Photoplethysmography Prototype using IoT-based Sensors for Continuous and Non-invasive Measurement of Vital Health Parameters

Project Report Submitted in Partial Fulfilment of the Requirements
for the Degree of

BACHELOR OF TECHNOLOGY
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Certificate

This is to certify that the dissertation entitled "**Photoplethysmography Prototype using IoT-based Sensors for Continuous and Non-invasive Measurement of Vital Health Parameters**" has been carried out by the team of four members, **Archit Soni** (20095014), **Shubhi Singh** (20095112), **Nishanth Gounder** (20095074), and **Devanshu Agrawal** (20095035), under the supervision of **Dr. Priya Ranjan Muduli**, towards partial fulfilment of the requirements for the award of the degree “**Bachelor of Technology” in Electronics Engineering** at the Department of Electronics Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi.

The work presented in this project report is original, has not been submitted elsewhere for any degree or diploma, and does not contain any material that has been previously published, except where due reference has been made in the text.

Supervisor
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Declaration

We declare that this project report entitled "**Photoplethysmography Prototype using IoT-based Sensors for Continuous and Non-invasive Measurement of Vital Health Parameters**" is a record of an original work carried out by us under the supervision of **Dr. Priya Ranjan Muduli**, Indian Institute of Technology (BHU), Varanasi, to fulfil the requirements of the degree **"Bachelor of Technology" in Electronics Engineering.** The work presented in this report has not been previously submitted for any degree or examination in any other institution. All sources of information used in this project have been acknowledged through proper citations and references.

Archit Soni **Shubhi Singh**

Nishanth Gounder **Devanshu Agrawal**

Acknowledgement

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Abstract

With the Covid-19 pandemic, the demand for remote health monitoring has increased. In response, this project report presents the design and development of a Photoplethysmography Prototype for continuous and non-invasive measurement of vital health parameters, i.e., SpO_2 and BPM. Our prototype includes IoT connectivity and an on-device OLED display. The design includes an ESP32 controller, MAX30102 Sensor Module, and the Maxim Algorithm to calculate SpO_2 and BPM values. Additionally, we developed a calibration algorithm to stabilise and adjust these values. The prototype provides accurate SpO_2 and BPM readings with finger detection and Push Notifications when the SpO_2 level is low. The IoT interface on Blynk for the device on web and mobile displays live values of SpO_2 and BPM, displays the no finger condition, and provides a live graph of the past recorded values. We have also developed a python script that in conjunction with the Blynk API provides past data in an easily accessible CSV file. We believe that our project contributes to the development of wearable health monitoring devices for remote healthcare applications.

1. Introduction

As mentioned above, this project aims to design and build a wearable **PPG (Photoplethysmography)** device to measure and transmit data about the **SpO_2 (Saturation of Peripheral Oxygen)** in the user in order to achieve continuous and non-invasive health parameter monitoring.

During the COVID-19 Pandemic, many patients have been afflicted with a condition known as **Silent Hypoxia.** Hypoxia occurs when the body or a region is deprived of adequate oxygen supply at the tissue level. In Silent Hypoxia, the patients do not suffer from shortness of breath until their oxygen levels have already dropped severely. It is usually a precursor to pneumonia in COVID-19 patients, and hence its detection is essential to preventing further damage.

Moreover, monitoring SpO_2 levels are essential in the diagnosis and treatment of several other **respiratory conditions,** such as Pneumonia, Hypoxia, COPD (Chronic Obstructive Pulmonary Disease), Sleep Apnea, Lung Cancer, and Asthma.

2. Literature Review

2.1. Common Terms and Definitions

2.1.1. Oxygen Saturation

Definition: The amount of oxygen-saturated haemoglobin in the blood divided by the total available haemoglobin in the blood.

2.1.2. Photoplethysmography (PPG)

Definition: It is a technique that detects changes in the pulsatile blood-flow volume (that change due to the cardiac cycle) in the micro-vascular tissue bed based on the intensity of reflected or transmitted light.

2.2. Early Photoplethysmography

2.2.1. Photoplethysmography in the 1930s

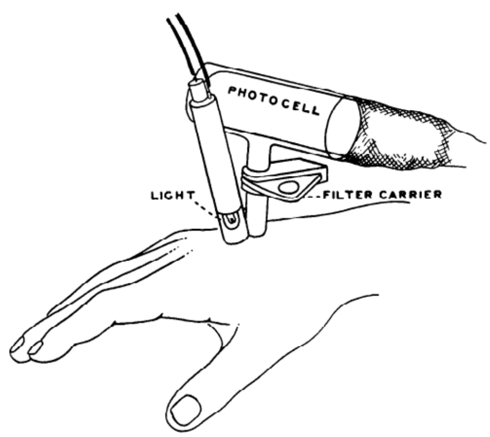


Fig. 1. The photoelectric plethysmograph in position over the skin of the hand

Image Taken from Hertzman (1938)

Reference: [1]: In the earlier stages of Photoplethysmography development, pencil flashlight bulbs carried on a metal plunger in a metal sleeve attached to the photocell housing is used for illumination, and vascular changes are detected with the photoelectric cell, as shown in the image above. Thus, the light reflected from the skin goes to the photocell through the metal sleeve.

Hertzman's (1938) study aimed to investigate the blood supply of different skin areas by using a photoelectric plethysmograph, a device that measures changes in blood volume in a specific tissue. The paper provides a detailed discussion of the principles and methodology of photoelectric plethysmography, including the use of light absorption to detect vascular changes in the skin. The author also discusses the sources of error involved in the quantitation of the skin plethysmogram, including the movement of the skin, the influence of large arteries in the immediate neighbourhood of the area being observed, the character of contact of the plethysmograph with the skin, and variations in illumination.

The study found significant variations in blood supply among different skin areas. The finger pad was found to have the richest arterial supply, followed by the earlobe, toe pad, palm of the hand, skin of the forehead and face, dorsum of finger, hand and foot, forearm, knee, and tibia.

The paper also provides data demonstrating the essential validity of the photoelectric plethysmogram in measuring vascular responses to common procedures. The author argues that under normal circulatory dynamics, the volume pulse of the skin area is a measure of the richness of the arterial blood supply of that area.

2.2.2. Photoplethysmography in the 1980s

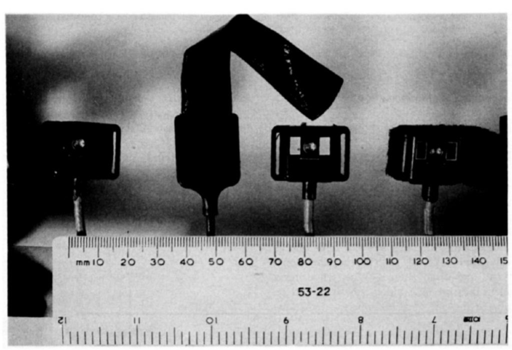


Fig. 2. Photograph of plethysmographs. From left to right: red LED photoplethysmograph, green LED photoplethysmograph, piezoelectric plethysmograph, and bulb photoplethysmograph.

Image taken from Kamal et al. (1989)

Reference: [6]: Almost 50 years later, Kamal et al. (1989) provide a comprehensive review of skin photoplethysmography (PPG). According to their paper, the PPG signal can be separated into two components: an oscillating (a.c.) component and a steady-state (d.c.) component. These components provide information about the structure and flow in the vascular bed and can be used for various applications such as pulse counting, skin colour, and haemoglobin saturation measurement.

The DC component of the PPG signal is particularly useful for measuring blood flux beneath the device. To obtain the best PPG signal, the authors recommend using an emitter in the 600-700 nm frequency range and analysing the a.c. component from the finger pulp. The electronic circuitry should have a frequency range from 0.01 to 15 Hz to extract all the information in the signal, particularly in the 0.01 to 2 Hz range where variations in the AC component reflects autonomic nervous system control of the cardiovascular system.

