Smart Pulse Oximeter

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Abstract

This project presents a Smart Pulse Oximeter designed to improve the accuracy of blood oxygen saturation measurements across diverse skin tones. The system combines a traditional photoplethysmography-based sensor with a computer vision module that analyzes the user's skin tone and selects optimal LED wavelengths including red, infrared, and yellow for enhanced precision. The device displays real-time SpO_2 and heart rate readings on an external digital screen and is powered by a battery with efficient power regulation. By dynamically adapting to individual melanin levels, this design promotes inclusivity in medical monitoring and supports equitable healthcare access through more reliable and responsive physiological measurements.

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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. A study done by the New England Journal of Medicine in 2020 found that black patients were 3x more likely to have hidden hypoxemia than their white counterparts[14]. In 2022, the FDA reported that pulse oximeters were 12% less accurate in black patients [13].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 access. 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. This concept is further backed by Aoyagi, the founder of pulse oximetry, who in 2007 concluded that 3 wavelengths of light is better than 2, when it comes to accuracy. 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 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

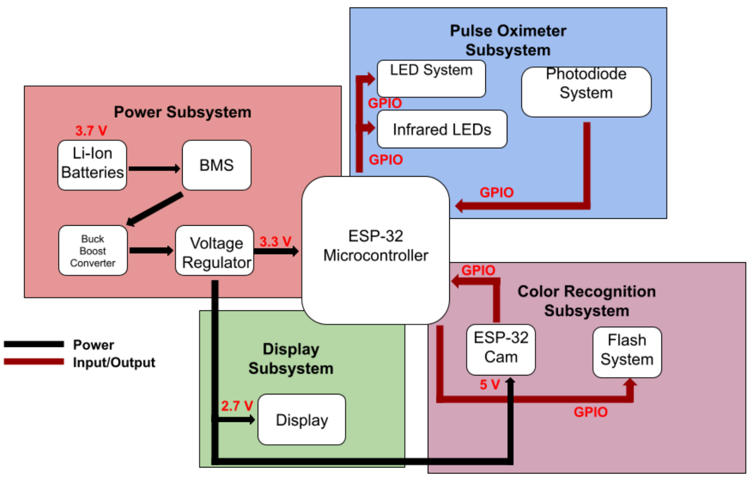


Fig. 1: Initial Block diagram

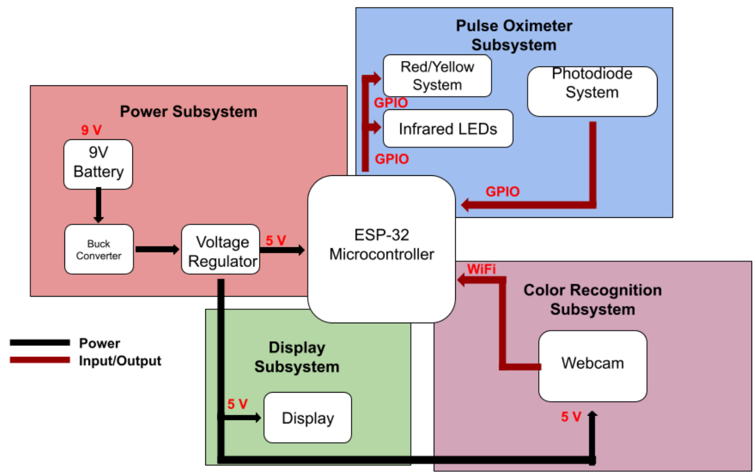


Fig. 2: Final Block diagram

The block diagram for the Smart Pulse Oximeter outlines the functional structure of the device, illustrating how each subsystem interacts to achieve accurate and reliable blood oxygen saturation (SpO_2) and heart rate measurements. The system is composed of four primary subsystems: the pulse oximeter subsystem, the color recognition via computer vision subsystem, the digital display subsystem, and the power supply subsystem. The pulse oximeter subsystem is responsible for capturing SpO_2 and heart rate data using a combination of infrared, red, and yellow LEDs along with a photodiode sensor. The computer vision subsystem utilizes an ESP-32 Camera Module to analyze the user's skin tone, ensuring that the correct wavelength combination is selected to improve measurement accuracy across diverse skin tones. The digital display subsystem processes and presents real-time SpO_2 and heart rate data on an external LED screen, ensuring user accessibility and feedback. Finally, the power supply subsystem integrates a rechargeable lithium-ion battery with a Battery Management System (BMS) and DC-DC converters to ensure a stable power supply while optimizing energy efficiency. Together, these subsystems work in a cohesive and adaptive manner, ensuring the device meets high standards of accuracy, efficiency, and reliability in medical monitoring.

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 will implement a yellow LED which is less absorbent to melanin.

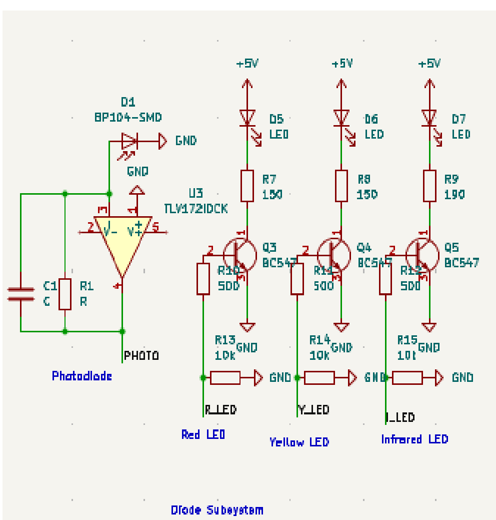


Fig. 4: Pulse oximeter KiCad schematic

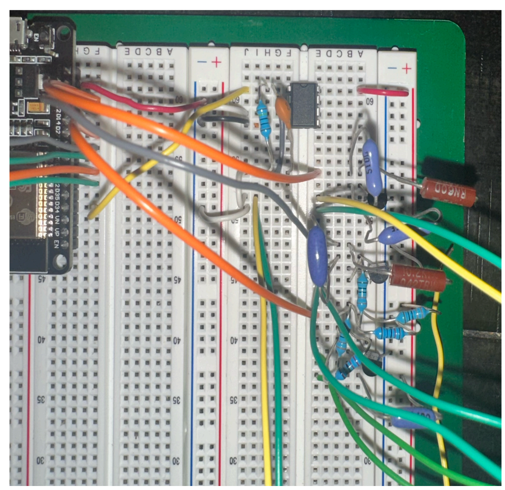


Fig. 5: Pulse oximeter breadboard circuit

For our pulse oximeter design, we utilized sequential switching of our lights which were then read by our photodiode. First, we designed our light switching system. Each light was designed for the average of 20 mA of current to flow through them. To accomplish this, the appropriate resistor had to be chosen. Using equation [1], a 150 Ω resistor was chosen for the red and yellow LEDs and a 190 Ω resistor for our IR emitter utilizing a supply voltage of 5V and LED voltage corresponding to each emitters datasheet. Connecting these to a transistor allowed for switching between ON and OFF modes depending on our I/O from the ESP32 microcontroller.

