English

During the COVID-19 wave in India, I saw a lot of people buying oximeters from medical stores and online to monitor oxygen levels at home. I was quite intrigued, how can a small device plugged to a finger could calculate heart rate and oxygen saturation? This question got me started to research and understand how these things actually work and whether I can make one from scratch. In the process I realized, it would be helpful to write all details in an understanding document which will serve as a memory to me and can be of help to others too. Also, I wanted to start learning LaTeX so as to create beautiful written documents for all future projects.

This writing tries to present a brief theory of what oximetery is, how electronic components can be used to get the oxygen saturation value and heart rate. Required circuit block elements and algorithms have also been discussed. It has been assumed that reader has knowledge of:

- Basic circuit analysis & electronic components
- Opamp & transistor working

I am a beginner in my electronics journey, hence there can be mistakes in this article. The accuracy of information presented has not been inspected by any other person than myself. This guide was written so that it can become a source of knowledge to anyone trying to understand how to make an oximeter or how oximeter works. Presented design is not be used in any life support systems.

This document was written in TexStudio editor.

All pictures have been produced with Inkscape.

Plots were generated in GNU Octave.

PCB & Schematics designed using Kicad.

Enclosure was designed in FreeCAD.

All project related files are at: `https://github.com/yskab/dhadak`

Video series: `https://youtu.be/QoOAn5z_qHc`

For reporting any mistakes or corrections raise an issue on Github.

You can reach me on Twitter for posts and messages @yskabhijeet

Y S K Abhijeet

October 12, 2021

Contents

1 Introduction

Oximetry is the process of measuring the concentration of oxygen in blood (oxygen saturation - SpO_2). Normal levels of SpO_2 should usually be around 95% to 100%, level below 90% could lead to Hypoxemia which can cause shortness of breath and headache[1].

1.1 Cardiac Cycle

Red blood cells contain Hemoglobin, a protein which when comes in contact with fresh oxygen via lungs forms Oxygenated Hemoglobin (HbO_2). This Oxygenated blood is carried from the lungs to left side of the heart, which pumps this blood around the body through arteries. The cells of the body convert the chemical energy from oxygen molecules in red blood cells into Adenosine Triphosphate (ATP). ATP is stored in the cell and can be used for organism's life support system as required. Absence of oxygen in red blood cells due to conversion into ATP forms Deoxygenated Hemoglobin (Hb).

This deoxygenated blood returns through the veins to right side of the heart, from there the blood is pumped into lungs to expel carbon dioxide and again fresh oxygen is inhaled and blood gets oxygenated. This completes a single Cardiac Cycle.

1.2 Oximetry Principle

Pulse Oximeter is based on PPG (Photoplethysmography) wherein a light source is projected and a detector is used to measure volumetric changes in blood. It has been observed that Hb has a higher absorption when red wavelength is passed through while HbO_2 has a higher absorption towards infrared wavelength source (Figure 1). If we can relate the detected output with concentration of Hb/HbO_2 in blood, a relation can be obtained to calculate SpO_2.

Heart pumps blood with each cardiac cycle and this leads to change in blood volume in the artery. When light is passed through (finger, earlobe, wrist[1] depending on it's wavelength, Hb/HbO_2 components will also get absorbed and PPG signal is obtained as an output. Signal peaks correspond to completion of a cardiac cycle (heart

---

[1] https://www.mayoclinic.org/symptoms/hypoxemia/basics/definition/sym-20050930
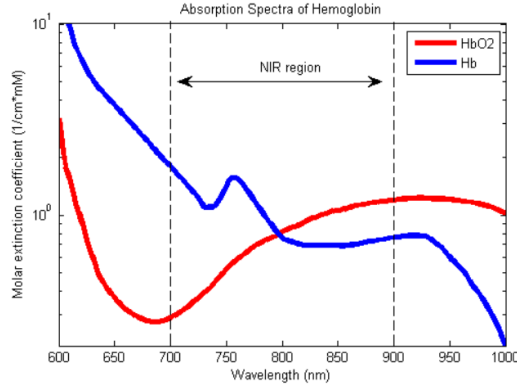
Figure 1: Absorption Spectra - Hb/HbO$_2$
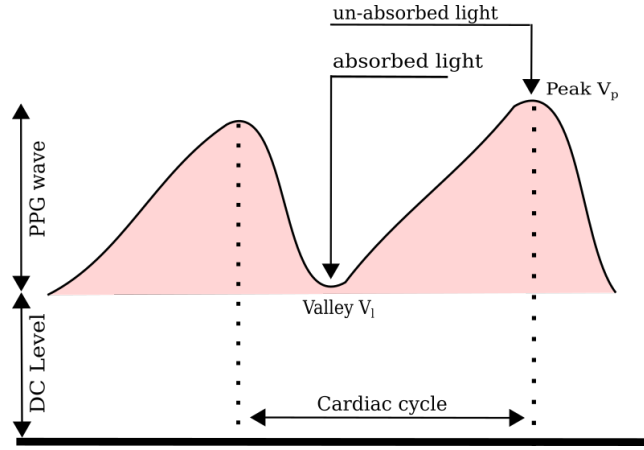
Figure 2: PPG waveform when a single light source is projected

beat). This varying signal also has a DC level due to absorption of light source by skin, venous blood and tissue.