Overall, the authors suggest that PPG has many applications in physiological and clinical investigations and that advancements in signal-processing techniques will continue to provide more information for researchers and clinicians.

2.3. Working Principle for PPG

A PPG waveform has two components:

- **DC Component:** This part exists due to the tissue structure, skin, muscle, bone, and the average volume of arterial and venous blood.
- **AC Component:** This part exists due to pulsation of the volume of arterial blood during the cardiac cycle. This part is superimposed over the DC component of the PPG signal.

The amount of absorption of light by different wavelengths of light in the visible region of the EM Wave Spectra is as shown below: [3]

Region of Light	Affected by which component of Blood
Blue	Absorbed by Red Blood Cells
Green-Yellow (500-600 nm)	Absorbed by Red Blood Cells
Shorter Wavelengths	Absorbed by Melanin
UV and longer IR	Absorbed by Water
Red (660nm) and IR (940nm)	Pass through tissue and blood

- **Red and IR** pass through blood and tissues and hence are used in PPG sensors.
- **Green light** can be used in cases where blood-flow-induced changes are to be monitored. Due to modern LEDs' increased power efficiency, the cardiac cycle difference shows up more in green light and has better SNR. Hence, green light can be used in Heart Rate monitors.[3][4]

The oxygen saturation in the blood is measured from the difference in absorption of light during the systolic and diastolic phases of the cardiac cycle for the two wavelengths **660 nm and 940 nm.** [2][4]

2.4. Mathematical Calculations

Sourced from [2], [3], [4], and [8].

Wavelengths of light typically used in a PPG device are

- **Red** (660nm)
- **Infrared** (940nm)

For oxygen-carrying haemoglobin,

$$S = \frac{O_2Hb}{O_2Hb + RHb} \tag{1}$$

where,

S = haemoglobin oxygen saturation

O_2Hb = Oxygenated Haemoglobin

RHb = Deoxygenated Haemoglobin

For extinction coefficient in the body,

$$E = (E_O \cdot S + E_R \cdot (1 - S)) \tag{2}$$

where,

E = Extinction coefficient of total haemoglobin

E_O = Extinction Coefficient of O2Hb

E_R = Extinction Coefficient of Rhb

Using the Bear Lambert Law for a blood sample, we get,

$$A \equiv log(\frac{I_O}{I}) = E \cdot C \cdot D \tag{3}$$

where,

A = light absorption

I_0 = incident light intensity

I = transmitted light intensity

E = extinction coefficient of Hb

C = haemoglobin concentration

D = thickness of blood sample

Now, the volume of arterial blood changes during the diastolic and systolic phases of the cardiac cycle. This can be shown as,

$$\frac{AC}{DC} = \Delta A \equiv log(\frac{I}{I-\Delta I}) = E \cdot C \cdot \Delta D \tag{4}$$

$$\text{or, } \Delta A \approx \frac{\Delta I}{(I - \frac{\Delta I}{2})} \tag{5}$$

where,

AC = amplitude of alternating current

DC = amplitude of direct current

ΔA = absorbance difference

ΔI = change in transmitted light intensity between the diastolic and systolic phases

ΔD = change in thickness of arterial blood

Note: Due to modern high-speed AD converters and advanced processors, it is possible to calculate the logarithmic values of ΔA from Eq.(4) instead of the approximate value from Eq. (5).

Now, we will calculate the light ratio (**R**), which is the ratio of change in absorption of the different wavelengths (660 nm and 940 nm), as follows,

$$R = \frac{\Delta A_{660}}{\Delta A_{940}} = \frac{AC_{660}/DC_{660}}{AC_{940}/DC_{940}} \tag{6}$$

Using equation (4) we have,

$$R = \frac{E_{660} \cdot C_{660} \cdot \Delta D_{660}}{E_{940} \cdot C_{940} \cdot \Delta D_{940}} \tag{7}$$

If we consider that the variations in blood pulsation and haemoglobin concentration to be negligible, that is,

$$C_{660} \approx C_{940} \; and \; \Delta D_{660} \approx \Delta D_{940}$$

Then we get,

$$R = \frac{E_{660}}{E_{940}} \tag{8}$$

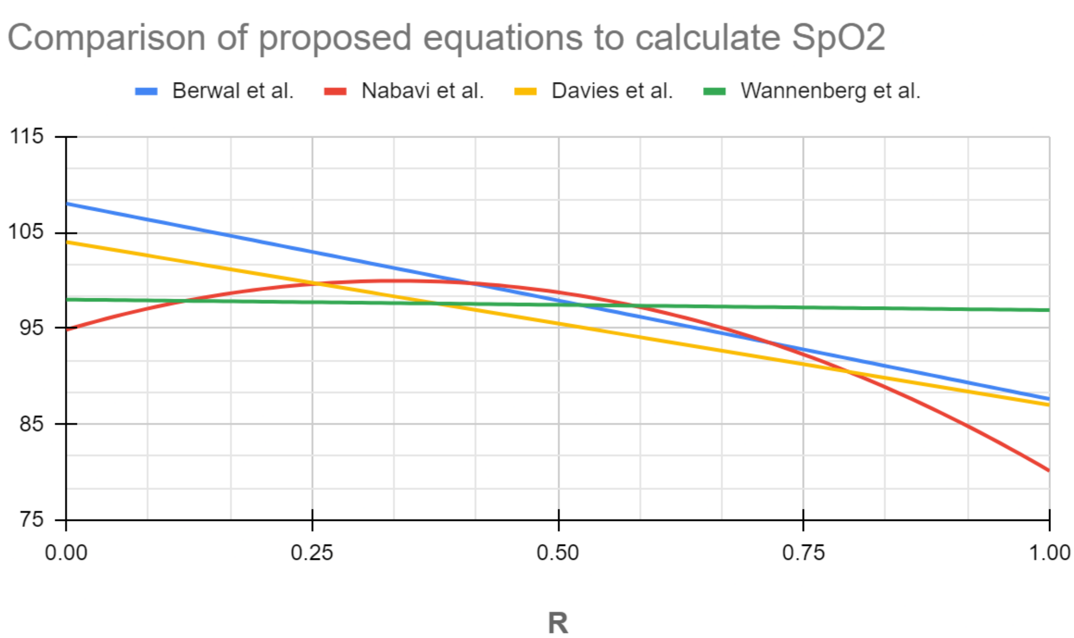
And on substituting the value of extinction coefficient from Eq. (2), we get,

$$R = \frac{E_{O(660)} \cdot S + E_{R(660)} \cdot (1-S)}{E_{O(940)} \cdot S + E_{R(940)} \cdot (1-S)} \tag{9}$$

This value **R** is then used to find the value of SpO_2.

Some contemporary proposed equations to calculate SpO2 from **R** are as follows:

Berwal et al. (2022)[10]	$-0.375R^2 - 20R + 108$
Nabavi et al. (2020)[11]	$-45.06R^2 + 30.354R + 94.845$
Davies et al. (2020) [12]	$-17R + 104$
Wannenberg et al. (2015)[13]	$-1.1R + 98$



Maxim's *spo2_algorithm.h* library uses the equation proposed by ***Nabavi et al.*** and stores the precomputed values in the header file itself.

