sensors read within a 5% error range comparative to any commercial pulse oximeter. The measurements of blood oxygen saturation and pulse/heart rate.
2. Ability to alter the utilized wavelengths depending on skin tone determined from computer vision. Camera will successfully capture and send data to the microcontroller. Assistance via computer color recognition to determine
3. Correctly display measured blood oxygen levels and heart rate in real time on the external LED display.

2. Design

2.1 Block Diagram



2.2 Subsystem Overview

2.2.1 Pulse Oximeter Subsystem

This subsystem will use infrared and red light to measure blood oxygen levels as well as heart rate. The way this works is that oxygenated blood will absorb more infrared light and pass through more red light. Deoxygenated blood does the opposite. Knowing this, we can capture and calculate the total blood oxygen level (SpO₂) based on the ratio of red and infrared light passing through with a photodetector and a calibration algorithm. In order to properly measure the heart rate, the system will measure the photoplethysmography signal (PPG). When the photodetector records the light intensity, the blood volume increases as the heart beats, causing more light to be absorbed, reducing the signal. These wave-like pattern peaks correspond to the heartbeats and use the time difference between each successive peak to calculate the heart rate in

BPM. Utilizing the red LED with lighter skin tones and when detecting higher melanin concentrations implementing a yellow LED which is less absorbent to melanin.

Requirements:

- Red LED (660nm), yellow LED(590nm) and infrared LED(940nm) emit the correct wavelength and are read by photodiode.
- Based on the computer vision subsystem utilize the necessary red yellow LEDs.
- Blood oxygen saturation and pulse measurement within 2% accuracy comparative to commercial store bought pulse oximeters.

2.2.2 Color Recognition via Computer Vision Subsystem

This subsystem will utilize the “ESP-32 Camera Module” in conjunction with a flashing light to image the skin tone of the user. Using these images, color recognition will be employed to determine whether multiple wavelengths of light would need to be used to provide higher blood oxygen level measurement accuracy depending on user skin tone.

Requirements:

- ESP-32 Camera Module outputs correct RGB data to ESP-32 Microcontroller.
- Flash system operates in conjunction with ESP-32 Camera Module to provide color-accurate visuals of skin tone.

2.2.3 Digital Display Subsystem

To display the contents of our measurements, data will be taken from the microcontroller and will be displayed on an external digital display. This will show the blood oxygen levels and heart rate to the user in real time.

Requirements:

- Displays SpO2 to LED display in real time updating as values change through algorithmic calculation
- Displays heart rate to LED display in real time updating as values change through algorithmic calculation

2.2.4 Power Supply Subsystem

This system must be able to operate on a rechargeable lithium-ion battery. This subsystem will provide appropriate power to each other subsystem/component using this battery with DC-DC converters (buck/boost converters). Reasonable operation time must also be available from one charge of the li-ion battery. Power efficiency can be managed via the

switching of the oximeter from one to two wavelengths depending on skin tone, leading to longer operation time on one charge and higher efficiency.

Requirements:

- Provide stable 5V power for the microcontroller and its modules.
- Provide 5V +/- 0.1V for the voltage regulators to step down for other subsystems.
- Must supply at least 1A current to the system.
- Shutdown safely when the device is not being actively used.

2.3 Tolerance Analysis

One critical aspect of the design that poses a risk to the successful completion of the project is the accuracy of the skin tone-based wavelength adjustment mechanism. If the computer vision system does not correctly determine the user's skin tone, the pulse oximeter may either use an incorrect number of wavelengths or fail to compensate for melanin absorption, leading to inaccurate SpO₂ readings. We can run multiple simulations of different skin tone levels while comparing it to an FDA approved pulse oximeter to quantify any deviation.

Power:

Component	Peak Voltage	Peak Current
ESP32-WROOM-32[10]	2.7 ~ 3.6V	80mA
Ai-Thinker ESP32-CAM WiFi + BT + BLE SoC with 2MP Camera [7]	5V	180mA
151051RS11000 - Red LED [8]	2.1V	30mA
QSD2030 - Photodiode [9]	1.3V	10nA
XTNI11W - Infrared LED [6]	1.2V	20mA
WEA012864DBPP3N00003- LED Display [11]	3.3V	20mA

Based upon the peak voltages we can determine that the power supply must supply at least 5V to the system in order to function properly. The 5V is within a very safe and comfortable range from the maximum ratings for all the components in the circuit. Making sure that the system is able to provide the necessary current to run each subsystem together we need to calculate the

total current that is needed. The total current being under 1A meaning that the system must be able to provide a supply of 1A with room to spare.