From this understanding, if we can find molecular concentrations of Hb and HbO$_2$ in a defined blood volume, SpO$_2$ can be calculated as a ratio of oxygenated blood concentration to total concentration:

$$SpO_2 = \frac{HbO_2}{Hb + HbO_2} \tag{1}$$

According to Beer-Lambert law:

$$\log_{10} \frac{I}{I_o} = \epsilon l c \tag{2}$$

2

$I-$ Transmitted light intensity

I_o- Incident light intensity

$l-$ length

$c-$ Molecular concentration

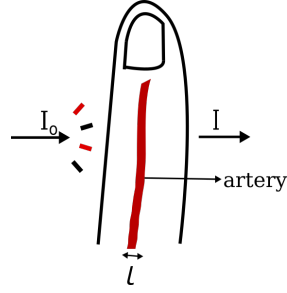$\epsilon-$ Molar absorption coefficient

Figure 3: Light source projected onto a finger

As seen in Figure 3, a light source is projected onto a finger and transmitted light is detected on the other end. Infrared and Red light is pulsed individually. For infrared source:

$$c_1 = \frac{\log_{10} \frac{I_1}{I_{o1}}}{\epsilon_1 l}$$

Since HbO_2 has higher absorption for infrared wavelength,

$$HbO_2 = \frac{\log_{10} \frac{I_1}{I_{o1}}}{\epsilon_1 l}$$

Similarly for red,

$$Hb = \frac{\log_{10} \frac{I_2}{I_{o2}}}{\epsilon_2 l}$$

According to (1),

$$SpO_2 = \frac{\frac{\log_{10} \frac{I_1}{I_{o1}}}{\epsilon_1 l}}{\frac{\log_{10} \frac{I_2}{I_{o2}}}{\epsilon_2 l} + \frac{\log_{10} \frac{I_1}{I_{o1}}}{\epsilon_1 l}}$$

if $R = \frac{\log_{10} \frac{I_2}{I_{o2}}}{\log_{10} \frac{I_1}{I_{o1}}}$,

3

$$SpO_2 = \frac{\frac{1}{\epsilon_1}}{\frac{R}{\epsilon_2} + \frac{1}{\epsilon_1}}$$

$$SpO_2 = \frac{\epsilon_2}{R\epsilon_1 + \epsilon_2} \tag{3}$$

SpO_2 mostly depends on R, we can consider calculating R and later comparing with a calibrated reference to get the actual SpO_2.

Since Incident light intensity level would be constant while pulsed, R would depend only upon I_1 and I_2,

$$R \approx \frac{\log_{10} I_2}{\log_{10} I_1} \approx \frac{I_2}{I_1} \approx \frac{AC_2}{AC_1}$$

We need not calculate the logarithm, as the actual SpO_2 would be obtained from a Look up table or an empirical equation which demonstrates relation of R to SpO_2. Standard oximeter manufacturers would test their device on large group of subjects and obtain the R values and subject's actual SpO_2 using a separate calibrated meter to prepare a relationship curve. Once this mapping is obtained, SpO_2 for any subject can be calculated using the relationship.

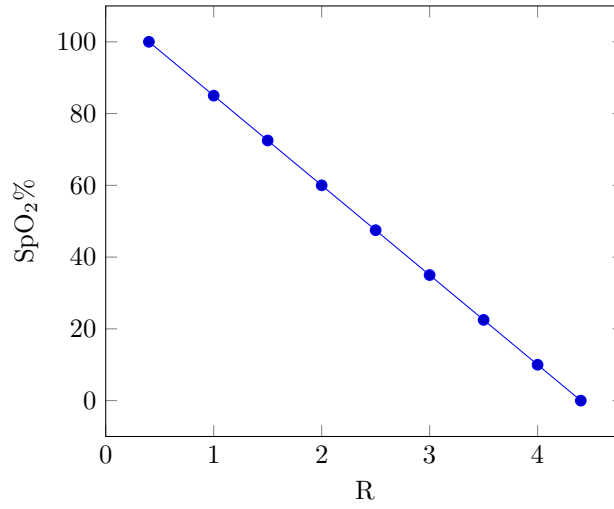Figure 4: A typical relationship curve R vs SpO_2