2.5. Practical Limitations of Existing Techniques

The PPG signal can have **noise** due to several factors. [3]

- Motion Artefacts
    - These errors are caused due to body movements.
    - Hence the way to eliminate these are by monitoring the body movements with an accelerometer, a moving average filter, or an adaptive filter.
- Influence of Venous Blood
- Difference in Optical Passage between R and IR light
- Ambient light from external light sources entering the photodiode
- Electric circuit noise

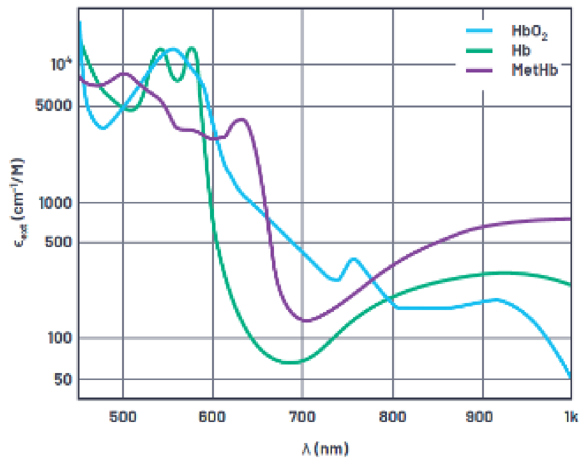
The **accuracy** of the PPG readings is also influenced by: [3]

- LED wavelength
- Signal Strength
- Abnormal Haemoglobin
- Measurement Site
- Spacing between the LEDs and Photodiode [2][4]

Some **proposed solutions** to these errors are: [2]

- **Rapidly Pulsing of the LEDs**
    - This reduces the 1/f noise to the overall signal.
    - Using synchronised modulation, we can reduce the influence of ambient light interference.
    - This also lowers the average current consumption.
- **Increasing Photodiode area**
    - This increases the CTR (current transformer ratio), i.e., LED output over PD return current.

- This reduces the effects of motion artefacts as well by capturing most of the photos that will eventually be reflected back to the photodiode.



Extinction factor of light through hemoglobin

Note about Calibration: Due to many sources of errors, Eq. (9) is not usable in practical situations as it is. Hence, we need to calibrate the device to develop an accurate correlation between **R** and SpO_2. This can be done via a **Hypoxia Study**, where the more accurate oxygen saturation readings of SaO_2* (Atrial Blood Oxygenation) are taken as well, and an equation or lookup table is generated. [2][8]

*: SaO_2 readings are taken via a lab-based blood gas analysis of a blood sample

2.6. Circuit Components for Commercial Oximeters

PPG devices can be of two types: [2][5]

- **Transmissive:**
  - Measures the transmitted light passed through a part of the body
  - Best suited for PPG devices that are used at locations that have higher capillary density, such as a finger or an earlobe.
- **Reflexive:**
  - Measures the reflected light from a part of the body

    - Best suited for areas where the LEDs and photodiode are to be placed next to each other, such as for the chest or a wrist.

The electrical circuit of a PPG sensor basically consists of the following:[3]

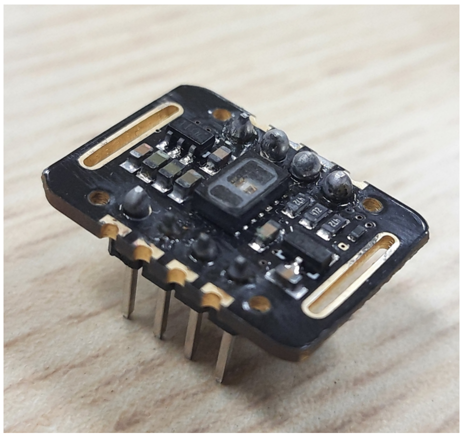
- **Amplifier:** To amplify the signal and increase the variation between the systolic and diastolic phases of the cardiac cycle readings.
- **High Pass Filter:** To remove the DC part of the PPG signal and leave only the AC component.
- **Low Pass Filter:** To remove High-Frequency noise.

And furthermore, a **wearable PPG device consists of** the following components: [3]

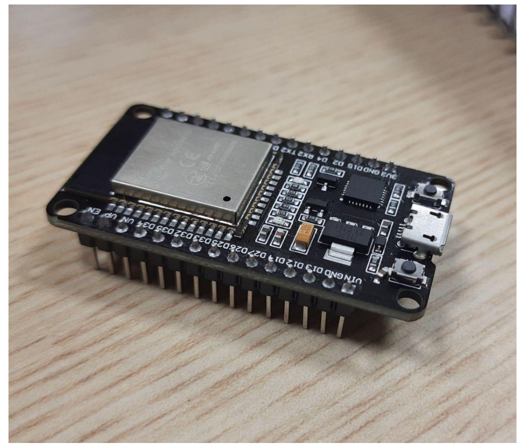
- Three-axis accelerometer
- IR and Red light LEDs
- Photo Diode / Sensor to detect the reflected or transmitted light
- Microprocessor / Microcontroller for processing the sensor data
- optionally, a wireless communication module for transmitting the data to other IoT devices

3. Results and Insights

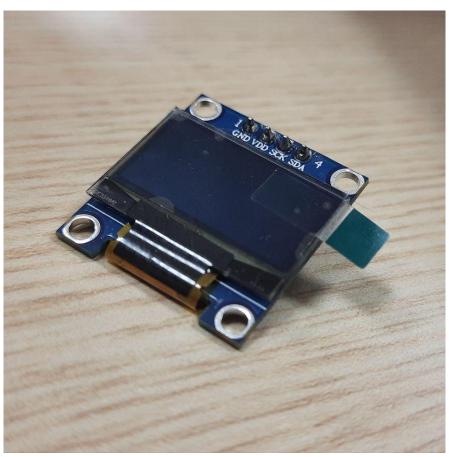
3.1. Components Used for the Circuit



MAX30102 **[Sensor Module]**
High-Sensitivity Pulse Oximeter and Heart-Rate Sensor
Application: Reading the IR and R values, removing noise using analog filters

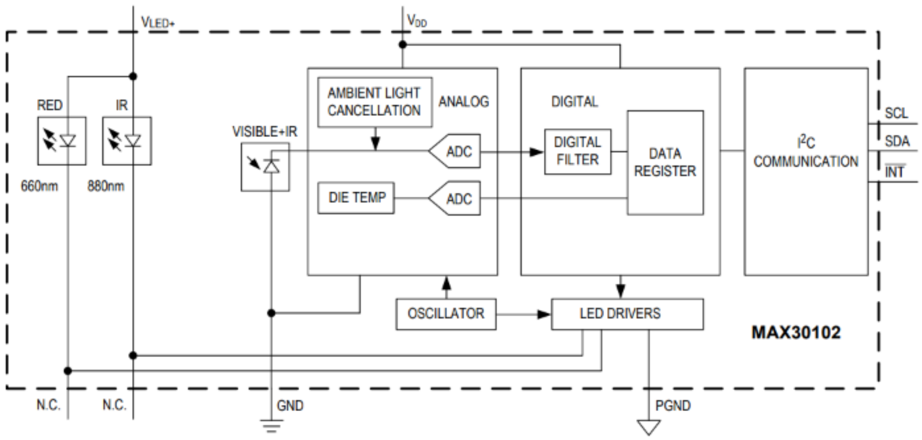


ESP32 **[Processor Module]**
Wifi and Bluetooth Enabled MCU
Application: Communicating with Sensor to get readings, Processing readings to get SpO_2 and BPM values, Controlling the display to show values, Sending the final values to Blynk IoT for remote monitoring