$$[1]\ R = \frac{V_{supply} - V_{LED}}{I}$$

The design for our most important component, the photodiode, will be discussed next. Our photodiode model the QSD2030 has an average reverse light current of around 25 uA. For our design, we need to feed the photodiode output into our ESP32 ADC pin from which the voltage applied will be converted into a digital signal. However, the ESP32 input pins require a voltage whereas the output of a photodiode is a photocurrent. Thus, a transimpedance amplifier (TIA) was utilized. The transimpedance amplifier takes this very small photocurrent output from the photodiode and converts it into a voltage which is then amplified to a desirable value. For our ESP32 I/O, we desired a voltage between 0.1 and 3.3 V since the peak allowable voltage is 3.3 V (higher would damage the chip).

Keeping these design constraints in mind, an initial resistor value of 100,000 Ω was chosen using equation [2]. However, after initial testing we found that this resistance value was much too small. Using this small resistor value resulted in almost invisible fluctuations of our voltage (basically noise). After measurement of our photocurrent when exposed to our red, infrared, and yellow light we found that it resulted in much smaller photocurrents than was average. Thus, a much higher feedback resistor was needed to boost our voltage and we opted for a 1 MΩ resistor.

$$[2]\ R = \frac{V_{out,MAX} - V_{out,MIN}}{I_{photo,MAX}}$$

To keep our system stable, a feedback capacitor has to be chosen in parallel with our feedback resistor. This capacitor is chosen based on switching frequency and operational amplifier physical constraints. Looking at our timing diagram (see fig. 6), we see that our sampling time is 250 us samples four times which is 1000 us (set this equal to Rx in equation [3]). Utilizing our initial value of 100 kΩ, we utilize equation [3] to calculate our capacitance value. This results in a feedback capacitor value of approximately 10 pF.

$$[3]\ R_{feedback} C_{feedback} \leq \frac{Rx\ Sample\ time}{10}$$

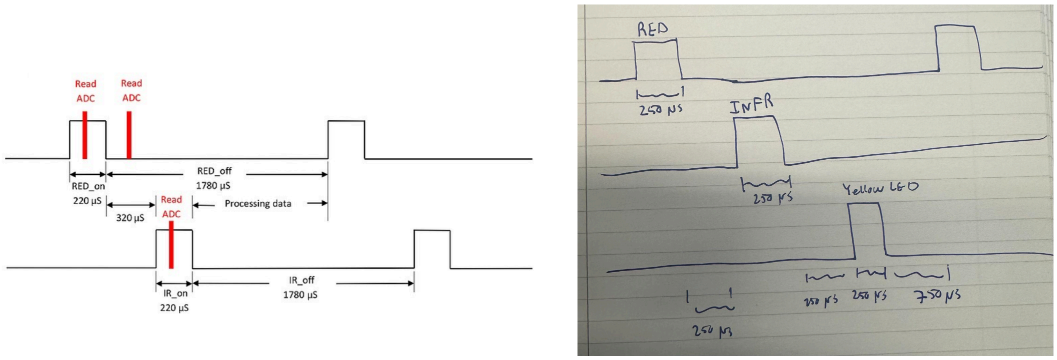
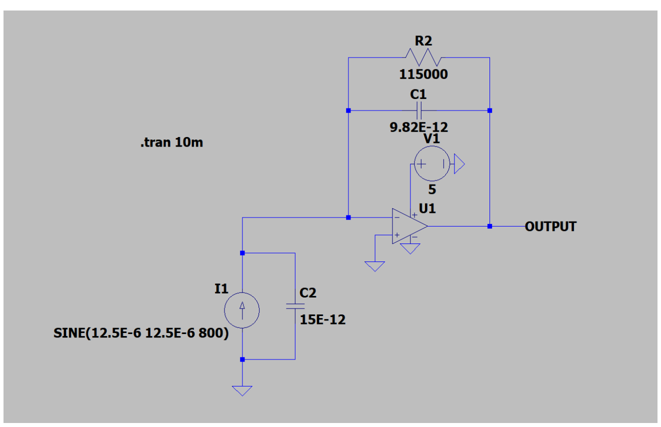


Fig. 6: Timing diagrams for red/infrared scheme (left) and red/infrared/yellow (right)

Before we built this on the breadboard, it was simulated using LTSpice. We utilized a generic operational amplifier model with a 1 MHz GBW as well as the previously calculated feedback resistor and capacitor values. Instead of a photodiode, used was an equivalent current source of 25 uA (maximum reverse light current) and capacitor (value found from the datasheet). See fig. 7 for the circuit schematic. We simulated the output of our TIA when the input current source (our photodiode) fluctuates from 0 to 25 uA input according to a square wave with the following characteristics seen in fig. 8. Found that our output voltage is variable between -0.5 and -2.8 V (voltage is negative in this case but for our real TIA, the voltage will be positive because the photocurrent will flow in the opposite direction). This was a favorable result, showing that our TIA amplified our current to a voltage output within our range.



