ECE 445
Project Proposal
Smart Pulse Oximeter

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1. Introduction

1.1 Problem

The problem at hand is the in accuracy 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:

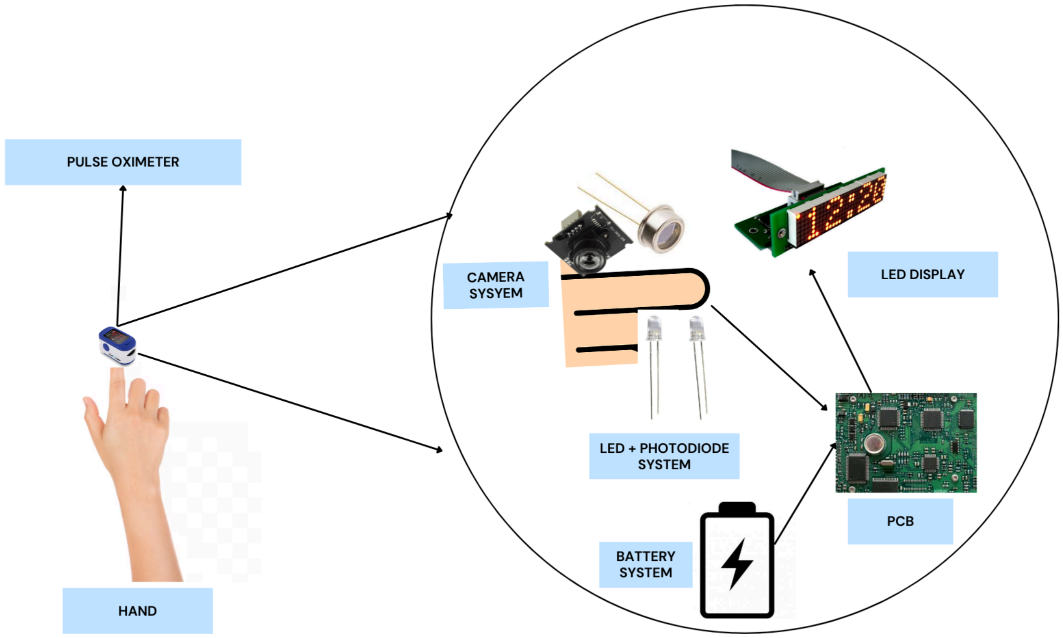


Fig. 1: Visual Aid

1.4 High-level Requirements

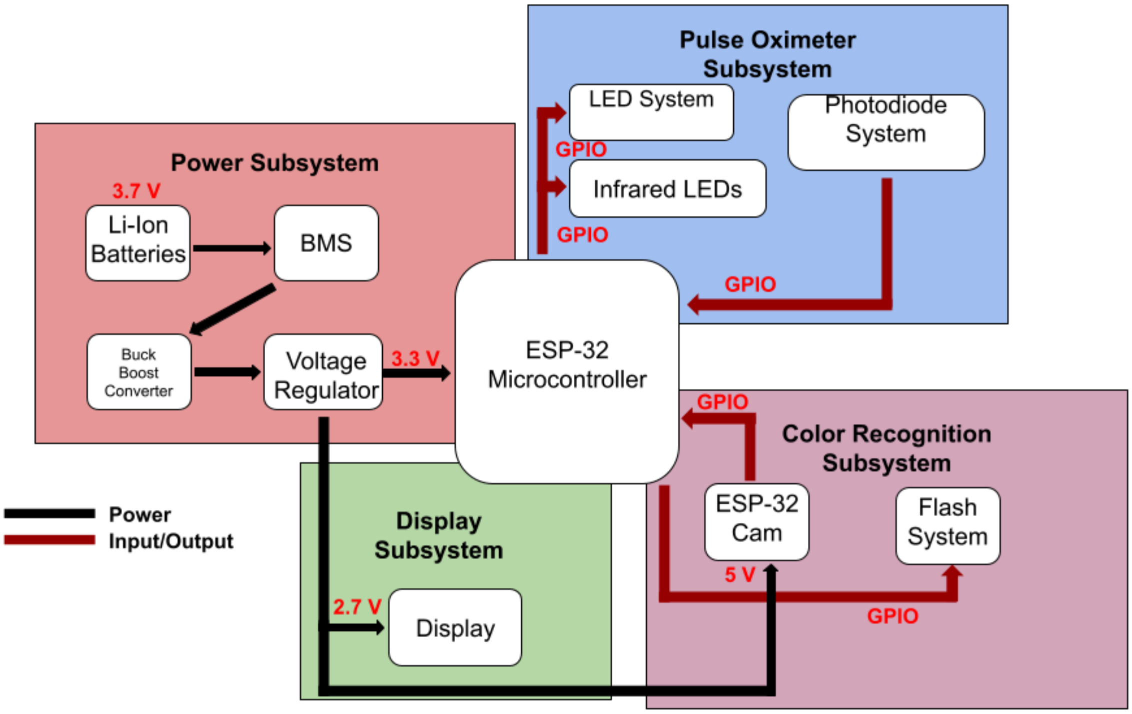
1. All sensors must measure blood oxygen saturation (SpO_2) within ±5% absolute error compared to a commercial pulse oximeter across a 70–100% SpO_2 range and heart rate within ±5 BPM across 40–180 BPM. Measurements must meet this accuracy for at least 95% of test subjects under standard indoor lighting conditions.