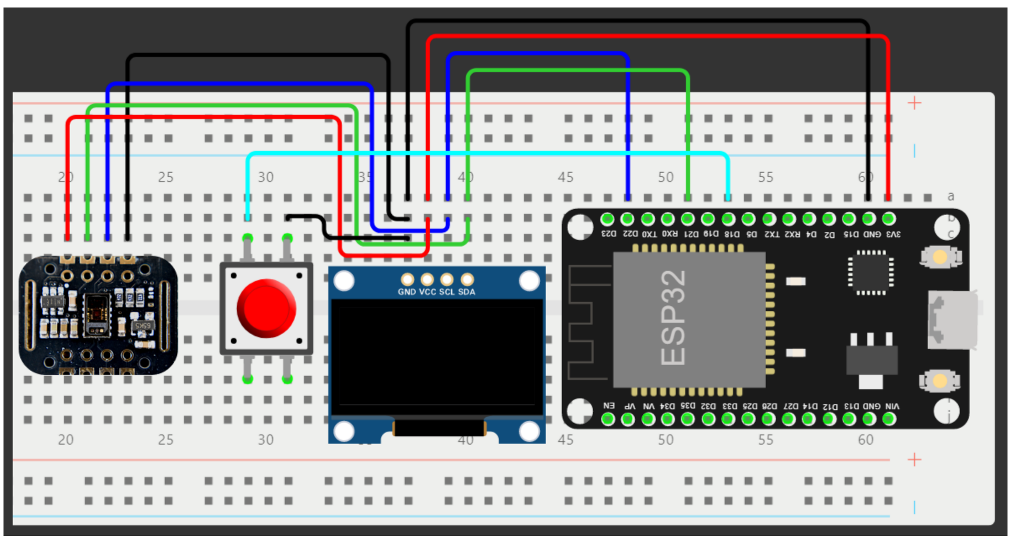
OLED 128x64 1.3" I2C **[Display Module]**
Graphic LCD Display Module OLED
Application: Display user interface/device usage instruction screens, displaying the SpO_2 and BPM values on the device, displaying no finger alert

Button
Applications: Prompting the processor to start taking readings when the user is ready



Functional Diagram of MAX30102 [16]

3.2. Circuit Connections of the Prototype



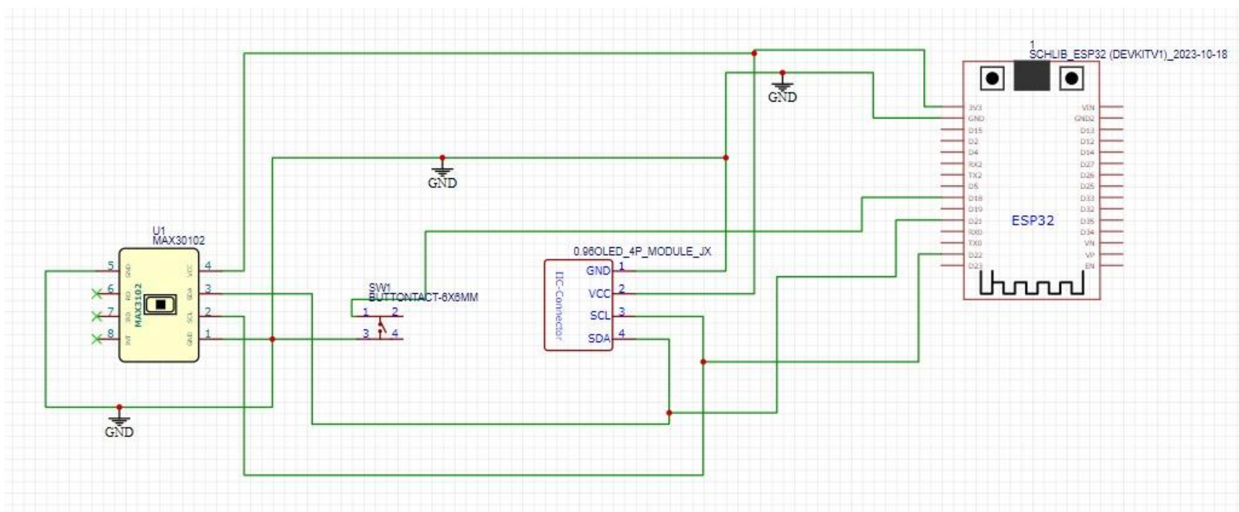
Circuit Connections on the PPG Prototype

Node [Wire Color]	ESP32	OLED Display	MAX30102	Button
Ground **[Black]**	GND	GND	GND	PIN1
VDD **[Red]**	3V3	VCC	VIN	-
SCL **[Blue]**	D22	SCL	SCL	-
SDA **[Green]**	D21	SDA	SDA	-
Button's Input **[Cyan]**	D18	-	-	PIN2

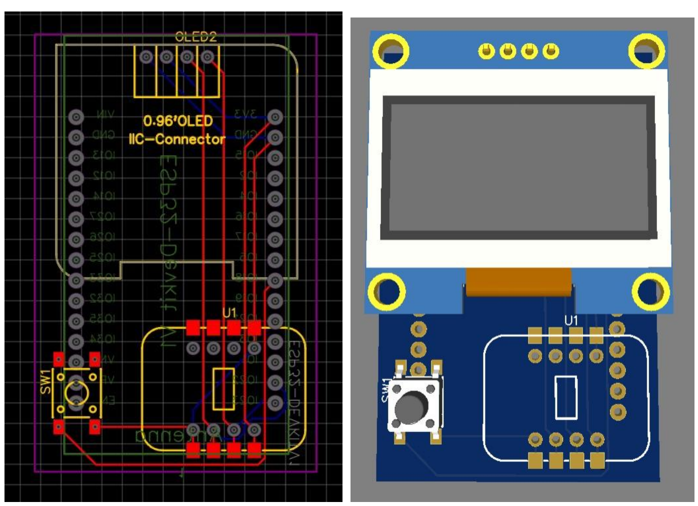
3.3. PCB Design of the Prototype

We used **EasyEDA** software to design a single layer version and a double layer version for the PCB for the prototype.

- **Single Layer PCB:** The single-layer PCB has all the components placed on one side of the board, resulting in a larger board area occupation.
- **Double Layer PCB:** On the other hand, the double-layer PCB features the ESP32 processor on one side and the MAX30102 sensor module and OLED display on the opposite side, making it a more space-efficient design.



Circuit Diagram for the PCB

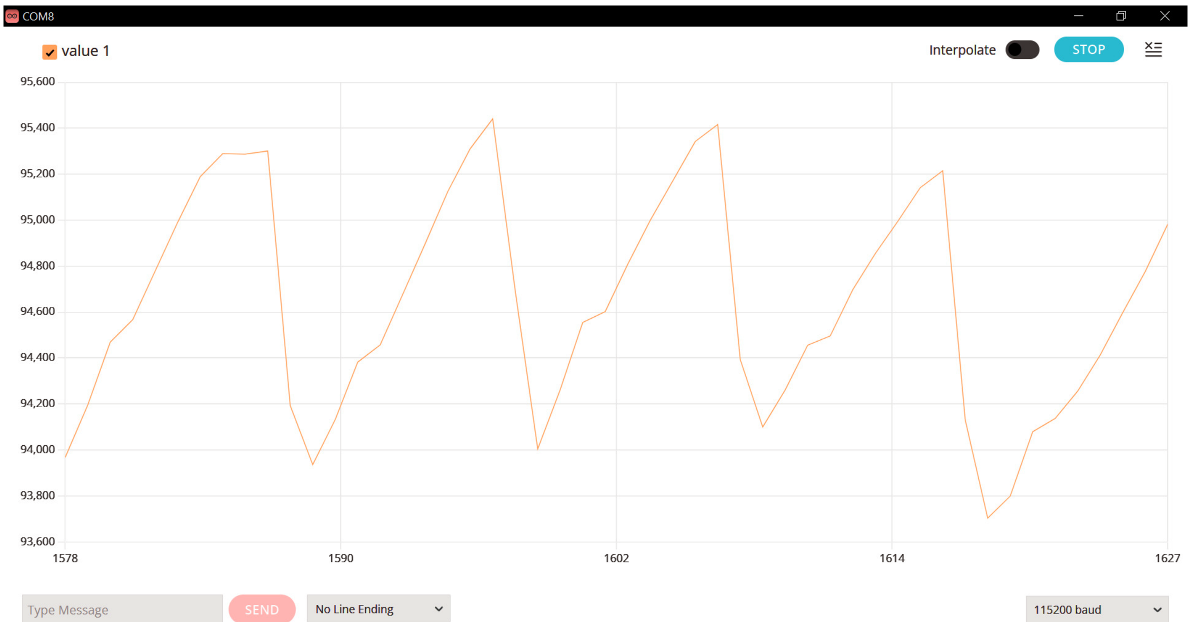


Schematic and 3D Visualisation of the PCB

3.4. Algorithm for Calculation of SpO_2 and BPM

3.4.1. IR V/S Time Graph

For a pulse, The IR readings vs. Time graph is as follows:



3.4.2. Maxim Algorithm [7]

The **MAX30102** sensor module[9] uses the **Maxim algorithm** to calculate the SpO_2 and BPM values from the raw photoplethysmography (PPG) data collected by the sensor. The Maxim algorithm is a proprietary signal processing algorithm developed by **Maxim Integrated**[10], which is designed to filter out the noise and extract meaningful information from the PPG signal.