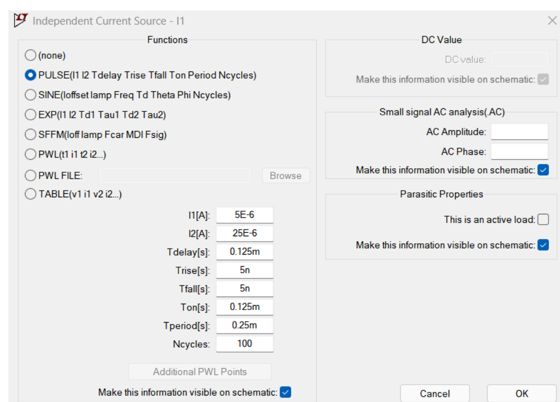


Fig. 7: LTSpice simulated TIA circuit

Fig. 8: LTSpice simulation square wave parameters

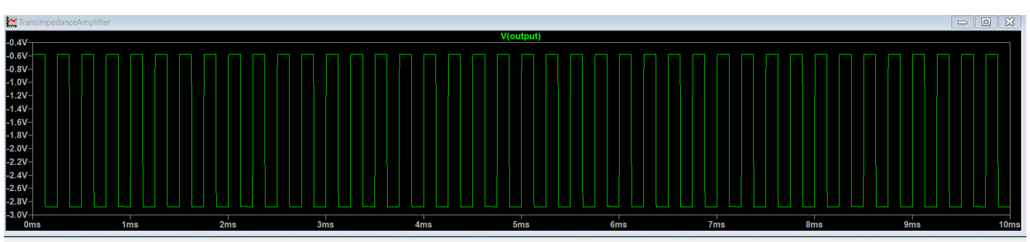


Fig. 9: LTSpice simulation output voltage waveform

To calculate our SpO2 values, the output results to our ESP32 were utilized. These measured voltages from our ESP32 ADC pin were first cleaned up using a moving average method to get rid of noise. A low-pass filter was also utilized to get rid of high-frequency components such as muscle movements, ambient light, and unnecessary harmonics. Our blood is made up of both pulsatile and nonpulsatile components. These, in engineering terms, can be coined as DC and AC components of our blood. Measuring these AC and DC components and manipulating them, we can calculate the SpO2 value for an individual. For the DC value, this is found by finding the average value of our resultant voltage from our photodiode. Our ESP32 code takes our calculated voltage values and adds them into a buffer. Once this buffer has been filled with approximately 80 samples for each red, infrared and yellow light, the DC and AC component calculations can be done. Utilizing equations [4] and [5] the AC and DC components are found. After finding the DC and AC components of each type of light (red/yellow/infrared), the ratios of these can be used to determine the R and Y values which are used in the final SpO2 calculations (see equations [6], [7], [8] and [9]).

$$[4]\ DC = \frac{V_{max} + V_{min}}{2}$$

$$[5]\ AC = V_{max} - V_{min}$$

$$[6]\ R = \frac{(AC_{red}/DC_{red})}{(AC_{infrared}/DC_{infrared})}$$

$$[7]\ Y = \frac{(AC_{yellow}/DC_{yellow})}{(AC_{infrared}/DC_{infrared})}$$

$$[8] SpO2_{TWO} = A - B * R.$$

$$[9]\ SpO2_{THREE} = A - B * R - C * Y$$

Our first requirement for our R&V table looks at the output voltages of our photodiode and TIA when hit with differing wavelengths of light. Utilizing a transimpedance amplifier with a feedback resistance of 1 MΩ, we were able to read the output voltages from our photodiode with voltages ranging from 0.1 to 3.3 V depending on their intensity. These ranges were chosen for the operable voltage ranges for our ESP32 input. As seen in our table (figures 11, 12 and 13), some of our measured voltages were lower than others because of our light intensities which will be discussed when we look at our 3rd R&V requirement.

IR EMITTER			
Diode Current (mA)	Diode Voltage (V)	Measured Voltage at ESP32 (V)	Photocurrent (uA)
19.76	1.1	3	3
20	1.12	3.1	3.1
19.5	1.05	2.87	2.87
20.1	1.15	3.25	3.25
20.5	1.21	3.12	3.12

Fig. 11: IR emitter output voltages from TIA and QSD2030 photocurrent

RED LED			
Diode Current (mA)	Diode Voltage (V)	Measured Voltage at ESP32 (V)	Photocurrent (uA)
20	2.3	0.25	0.25
19.85	2.3	0.22	0.22
20	2.34	0.31	0.31
19.5	2.2	0.21	0.21
19.6	2.22	0.23	0.23

Fig. 12: Red LED output voltages from TIA and QSD2030 photocurrent

YELLOW LED			
Diode Current (mA)	Diode Voltage (V)	Measured Voltage at ESP32 (V)	Photocurrent (uA)
20	1.98	0.85	0.85
19.9	2	0.8	0.8
19.85	1.95	0.8	0.8
20	2	0.88	0.88
19.94	2.01	0.9	0.9

Fig. 13: Yellow LED output voltages from TIA and QSD2030 photocurrent

Looking at our 3rd requirement - “Blood oxygen saturation (SpO_2) and pulse measurement within 5% accuracy comparative to commercial store bought pulse oximeters” - and comparing with our results from figures 11, 12 and 13, we see that this requirement has not been hit. Our table shows a consistent percent error from 9 to 11 percent consistently. This error may come from many sources.

The first issue that we will explore is the mismatch of intensities between our visible light LEDs of both yellow and red light as well as our IR emitter intensity. While the visible light emitters are measured in millicandela (mcd), a unit of visible intensity, the IR emitter is measured in milliwatts per steradian (mW/str). Though usually a difference in units is a trivial matter, these two units of intensities are fundamentally different. While one measures how the eye perceives the light in terms of intensity, the other is a measure of power dissipation. To consolidate these values, the emitter manufacturers would need to be contacted and a conversion value would have to be provided. Without a way to consolidate these values, there is no way to see how the IR and visible light intensities compare at 20 mA operation and no way to create a ratio which can be used to operate them at the same intensity.

Similar in content to this initial problem with our mismatch of intensities because of our physical constants of our emitters and LEDs, there is also the issue of a mismatch in intensities due to our photodiode. The QSD2030 OnSemi photodiode operates in a range of wavelengths from around 620 to 1100 nm. However, it has a peak sensitivity at 920 nm which is indicative of infrared light sensitivity. Thus, the resultant photocurrent out of our QSD2030 will be much greater for the infrared light that it receives rather than the red and yellow wavelengths.

The final issue that may have caused our high percentage error in our SpO2 values could have resulted from an instability within our light measurements. Our QSD2030 photodiode has an angular responsivity of around ±15 degrees from its center according to figure 15. Once it goes outside of this range, the responsivity of the photodiode is greatly reduced, giving out around 25-75% of its original photocurrent. Thus, inconsistent placement of our photodiode and lights in relation to it could have led to inconsistencies within our resultant intensities.