2. A computer vision system must analyze skin tone using a 16-bit RGB or YUV color space with a minimum resolution of 640x480 pixels, selecting optimal LED wavelengths from a 600–700 nm (red), 850–950 nm (infrared), and 570–590 nm (yellow) range within 200 ms.

3. The external LED display must update SpO_2 and heart rate at a minimum refresh rate of 1 Hz, displaying SpO_2 and heart rate. The system must process and display new readings within 500 ms from sensor acquisition to output.

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 5% 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.
- Process the module data and selecting optimal LED wavelengths within 200 ms.
- 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 (minimum refresh rate of 1 Hz) updating as values change through algorithmic calculation.
- Displays heart rate to LED display in real time (minimum refresh rate of 1 Hz) updating as values change through algorithmic calculation.
- The system must process and display new readings within 500 ms from sensor acquisition to output.

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 SpO_2 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
151051YS04000 - Yellow LED	2.0 V	20 mA
BC547 NPN Transistor	$V_{CE,MAX} = 45\ V$	$I_{C,MAX} = 100\ mA$
QSD2030 - Photodiode [9]	1.3V	10nA
XTNI11W - Infrared LED [6]	1.2V	20mA

WEA012864DBPP3N00003-LED Display [11]	3.3V	20mA
Samsung 25R 18650 Lithium Ion Battery	$V_{nominal} = 3.7\ V$ $V_{full\ charge} = 4.2\ V$ $V_{discharge\ cutoff} = 2.5\ V$	20 A (Continuous Discharge) 2500 mAh (Capacity)

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.

The current batteries that are being used within our system are the Samsung 25R 18650 batteries. Two of these batteries in parallel will provide us with a total capacity of 5000 mAh or 40 A of continuous discharge. Since our system will need a 5V voltage at some areas as stated above, the following calculations can be done to find out our current after the usage of a boost converter to boost the 3.7 V Li-ion to a 5 V.

$$P_i = I_i * V_i = P_f$$

$$I_i = 40\ A,\ V_i = 3.7\ V,\ V_f = 5\ V$$

$$P_i = 40 * 3.7 = 148\ W = 5 * I_f$$

$$I_f = 29.6\ A$$

We see that the current flowing out of our boost converter will be 29.6 A at 5 V. To ensure that each of our components that need a voltage are not being overloaded with current, a current limiting resistor can be placed in front of each component. These resistors will be at relatively high resistances such that much less current will flow through them. Looking at our above voltage requirements, we can calculate the limiting resistor values by the following.

$$R_{limiting} = \frac{V_{supply} - V_{max}}{I_{max}}$$

Using Ohms law, the following resistor values can be used to limit current at each device.

ESP32-WROOM-32: $R_{limiting} = 17.5\ to\ 28.75\ \Omega$

151051RS11000 - Red LED [8]: $R_{limiting} = 96.67\ \Omega$
151051YS04000 - Yellow LED: $R_{limiting} = 150\ \Omega$
XTNI11W - Infrared LED [6]: $R_{limiting} = 190\ \Omega$

When limiting the current to our ESP32-CAM device, a different approach must be used so that there is much less of a voltage drop across our current limiting method which will allow for almost the full 5 V to drop across the ESP32-CAM device. This can be achieved with the use of an OpAmp and MOSFET circuit.

We must also take into account the possible hazards of overcurrent and overvoltage. In the case of the Li-Ion battery, the battery management system will ensure that there is no overdischarge of the Lithium ion battery. This BMS will also take care of the overcharge, temperature, and other components of battery recharging which need maintenance. The power subsystem will also be utilizing a voltage regulator which will ensure that overvoltages are dealt with and do not cause irreparable damage to our circuit. These protections will prevent harm to our Smart Pulse Oximeter circuit.

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.

$$I_{R,FINAL} = I_R - I_{DARK}$$
$$I_{Y,FINAL} = I_Y - I_{DARK}$$
$$I_{IR,FINAL} = I_{IR} - I_{DARK}$$

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.

4. References

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