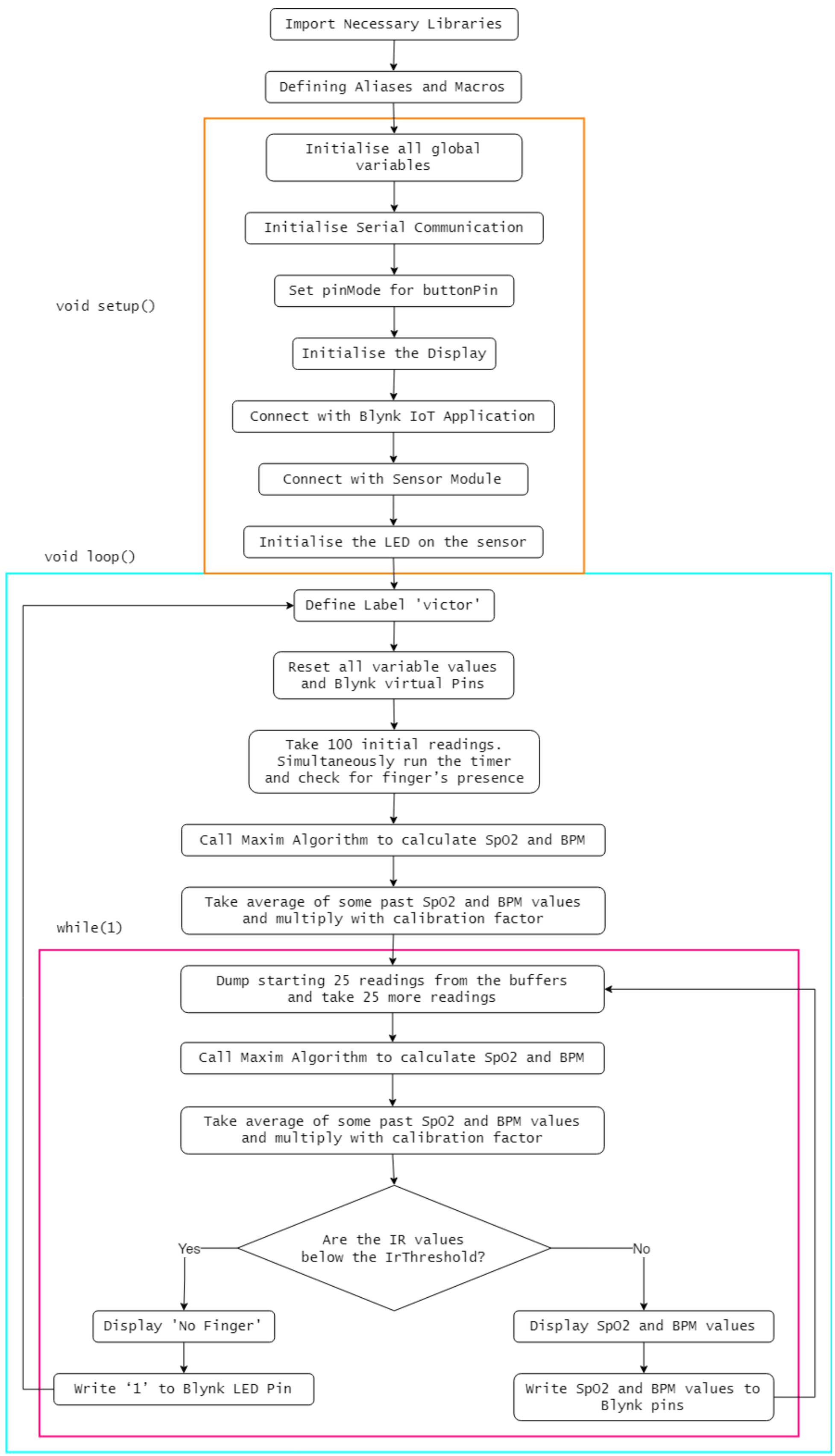
- **To calculate SpO_2:**
  - The Maxim algorithm first separates the red and infrared PPG signals, which are then passed through a series of digital filters to remove motion artefacts and other sources of noise.
  - The filtered signals are then analysed to determine the ratio of the red to infrared signal, which is used to calculate the SpO_2 value using an empirical calibration curve as mentioned in Section 3.4 Mathematical Calculations.

- **To calculate BPM:**
  - The Maxim algorithm first identifies the peaks in the PPG signal using a peak detection algorithm. The time intervals between these peaks are then calculated and used to derive the BPM value.
  - The Maxim algorithm also incorporates several other features, such as adaptive thresholding and baseline filtering, to improve the accuracy and reliability of the BPM calculation.

3.4.3. Program Flow

Since our program for the ESP32 expands over approximately 500 lines of code, we have included a link to the GitHub Repository for the code. The following is a flowchart describing the flow of the program.

Github: https://github.com/koderchit/B.TechProject/blob/main/SpO2andBPMcode.ino

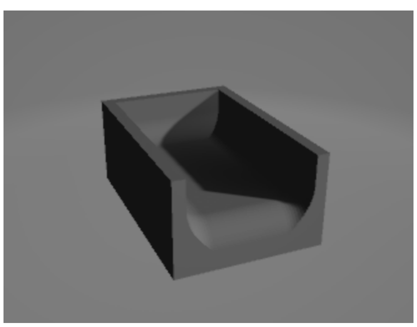
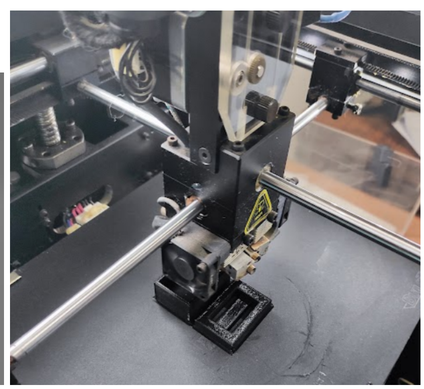
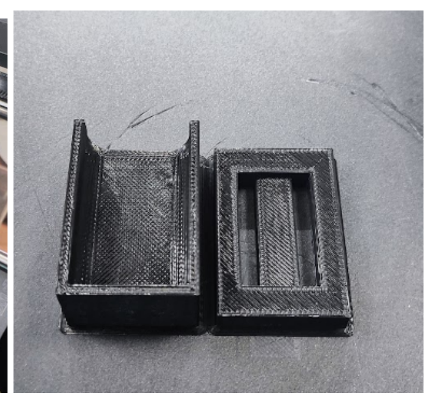

Import Necessary Libraries
Defining Aliases and Macros
void setup()
Initialise all global variables
Initialise Serial Communication
Set pinMode for buttonPin
Initialise the Display
Connect with Blynk IoT Application
Connect with Sensor Module
Initialise the LED on the sensor
void loop()
Define Label 'victor'
Reset all variable values and Blynk virtual Pins
Take 100 initial readings. Simultaneously run the timer and check for finger's presence
Call Maxim Algorithm to calculate SpO2 and BPM
Take average of some past SpO2 and BPM values and multiply with calibration factor
while(1)
Dump starting 25 readings from the buffers and take 25 more readings
Call Maxim Algorithm to calculate SpO2 and BPM
Take average of some past SpO2 and BPM values and multiply with calibration factor
Are the IR values below the IrThreshold?
Yes
No
Display 'No Finger'
Write '1' to Blynk LED Pin
Display SpO2 and BPM values
Write SpO2 and BPM values to Blynk pins

3.5. Design Challenges

3.5.1. Hardware-related Challenges

- **Motion Artefacts:** One of the most significant challenges faced when designing the prototype is the presence of motion artefacts. This occurs when the user's finger is not placed on the sensor module with constant pressure, causing fluctuations in the reflected IR and red light readings.
- **Ambient Light:** Additionally, ambient light can pass through the user's finger and affect the highly sensitive photodiode, leading to corrupted sensor readings.
- **Shorting / Insulation:** When the sensor is used without any insulation, the user's finger can sometimes short the ground and VDD pins of the sensor's pins.