Trial	Our SpO2 (%)	R	Commercial SpO2 (%)	Percent Error (%)
1	89	0.882352941	98	9.183673469
2	89	0.882352941	98	9.183673469
3	88	0.941176471	99	11.11111111
4	89	0.882352941	98	9.183673469
5	88	0.941176471	97	9.278350515
6	88	0.941176471	98	10.20408163
7	88	0.941176471	98	10.20408163
8	87	1	97	10.30927835
9	86	1.058823529	97	11.34020619
10	88	0.941176471	97	9.278350515

Fig. 14: Calculated SpO2 vs commercial SpO2 values from red, infrared scheme

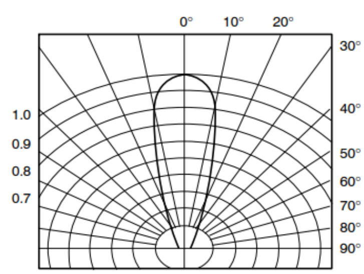


Figure 2. Angular Response

Fig. 15: Angular responsivity of QSD2030 photodiode

2.2.2 Color Recognition via Computer Vision Subsystem

Initially, this subsystem was designed to utilize the "ESP-32 Camera Module" in conjunction with a flashing light to image the skin tone of the user. Towards the end, due to component failures, we opted for a laptop webcam, with ESP-32 connection over WiFi. 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. The subsystem utilizes python's OpenCV library to analyze pixels in a circular area in the center of the webcam, and compares it to a "median" skin RGB value set in place as a parameter.

<u>Pseudocode:</u>

- Capture screen images using webcam
- While capturing images:
    - Create a circle with radius 2 in the center of the screen
    - Average out RGB values in circle using OpenCV
    - Depict to User
- If average R, G, and B values are past 217, 167, 134 respectively (median skin):
    - Send HTTP request signalling 2LED
- Else:
    - Request 3LED

The first requirement of this subsystem was that the camera (ESP-32 CAM to Webcam) was able to correctly output the correct RGB data to the ESP-32 microcontroller. In order to test this requirement we captured an image of the user and their skin tone in controlled lighting conditions. Then we were able to transfer the image data to the computer vision system to extract the RGB values while displaying the values in real time. Next the software would compare the RGB values obtained to the referenced threshold value and color calibration chart. The sample images in figure 16 had proven with multiple testing subjects that this requirement was successful.

The second requirement was that the module must be able to process this data from the camera and select the optimal LED mode within 200 milliseconds. To test this requirement we made sure to capture an image of the user's skin tone and process the RGB values over wifi to the microcontroller within the 200 milliseconds. With this data processed the correct LED mode was chosen. The verification of the requirement comes from the real time update of the LED mode on the display alongside the diodes updating as soon as the RGB value in the given circular area is changed.

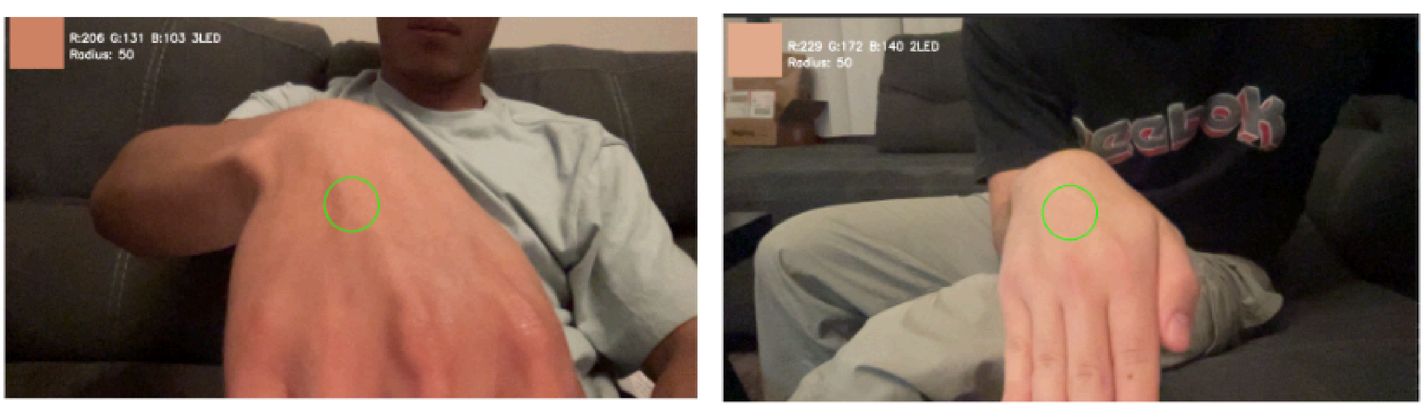


Figure 16: Webcam Color Recognition for 2LED (right) & 3LED (left)

Schematics:

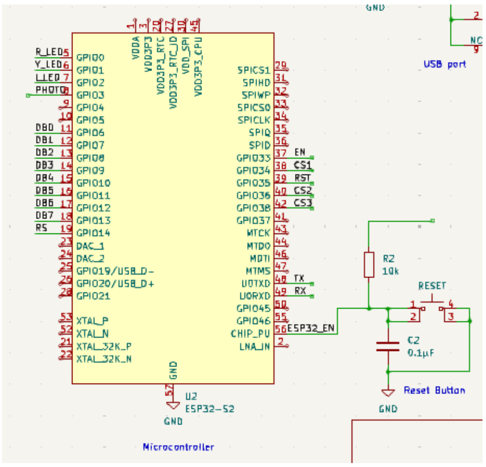


Fig. 17: ESP-32 Module with Reset Button

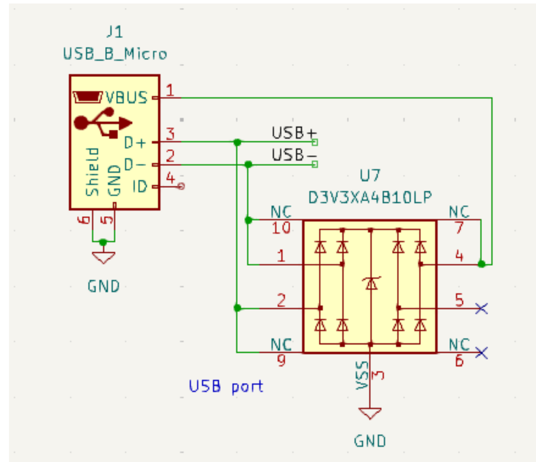


Fig. 18: ESP-32 USB Connection

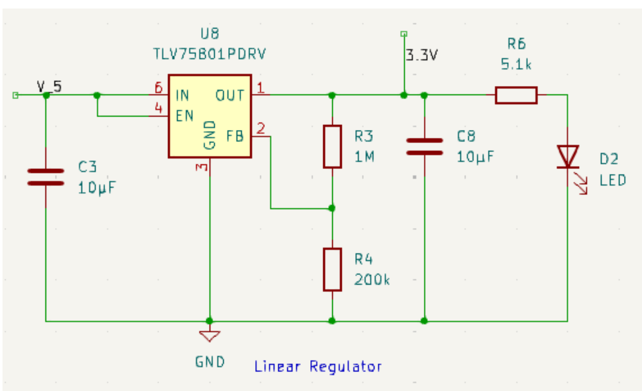


Fig. 19: ESP-32 3V3 Regulator

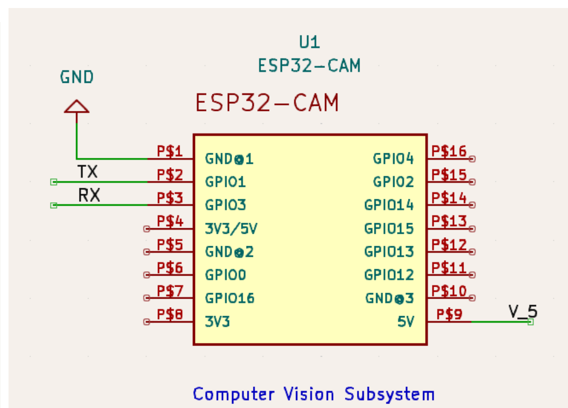


Fig. 20: ESP32-CAM Module

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. For the LCD, we opted to use the NHD-0216K1Z-NSW-BBW-L display. This display utilized either a 4-bit or 8-bit display initialization. In order to print to the display, you needed to map each pin out on the LCD to its external connection. Ensuring that each GPIO port connected to the microcontroller was able to properly write to the LCD. The other aspect of the LCD was the cursor, enabling where to print on the display. This LCD in particular was bound with the display size of 16 columns and 2 rows. After designating where to print on the display the liquid crystal library that contains all the stored fonts, the microcontroller can print out any of the characters in real time.

The design issues that occurred during the process was that there were pins that were taken for the ESP-32 CAM that needed to be rerouted to different GPIO ports on the microcontroller. The pin that was originally used to write to the display from the microcontroller was needed for the color recognition software since it was the only pin that would work with the wifi. Thus we needed to change the pin connections towards the microcontroller, which then led to the rearranging of multiple pins to ensure reading and writing capabilities. This resulted in the PCB being unable to properly be connected to the new display layout.

<u>Schematics:</u>

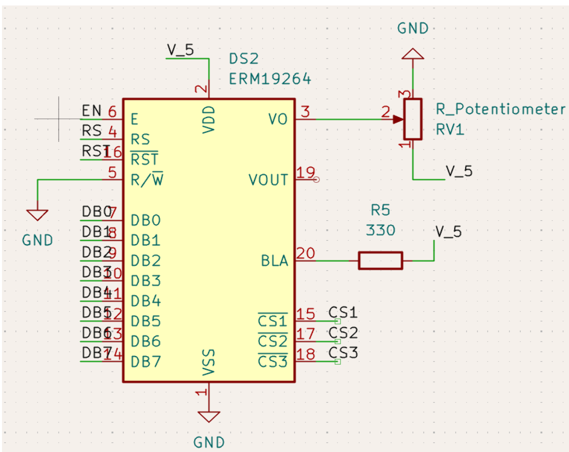


Fig. 21: LCD Display Schematic

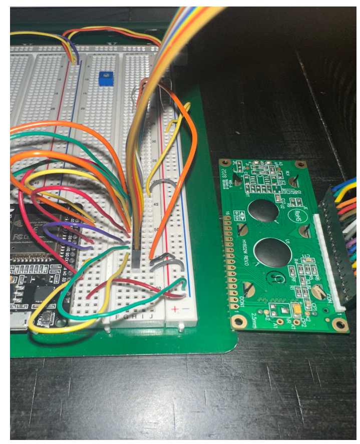


Fig. 22: LCD Display Breadboard Circuit

<u>Display Layout:</u>

Figure 23: Layout of the Display Subsystem, SpO2 value (top left), Mode (top right), and Heart Rate (bottom left)

Our first requirement of our display subsystem was to be able to display the SpO_2 and the heart rate to the LCD within real time. This meant that we needed to ensure that the display was being updated with a minimum refresh rate of 1 Hz. To test that this requirement was fulfilled we first obtained the measurements through the pulse oximeter subsystem and displayed the data to both the LCD and the serial monitor. With both forms of confirmation we were able to correctly identify that the device was updating in real time. When comparing this real time changing value to that of a commercially available pulse oximeter, we could determine that both oximeters were updating almost simultaneously.

The second requirement of our display subsystem was to update the correct LED mode that the device was in during real time. This also meant that we needed to ensure that the display was being updated with a minimum refresh rate of 1 Hz. Based upon the color recognition subsystem we were able to determine the RGB value of the user's skin tone, indicating which LED mode to use. Everytime the RGB value on the webcam was updated, the LCD would accurately update and display either 2L or 3L, showing the correct mode the device was in.

3. Cost and Schedule

3.1 Cost Analysis

Labor:

The average starting salary for an electrical engineering graduate is $88,321 with an average signing bonus of $5,000. With this estimation, we can determine the cost for labor per hour to be approximately $40 an hour. This is a value taking the current socio economic state of the country into account. To account for us being students, we are lowering the salary by $5 an hour. The total hours nearing approximately 9 hours a week for each member of the group over the span of 8 weeks.

$(\$/hour)\ x\ 2.5\ x\ hours\ to\ complete\ =\ TOTAL$

$(\$35/hr)\ x\ 2.5\ x\ 9\ x\ 8\ =\ \$6300$ per person or a total of $18,900.