Pulse Oximetry:

The main variation of error that is introduced into this project is reading of blood oxygen saturation. To break it down you must first take into account the Beer-Lambert law which is used in pulse oximetry to calculate the amount of oxygen in your blood.

$$I = I_0 e^{-\epsilon c L}$$

I_0 = Incident light intensity

I = Transmitted light intensity

ϵ = Molar Absorptivity

C = Concentration of the absorbing substance

L = Path length of light through the tissue.

To simplify this equation for use of the three LED wavelengths we can split the equations into 2 equations solving for the ratio R. The R ratio is calculated from the AC and DC components of the light signals. AC component being the light absorbed due to arterial blood and the DC component being the light by tissues, skin and venous blood.

$$R = \frac{(AC_{red}/DC_{red})}{(AC_{infrared}/DC_{infrared})}$$

$$Y = \frac{(AC_{yellow}/DC_{yellow})}{(AC_{infrared}/DC_{infrared})}$$

The SpO₂ is derived from a calibration curve based on the data read from the sensors using this equation: $SpO_2 = A - B * R$. To then account for the extra wavelength you need to factor in the yellow to infrared absorption to estimate and correct for the melanin interference. Thus the new equation becomes $SpO_2 = A - B * R - C * Y$. With A, B and C being calibration constants, to estimate these values we can simulate the model.

The use of multiple wavelengths will be beneficial to the increased accuracy of different skin tones within our project. However, utilizing multiple wavelengths of visible light simultaneously results in issues with blood oxygen measurements as the very small difference in their wavelength will be difficult to pick up by the photodiodes.

Time-Multiplexing, where the LEDs turn on and off in a rapid, alternating pattern, can be used as a solution. Sequential pulsing is also another viable method. To utilize the sequential pulsing method, each LED would be turned ON for a few hundred microseconds before switching to the next one (with a cycle of red, yellow, infrared, and then a dark period to measure ambient light levels). This would repeat at a high frequency so that multiple cycles can occur within a heartbeat allowing for reliable SpO₂ calculations. The following equations can be used to find the correct values from the photodiodes, taking into account ambient light noise.

$$\begin{aligned}
 I_{R,FINAL} &= I_R - I_{DARK} \\
 I_{Y,FINAL} &= I_Y - I_{DARK} \\
 I_{IR,FINAL} &= I_{IR} - I_{DARK}
 \end{aligned}$$

Another method to solve this issue would be phase-division multiplexing. This employs a phase difference between our LEDs which allows for us both LEDs to be on without interfering with each other. We see that the total waveform that the photodiode detects is the following.

$$I(t) = A_R \cos(\omega t) + A_Y \cos(\omega t + 120) + A_{IR} \cos(\omega t + 240)$$

Then using FFT (Fast Fourier Transform) analysis, each contribution can be extrapolated by looking at the three dominant frequency components corresponding to red, yellow, and infrared signals.

3. Ethics

The development of an adaptive pulse oximeter aligns closely with the IEEE Code of Ethics, particularly in promoting fairness, safety, accuracy, and societal well-being. The IEEE emphasizes the duty of engineers to uphold the highest standards of integrity and avoid bias in technology. Traditional pulse oximeters have been shown to disproportionately misread oxygen saturation levels in individuals with darker skin tones, which can lead to delayed or inadequate medical care. By designing a more inclusive and accurate device, this project directly addresses IEEE Principle #1, advancing public health, safety, and welfare.

This design integrates adaptive technology, such as computer vision for skin tone detection, to ensure more accurate readings across diverse populations. This improvement upholds IEEE Principle #3, ensuring honesty and transparency by providing reliable, unbiased data in clinical settings. The inclusion of real-time safety alerts for abnormal readings further enhances patient outcomes and aligns with IEEE Principle #1 by prioritizing public health and safety.

The project also promotes equity and fairness (IEEE Principle #8) by addressing racial disparities in healthcare technology, fostering a more ethical and just medical system. Additionally, the device is designed with safety features, including sensor fault detection and low-power alerts, ensuring reliable and continuous operation, which is essential for patient safety.

Finally, this effort embraces IEEE Principle #5 by focusing on continuous improvement and sustainable practices. The design balances accuracy with power efficiency, optimizing the use of resources while enhancing health outcomes. The adaptive pulse oximeter represents a responsible, inclusive, and ethical advancement in medical technology, fully aligning with the IEEE Code of Ethics.

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