These challenges were addressed by creating a casing for the sensor that provides constant pressure around the user's finger, blocks out ambient light, and insulates the sensor's circuitry from the user's finger. The casing is developed using Autodesk Fusion 360.

3D Print of the Casing

3.5.2. Software-related Challenges

- **Computational and Calibration Issues:** Taking multiple readings in one go, calculating and updating health parameters, sending this data to the display module, and transmitting it to the Blynk IoT device resulted in slight delays and errors in the calculation of the health parameters.

This challenge was addressed by implementing a running average of several past values to smooth over fluctuations and using a **calibration factor** to scale the readings obtained from the Maxim Algorithm according to a commercial Oximeter.

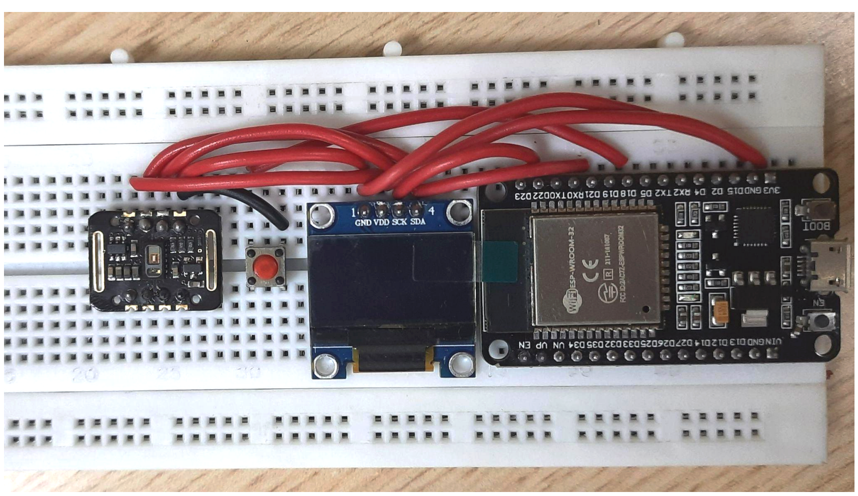
4. Inferences, Discussions, Conclusions

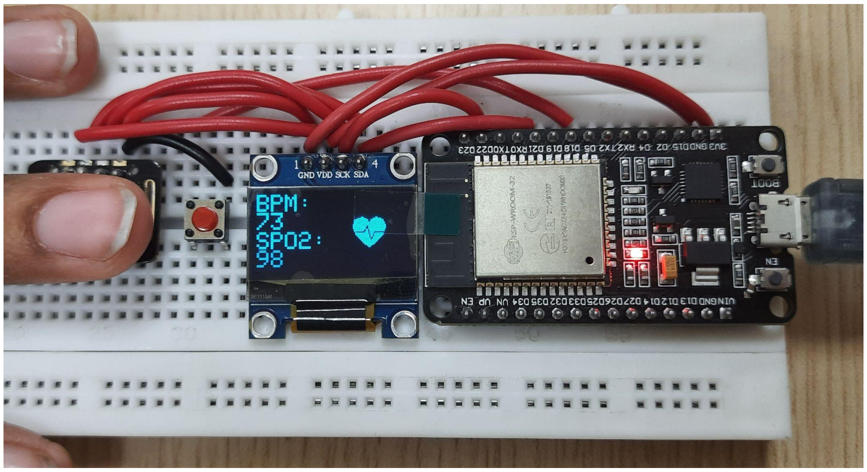
4.1. Results

The current Photoplethysmography Prototype has yielded successful results. The prototype provides accurate readings of SpO_2 with ±1 error and BPM with ±2 error, which are comparable to commercial oximeters. The prototype's readings enable users to monitor their vital health parameters effectively.

Moreover, the prototype's IoT capabilities enable **remote monitoring** of vital health parameters. The device is equipped with WiFi and Blynk connectivity, which allows users to monitor their health parameters on a remote device. This feature adds to the convenience of the device and allows users to monitor their health parameters more effectively.

4.2. Prototype Images



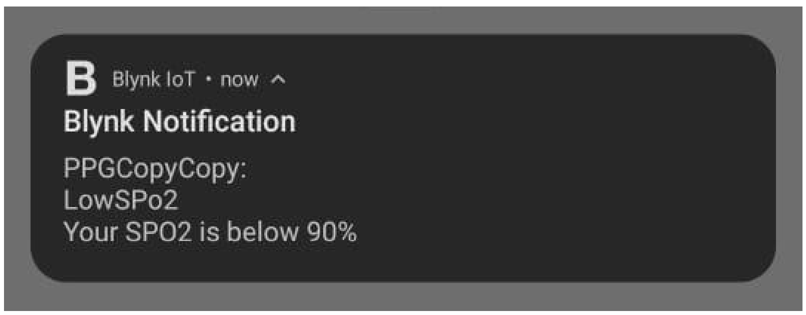


4.3. *Novelty*

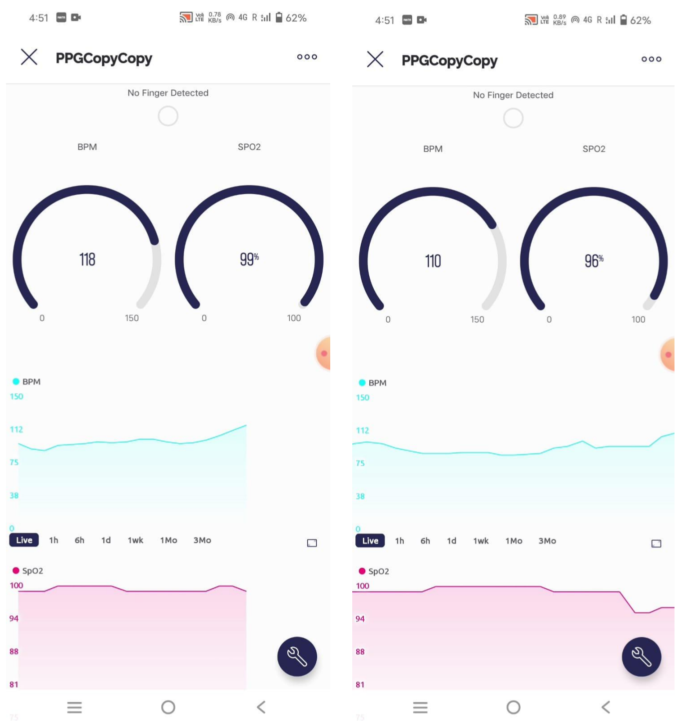
- **Real-Time Monitoring:** The device connects to a Blynk IoT application using an authorization code. It is then able to send SpO_2 and BPM values to the IoT application and update them each second, which allows real-time monitoring of the user's health parameters.