Parts:

Description	Manufacturer	Part #	Quantity	Cost
Infrared LED	SunLED	XTNI11W	1	$0.38
Yellow LED	Wurth Elektronik	151051YS04000	1	$0.20
Red LED	Wurth Elektronik	151051RS11000	1	$0.15
Green LED	Wurth Elektronik	151051VS04000	1	$0.24
NPN General Purpose Transistor	OnSemi	2N4401	3	$0.78
SENSOR PHOTODIODE	OnSemi	QSD2030	1	$0.63

880NM RADIAL				
Dual General Purpose Operational Amplifier	Texas Instruments	MC1458P	1	$0.49
ESOP-8 Battery Management ROHS	TOPPOWER (Nanjing Extension Microelectronics)	TP4056-42-ESOP8	5	$0.88
Boost Switching Regulator IC Positive Adjustable 2.2V 1 Output 2.5 A SOT-23-6	Texas Instruments	TLV61070ADBVR	1	$0.38
Linear Voltage Regulator IC Positive Fixed 1 Output 800 mA TO-252-3	Texas Instruments	LM1117DT-5.0/NOPB	1	$1.69
P-Channel 60 V 300 mA 270 mW Surface Found MOSFET	Nexperia USA Inc.	BSS84AKW	1	$0.21
Zener Diode 5.6 V 300 mW Surface Mount	Diodes Incorporated	BZT52C5V6T-7	1	$0.11
Graphic LCD Display Module	EastRising Technology Co., Limited	ERM19264-1 Series	1	$14.76
ESP32, OV2640 - Image Sensor Evaluation Board	CANADUINO, UNIVERSAL-SOLDER Electronics Ltd	26387	1	$11.38
ESP32	Espressif Systems	1965-ESP32-S2-DEVKITC-1R-ND	1	$0
Resistors (Through hole)	N/A	140 Ω, 196 Ω, 510 Ω, 10.02k Ω, 330k Ω, 1k Ω, 9k Ω	2, 1, 3, 4,1, 1	$0
Capacitors (Through hole)	N/A	10 uF 22 uF	3 1	$0
Inductors (Through hole)	N/A	2.2 uH	1	$0
SMD Resistor 115k Ohm	YAGEO	311-2701-2-ND	6	$0.6
SMD Capacitor 10pF	KEMET	399-C0805C100JDGACTUTR-ND	6	$2.34
SMD Capacitor 4.7nF	KEMET	399-C0805C472G3GECTUTR-ND	6	$3.78
Micro USB Connector	Molex	WM1399TR-ND	2	$1.84
TVS Diode 3.3VWM	Diodes Incorporated	31-D3V3A4B10LP-7CT-ND	3	$0.84

IC OpAmp GP 1 Circuit	Texas Instruments	296-45202-1-ND	3	$4.44
Conn Header Vert 2POS 2.54MM	Molex	WM13440-ND	10	$1.39
Conn Header Vert 16POS 2.54MM	Molex	WM13440-ND	3	$2.70
Switch Tactile	2223-TS02-66-70-BK-160-LCR-D-ND	Same Sky	3	$0.30
Trimmer 100 Ohm	Bourns Inc	3314G-101ECT-ND	2	$3.16
2.54MM 0.1 Pitch 16-Pin Jumper	Adafruit Industries	1528-4944-ND	1	$1.75
2.54MM 0.1 Pitch 2-pin Jumper	Adafruit Industries	1528-4934-ND	5	$3.75

Total Part Cost: $146.92
Total Cost including labor and parts: $19,046.92

3.2 Schedule

Week	Goals and Work	Week	Goals and Work
2/24	Work: Finish each subsystem schematic and try to finish PCB in time for first order, Work on Design document. (All) Due: PCB Review - 2/28	4/7	Work: Complete initial testing stages to fix problems and debug (All) Begin Final Paper write up (Jason then All) Due: Fourth Round PCBway AUDIT - 4/7
3/3	Work: Design Document and Schematic work (All) Breadboard Parts - Jason, Sidney Breadboard Implementation (All) Due: First Round PCBway AUDIT - 3/3 Teamwork 1 Evaluation - 3/5 Design Document - 3/6	4/14	Work: Begin Final Paper write up (All) Testing stages to fix problems and debug (All) Prepare for Mock Demo with TA (All) Due: Team Contract Assessment - 4/18
3/10	Work: Breadboard Implementation (All) PCB schematic finish and review for Second Round (All, Sidney) Order all Parts (All) Due:	4/21	Work: Final Testing and preparation for final demo (All) Prepare for Mock Demo with TA (All) Prepare for Final Demo (All) Final Paper write up (All)

	Breadboard Demo - 3/11 Second Round PCBway AUDIT - 3/13		<u>Due:</u> Mock Demo with TA - 4/21
3/17	<u>SPRING BREAK</u> If time, work on the software aspect.	4/28	<u>Work:</u> Prepare for Final Demo (All) Final Presentation Prep (All) Final Paper write up (All) <u>Due:</u> Final Demo with Instructors - 4/29 Mock Presentation with TA -5/2
3/24	<u>Work:</u> Computer Vision and SpO2 / Heart Rate programming - Stage 1 Aim to Complete (Faris, Jason) Camera Integration and Code (Faris) Battery and Power System (Sidney) If PCB, then Solder PCB and begin assembly to test (All) <u>Due:</u> NA	5/5	<u>Work:</u> Final Presentation Prep (All) Final Paper write up (All) <u>Due:</u> Final Presentation - 5/6 Final Paper Due - 5/7 Lab Checkout - 5/8 Lab Notebook - 5/8
3/31	<u>Work:</u> Computer Vision and SpO2 / Heart Rate programming - Stage 2 Aim to complete (Faris, Jason) Camera Integration and Code (Faris) Battery and Power System (Sidney) If PCB does not work then prepare and fix for round 3 (All) <u>Due:</u> Third Round PCBway AUDIT - 3/31 Individual Progress Reports - 4/2		

5. Conclusion

5.1 Accomplishments

The Smart Pulse Oximeter project achieved successful integration of its major subsystems, resulting in a functional and adaptable health monitoring device. The design focused on improving the accuracy of blood oxygen saturation (SpO_2) readings across diverse skin tones by combining traditional photoplethysmographic sensing with computer vision-based wavelength selection.

The pulse oximeter subsystem marked a significant success in both hardware and signal processing design. The team successfully developed and implemented a time-multiplexed LED driving system, allowing precise control over red, infrared, and yellow wavelengths. The photodiode signal was accurately converted using a custom transimpedance amplifier tailored to the low-current output, and the amplified signals were reliably sampled within the ESP32's operating range. Through extensive testing and calibration, the subsystem produced consistent waveform data, from which AC and DC components were extracted with sufficient clarity to enable real-time SpO_2 and heart rate calculation. The system's ability to filter out ambient noise and maintain clean signal acquisition confirmed the robustness of both the analog front end and digital processing pipeline. Despite not meeting the strict ±5% error target, the subsystem consistently tracked physiological changes and validated the feasibility of a low-cost, adaptive oximeter. Its stable performance under varying light and skin conditions demonstrates a strong foundation for continued development.The computer vision subsystem, implemented using a webcam and OpenCV, analyzed user skin tone in real time and selected the appropriate LED wavelength combination. The system consistently met the processing time requirement, completing skin tone classification and LED selection within 200 milliseconds. This adaptive feature allowed the device to adjust to different levels of melanin and optimize measurement accuracy. The digital display subsystem successfully provided real-time output of SpO_2 and heart rate values on an external LCD screen. The display updated at a refresh rate of at least 1 Hz and showed current readings and operational modes clearly and reliably.