    - **Blynk** is an IoT platform that allows developers to build and manage IoT applications easily. The platform operates on a cloud-based server and provides a user-friendly interface and an app builder.

- **Push Notifications:** The Blynk platform allows developers to add events for their devices. In our case, the prototype's IoT application has an event that alerts the user when the SpO_2 value is below 90% using Push Notifications. The notification works in-app, as well as when the app is not open on the monitoring device. (The alert is rate-limited to log not more than once per minute.)



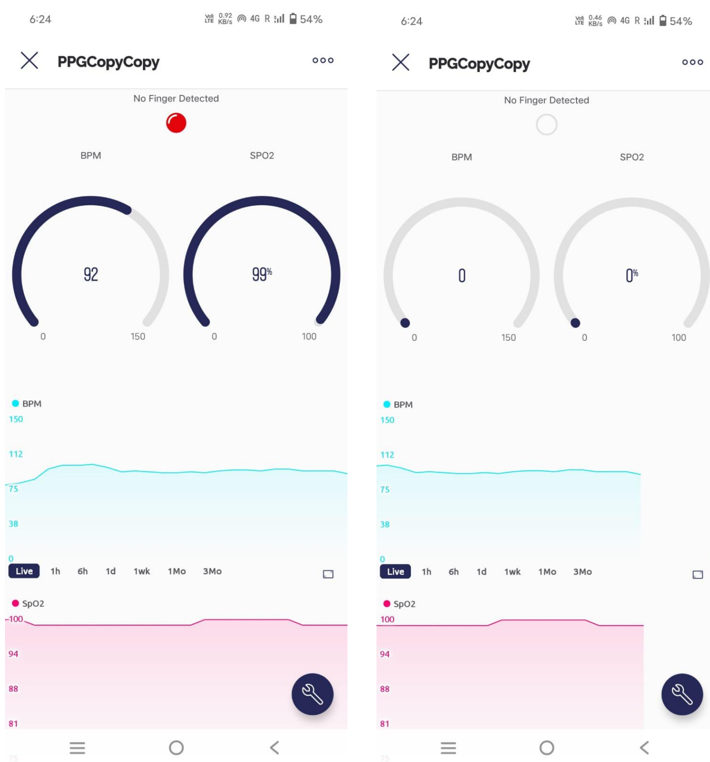
- **Graphing Feature:** Users can visualise their heart rate (BPM) and oxygen saturation (SpO2) data over time with various scaling options. These scales include live, 1 hour, 6 hours, 1 day, 1 week, 1 month, and 3 months, allowing users to monitor and analyse their health data more comprehensively. This feature provides valuable insights and a dynamic way to track vital statistics.
    - The live values are updated every second and can be viewed on the interface with the help of gauges and graphs.
    - The user can switch between different resolutions/time periods while the device is running as well.



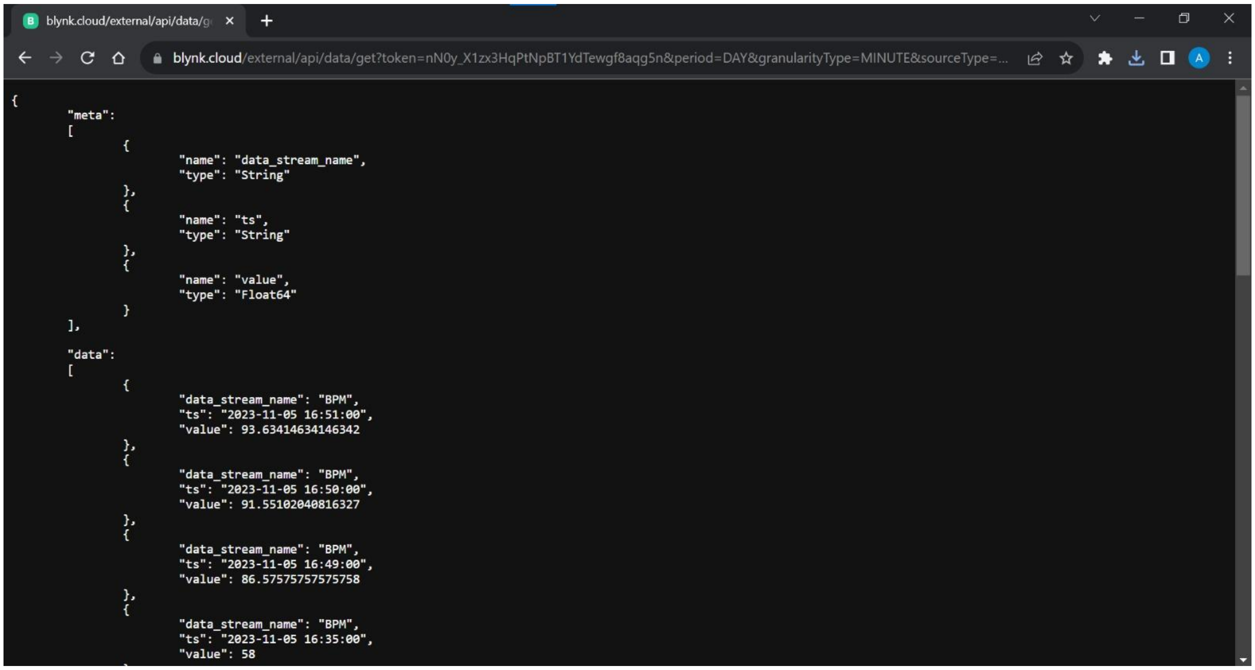
- **No Finger Detected:** The prototype can detect if a finger isn't placed on the sensor module. It does so by comparing the IR values with a threshold defined in the code. If no finger is detected, it resets all the variables used in the algorithm and prompts the user to place their finger on the sensor and start taking the readings again.

  The device features two distinct modes, with adjustable time constants to accommodate different usage scenarios:

  - **Temporary Pause Mode:** When the user briefly removes their finger from the device, the readings will temporarily freeze. Upon placing the finger back on the device, the readings will resume from where they left off.
  - **Reset Mode:** If the user removes their finger for an extended period, currently set to 5 seconds, the device will automatically reset to its initial landing screen. This time constant can be varied according to the use case. To resume using the device, the user must press the start button again.



- **Scalability:** The same IoT application can be logged into by multiple devices (i.e., Phones or Web Browsers), allowing multiple users to monitor the device at the same time.
- **API Call and Data Extraction using Python script:** The IoT component includes the capability to make API calls[14] and extract valuable information in JSON format. A Python script has been introduced to facilitate this process, enabling users to make API calls and retrieve essential data. The extracted data is then conveniently converted into a CSV file format, making it easier for users to further analyse and work with the information for their specific needs. This feature enhances the versatility and accessibility of the collected health data.
    - **Python Script code:** https://github.com/koderchit/B.TechProject/blob/main/APIDataExtractor.py
    - **Note:** For a free tier account in Blynk, the API calls for historical data can only be made upto 10 times a day.