Overall, the project represents a significant engineering achievement in adaptive health monitoring. By addressing disparities in pulse oximetry performance across skin tones, this work contributes to more inclusive and equitable medical technology. The final prototype confirms the viability of the design and lays the groundwork for future refinement and clinical validation.

5.2 Uncertainties

The main uncertainty that was present in our device was in our pulse oximeter subsystem. These issues were previously mentioned in this report in the pulse oximeter subsystem but these slight flaws in the design caused the slightly higher error percentage for the SpO_2 and heart rate accuracy compared to a commercial pulse oximeter. Another uncertainty arose from our PCB design. With the failure of one of our main components, the ESP-32 CAM, we were forced to pivot away from that part and opted for a webcam over a wifi network in order to compensate. This led to a domino effect of small issues such as the pinout for the display and ESP-32 microcontroller. Although these issues were small it did affect the utilization of our PCB and thus the entire device itself. Alongside this was the micro USB connector breaking off so we were unable to program the PCB forcing us to shift towards a breadboard final demonstration. A physical uncertainty that we ran into was the device casing. The casing for the device was 3D printed and was printed and designed ourselves. CAD was quite a new experience for everyone on the team and we had determined that it would be more beneficial to ourselves if we tried to design and print the casing by ourselves. This led to not only a few design issues but also printing issues. The design was created through a series of trial and error but this design was unsatisfactory when it came to printing. Not only did we utilize subpar printers, but there were contant printing issues. Nearing double digit printing attempts we had concluded that the latest print would be the best. Unfortunately we were unable to remove all the 3D support filaments that were inserted into the device finger insert which had left us unable to add any of the diodes into the casing. The only workable solution was to utilize a makeshift clamp made from cardboard, a clip and electrical tape. This clamp was able to help us isolate the pulse oximeter subsystem but was not perfect in holding the photodiode and LEDs in perfect alignment. This caused some inaccuracies in our results leading to the 9 to 11% error when compared to the commercially available pulse oximeter.

5.3 Future Work / Alternatives

This project had a bright future ahead of itself. With the improvement of some aspects of the pulse oximeter subsystem we can sort out some of those issues. To address the disproportionate photocurrent response caused by the photodiode's peak sensitivity at 920 nm, future designs should incorporate a photodiode with a flatter or more uniform spectral responsivity. To help to avoid the unit conversion issues, in future implementations, all emitters should be selected from a product family with comparable specifications and output units, or calibrated experimentally using an integrating sphere or calibrated photodetector to equalize perceived intensity at the sensor. An alternative that was introduced to us by the professor was to make the color recognition software automatic within the pulse oximeter subsystem. Rather than having a separate subsystem that would require utilizing the RGB value of one's skin tone to change the LED method but to have the melanin concentration in their skin be analyzed through the pulse oximetry method and having it automatically swap LED modes depending on the measurements through the photodiode. Another area we could improve upon is the 3D casing. Not only improving the design to make it a little easier to disassemble but also to make sure that the finger insert will remain clear and precise for the usage of the pulse oximeter subsystem. Utilizing more experienced CAD designers to help us create a better casing while also making sure that the printing process is smooth. Overall, building upon this brand new technology and making this device more stable and accurate can help to open great opportunities for helping the healthcare industry become more efficient and inclusive.

5.4 Ethics

The Smart Pulse Oximeter aligns closely with the IEEE Code of Ethics by promoting fairness, transparency, and public welfare. Traditional pulse oximeters have been shown to inaccurately measure oxygen saturation in individuals with darker skin tones, potentially delaying medical intervention. This project addresses that disparity by integrating adaptive technologies such as computer vision-based skin tone detection, thereby supporting IEEE Principles #1 and #3 through its commitment to public well-being and honest, unbiased data reporting. The design also considers ethical responsibilities around data privacy and protection of personal health information, incorporating secure data handling practices in accordance with IEEE Principle #5. By tackling racial disparities in device performance, the project furthers healthcare equity, as outlined in Principle #8, while its emphasis on power efficiency and sustainable design supports environmentally responsible engineering (Principle #6). Overall, the Smart Pulse Oximeter represents an ethically grounded advancement in medical technology, prioritizing accuracy, inclusivity, and patient safety.

6. References

[1] IEEE, "IEEE Code of Ethics," *ieee.org*, Jun. 2020. https://www.ieee.org/about/corporate/governance/p7-8.html

[2] Raghda Al-Halawani, P. Charlton, Meha Qassem, and P. A. Kyriacou, "A review of the effect of skin pigmentation on pulse oximeter accuracy," *Physiological Measurement*, vol. 44, no. 5, pp. 05TR01–05TR01, May 2023, doi: https://doi.org/10.1088/1361-6579/acd51a.

[3] D. Martin *et al.*, "Effect of skin tone on the accuracy of the estimation of arterial oxygen saturation by pulse oximetry: a systematic review," *British Journal of Anaesthesia*, Feb. 2024, doi: https://doi.org/10.1016/j.bja.2024.01.023.

[4] P. A. Kyriacou, P. H. Charlton, R. Al-Halawani, and K. H. Shelley, "Inaccuracy of pulse oximetry with dark skin pigmentation: clinical implications and need for improvement," *British Journal of Anaesthesia*, vol. 130, no. 1, Apr. 2022, doi: https://doi.org/10.1016/j.bja.2022.03.011.

[5] A. Yartsev, "Principles of pulse oximetry," *Deranged Physiology*, Dec. 23, 2023. https://derangedphysiology.com/main/cicm-primary-exam/respiratory-system/Chapter-410/principles-pulse-oximetry (accessed Feb. 14, 2025).

[6] "Part Number: XTNI11W," 2023. Accessed: Feb. 14, 2025. [Online]. Available: https://www.sunledusa.com/products/spec/XTNI11W.pdf

[7] "Ai-Thinker ESP32-CAM WiFi + BT + BLE SoC with 2MP Camera," 2021. Accessed: Feb. 14, 2025. [Online]. Available: https://www.universal-solder.ca/downloads/ESP32-CAM.pdf

[8] "Dimensions: [mm]." Accessed: Feb. 14, 2025. [Online]. Available: https://www.we-online.com/components/products/datasheet/151051RS11000.pdf

[9] "ONSM-S-A0006525354-1.pdf," *Widen.net*, 2024. https://rocelec.widen.net/view/pdf/ctvgfn5oib/ONSM-S-A0006525354-1.pdf?t.download=true&u=5oefqw

[10]"Espressif Systems." Accessed: Feb. 14, 2025. [Online]. Available: https://www.mouser.com/datasheet/2/891/esp-wroom-32_datasheet_en-1223836.pdf?srsltid=AfmBOorUCmMDeW7RNKrR16aYtDXmkMxnWaXPfvNWayv6rCcKoh-RD083

[11]“OLED SPECIFICATION WEA012864DBPP3N00003 ■APPROVAL FOR SPECIFICATIONS ONLY □APPROVAL FOR SPECIFICATIONS AND SAMPLE ( ) Model No.” Accessed: Feb. 14, 2025. [Online]. Available: https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/5485/WEA012864DBPP3N00003.pdf?_gl=1

[12]A. Winny and N. Jurmo, “Pulse Oximeters’ Racial Bias | Johns Hopkins | Bloomberg School of Public Health,” *publichealth.jhu.edu*, Jul. 08, 2024. https://publichealth.jhu.edu/2024/pulse-oximeters-racial-bias

[13] E. Fiore, “ICU Delirium: A Serious, Often Preventable Condition,” *MedPage Today*, https://www.medpagetoday.com/criticalcare/generalcriticalcare/99659 (accessed May 5, 2025).

[14] M. F. Sjoding, R. P. Dickson, T. J. Iwashyna, S. S. Gay, and J. P. Valley, “Racial Bias in Pulse Oximetry Measurement,” N. Engl. J. Med., vol. 383, no. 25, pp. 2477–2478, Dec. 2020, doi: 10.1056/NEJMc2029240.

[15] T. Aoyagi, M. Fuse, N. Kobayashi, K. Machida, and K. Miyasaka, “Multiwavelength Pulse Oximetry: Theory for the Future,” *Anesthesia & Analgesia*, vol. 105, no. 6, pp. S53–S58, Dec. 2007, doi: https://doi.org/10.1213/01.ane.0000268716.07255.2b.

7. Appendix A

7.1 Requirements & Verification Table

Table 1 - Pulse Oximeter Subsystem R&V Table

Requirements	**Verification**
Red LED (660nm), yellow LED(590nm) and infrared LED(940nm) emit the wavelengths / voltages and are read by photodiode.	Equipment: Use a photodiode to verify the voltage of the LEDs. Test Procedure: 1. Power each LED individually and measure the emitted wavelength / voltage 2. Place the photodiode in the circuit and measure the output signal when each LED is turned on. 3. Confirm that the photodiode detects a signal for each LED at the specified voltage. Presentation of Results: Record the measured voltages and compare with the datasheet.
Based on the computer vision	Equipment: Camera module, image processing software, and controlled lighting conditions.

subsystem utilize the necessary LEDs. Either choosing the red and infrared LEDs or the red, infrared and yellow LEDs.	Test Procedure: 1. Capture images of different subjects under controlled lighting using the camera module. 2. Process the images using the computer vision algorithm to determine the detected skin tone classification. 3. Verify that the system correctly categorizes skin tones and selects the corresponding LEDs based on predefined thresholds. 4. Compare the system's LED selection decision against a manually verified skin tone classification. Presentation of Results: Display the RGB values of test subjects and their actual skin tone classification (as determined manually).
Blood oxygen saturation (SpO_2) and pulse measurement within 5% accuracy comparative to commercial store bought pulse oximeters.	Equipment: Commercial pulse oximeter for reference, test subjects, and data collection software. Test Procedure: 1. Measure blood oxygen saturation and pulse rate using the designed system and a commercial pulse oximeter simultaneously. 2. Collect data from at least 10 different individuals under different conditions (e.g., rest, mild activity). 3. Compare the recorded values from both systems and calculate the percentage error. Presentation of Results: Present results in a table showing measured values from both systems and error percentages, along with statistical analysis confirming the accuracy within 5%

Table 2 - Color Recognition Subsystem R&V Table

Requirements	**Verification**

ESP-32 Camera Module outputs correct RGB data to ESP-32 Microcontroller. (Altered to Webcam over WiFi)	Equipment: ESP-32 Camera Module, ESP-32 Microcontroller, color calibration chart, image processing software, Webcam Test Procedure: 1. Capture an image using the ESP-32 Camera Module / Webcam under controlled lighting conditions. 2. Transfer the image data to the ESP-32 Microcontroller and extract the RGB pixel values. 3. Compare the extracted RGB values with expected color values from a color calibration chart 4. Verify consistency of RGB values over multiple tests with different lighting conditions. Presentation of Results: Sample images processed by the ESP-32 with extracted RGB values.
Process the module data and selecting optimal LED wavelengths within 200 ms.	Equipment: ESP-32 Camera Module, ESP-32 Microcontroller, image processing software, Webcam Test Procedure: 1. Capture an image with the ESP-32 Camera Module / Webcam and pass it to the microcontroller. 2. Process the image to analyze skin tone and select the appropriate LED wavelengths. 3. Repeat the test for at least 20 trials and verify that the processing time does not exceed 200 ms. Presentation of Results: Confirmation that all trials meet the 200 ms requirement

Table 3 - Display Subsystem R&V Table

Requirements	**Verification**
Displays SpO_2 and heart rate to LCD display in real time (minimum refresh rate of 1 Hz) updating as values change through algorithmic	Equipment: ESP-32 Microcontroller, LCD display, commercial pulse oximeter (for reference) Test Procedure: 1. Capture SpO_2 and heart rate data from the sensor and process it using the microcontroller. 2. Display the calculated SpO_2 and heart rate values on the LCD display. 3. Compare displayed values to a commercial pulse oximeter and ensure updates reflect algorithmic calculations in real time. Presentation of Results: Serial Monitor compared to the showing of real-time updates on the LCD

calculation.	display.
Displays Correct LED Mode	Equipment: ESP-32 Microcontroller, LCD display Test Procedure: 1. Display correct LED mode onto display based on chosen mode from color recognition subsystem. Presentation of Results: LCD display will correctly display the correct mode the device is operating in.