Screenshot of API call JSON response

	A	B	C	D	E	F	G	H	I	J
1	DATE	TIME	BPM	SPO2						
2										
3	10-10-2023	21:23:00	85.5208	99.5417						
4										
5	10-10-2023	21:24:00	88.5833	99.7292						
6										
7	10-10-2023	21:25:00	90.3878	99.5102						
8										
9	10-10-2023	21:26:00	87.6458	99.6042						
10										
11	10-10-2023	21:27:00	88.5833	99.625						
12										
13	10-10-2023	21:28:00	90.3673	99.6327						
14										
15	10-10-2023	21:29:00	89.0625	99.5208						
16										
17	10-10-2023	21:30:00	91.1224	99.7143						
18										
19	10-10-2023	21:31:00	91.75	98.6458						
20										
21	10-10-2023	21:32:00	87.9792	99.4167						

Screenshot of the CSV generated by the python script

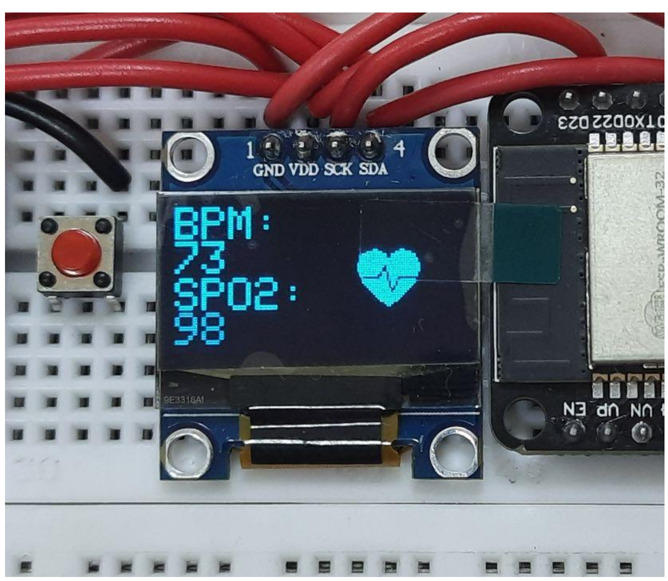
- **Reduced Initial Reading Time:** Over the course of the project duration, significant progress has been made in optimising the device's performance. The initial reading time, which previously took 15 seconds, has been drastically reduced to just 6 seconds. This improvement enhances user efficiency by providing quicker access to essential data and information, making the device more responsive and user-friendly.

- **Security:**
  - **Blynk** relies on industry-standard security protocols, including the Transport Layer Security (TLS) protocol. The platform's server system tries to use the latest available TLS protocol version, TLSv1.3, to ensure secure communication.
  - Each device in Blynk has its **unique OAuth token** and Product Id, and a combination of both fields grants access only to authorised users within an organisation. The platform constantly monitors its system to respond quickly to any possible incidents.

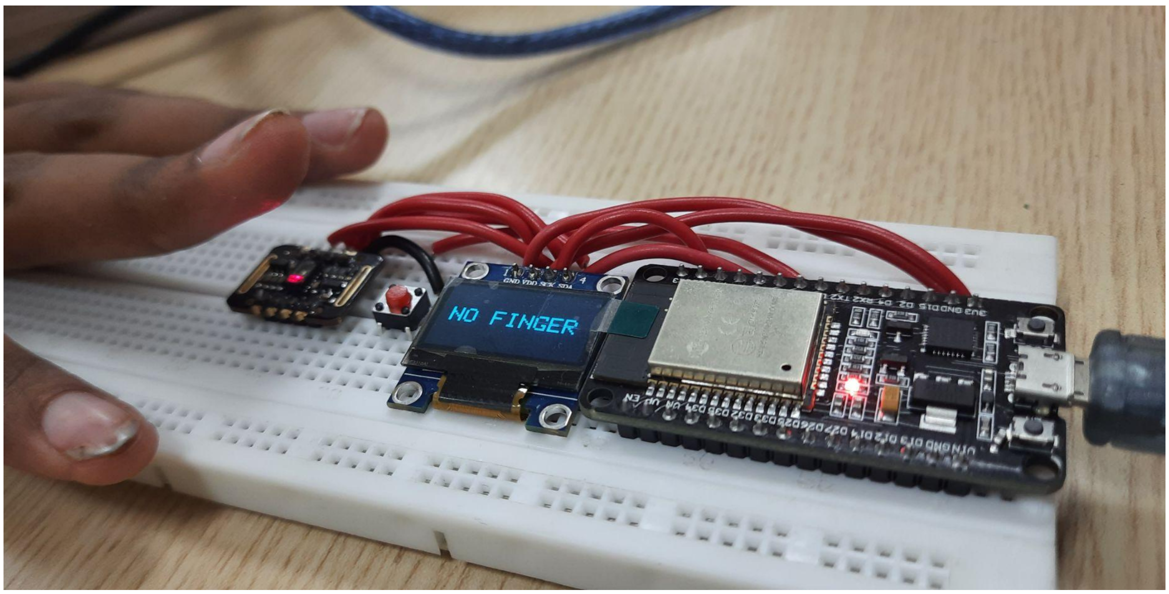
4.4. Prototype's Current Features

- **BPM and SpO_2 values:**

  Our Photoplethysmography Prototype has been designed to provide accurate readings of SpO_2 with ±1 error and BPM with ±2 error as compared to a commercially available Oximeter. These levels of accuracy make the device an effective tool for monitoring vital health parameters. The device enables users to monitor their health parameters accurately and make informed decisions regarding their health.



- **Cost-Effective:** Users can achieve the same level of accuracy and reliability at a fraction of the cost of a commercial oximeter. This feature makes the prototype a cost-effective alternative to commercially available devices, making it accessible to a broader audience.
- **No Finger Detection:** The IoT application also displays when the user's finger is not placed over the sensor, and all value gauges are reset in such a case. It has been described at length in ***Section 5.3.***



No Finger Detected Displays

- **IoT Connectivity with Blynk:**

  The following features have been described at length in ***Section 5.3.***
  - **Real-Time Monitoring:** ESP32 transmits the BPM and SpO_2 readings each second to an IoT application hosted on the Blynk IoT Platform, allowing for remote monitoring of health parameters.
  - **Real-Time Graph:** Integrated heart rate (BPM) and oxygen saturation (SpO2) visualisation graphs with adjustable scaling options for users.
    - **Scales Available:** Live, 1 hour, 6 hours, 1 day, 1 week, 1 month, 3 months

    - **Real-Time Alerts:** The IoT application is designed to send push notifications to the devices in which it is logged on whenever the SpO_2 readings from the Prototype are less than 90%.
    - **Scalability:** The IoT application can be logged into multiple devices, allowing multiple users to monitor the health parameters at the same time.
- **User Interface:**
  The prototype has an OLED Display module that displays the following screens:
    - **Project Title:** Displays our Supervisor's name and the health parameters that we are going to provide the user (SpO_2 and BPM).
    - **Blynk:** Displays while the prototype is connecting to the IoT Application
    - **Sensor Initialisation:** Displays while ESP32 finds the MAX30102 Sensor Module
        - **Success:** Displays if the sensor is found
        - **Error:** Displays if the sensor isn't found and asks the user to check the wiring
    - **Ready:** Asks the user to place their finger on the sensor, and start taking readings
    - **Timer:** Displays a timer that plays while the sensor takes initial readings and the processor's final outputs stabilise
    - **Readings:** Displays the values of BPM and SpO_2 and a heart animation
    - **No Finger:** Displays when the prototype detects the absence of a finger on the sensor.

4.5. Conclusion

In conclusion, this project was aimed at developing a Photoplethysmography Prototype that utilises various sensors and IoT for continuous and non-invasive measurement of vital health parameters. We first discussed the historical development of Photoplethysmography techniques from the 1930s to the 1980s, highlighting the advancements in technology. The working principle of PPG was also discussed, along with the Mathematical Calculations required for calculating SpO_2 readings, and some of the practical limitations of existing PPG techniques and the circuit components required in commercial oximeters were described.

Moving on to our own prototype, we list the components used, and the circuit connection, the PCB design, and the algorithm used for the calculation of SpO_2 and BPM were explained in detail. The challenges faced by us and our solutions to them, along with the results obtained from the prototype, are then mentioned. The novelty of the design with IoT connection and remote monitoring was highlighted, along with the prototype's current features.

Overall, this project aims to contribute to the development of a non-invasive health monitoring device which provides a means for remote monitoring, allowing healthcare professionals to keep track of patients' vital health parameters (SpO_2) in real-time.

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