Since detected IR and Red signals can have varying DC levels, we need to normalize the ratio first by dividing the DC levels so that a direct comparison of the PPG (AC component) can be performed

as that caries the absorbed/un-absorbed information, hence R now becomes:

$$R = \frac{AC_2}{DC_2}/\frac{AC_1}{DC_1}$$
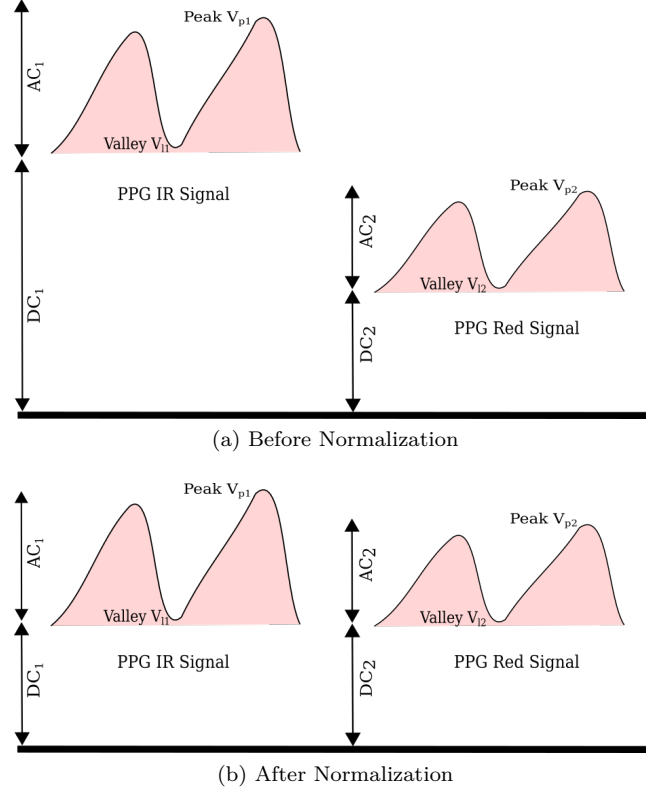

(a) Before Normalization

(b) After Normalization

Figure 5: Effect of Normalization

$$R = \frac{V_{p2} - V_{l2}}{DC_2}/\frac{V_{p1} - V_{l1}}{DC_1} \tag{4}$$

As shown in Figure 5,

$V_{p1}-$ Ir Peak

$V_{l1}-$ Ir Valley

$V_{p2}-$ Red Peak

$V_{l2}-$ Red Valley

DC_1- Ir DC level

DC_2- Red DC level

This value of R when compared with relationship curve would give the actual SpO_2.

We can consider calculating R for a set of samples and average them, instead of waiting for peaks and valleys to arrive. In this implementation, R is calculated between neighboring samples and a weighted average[9] is calculated for final value. This is discussed further in SpO_2 calculation algorithm section.

2 Main System Components

2.1 Photodiode

Photodiode will be used as a detector in a reflective configuration, wherein light is projected from one end using LEDs and photodiode is detecting light at the opposite end converting it to current. This current would be proportional to LEDs brightness.
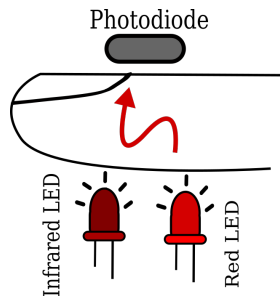

Figure 6: Reflective finger setup

Photodiode needs to be sensitive in both red (700nm) and infrared (900nm) regions. QSB34CGR was used in this design which can work in both regions as seen in the sensitivity graph from part's datasheet.
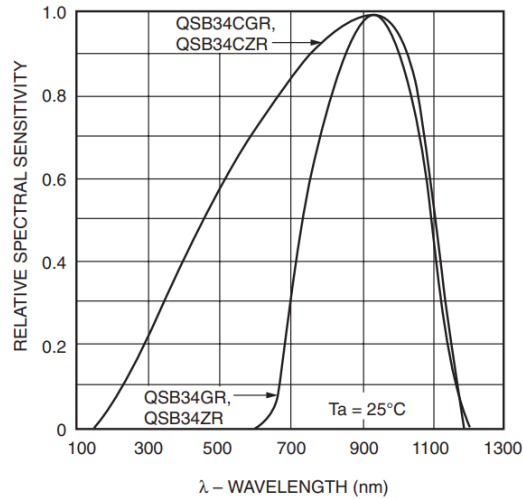

Figure 7: QSB34CGR sensitivity spectrum

7

2.2 Microcontroller

Microcontroller(μC) is responsible for the algorithm in calculating the SpO$_2$ by reading the red and ir amplified channels via ADC. Also it performs the following tasks:

- Interfaces with an OLED 128x64 display to show the calculated SpO$_2$ and heart beat.

- Interfaces with DACs.

Atmega4808 is used in this design.

2.3 Dual DAC

Dual digital to analog converter - MCP47FEB02A0 was used in design.

- DAC1 is required in LED driver stage so that μC can instruct the DAC to generate a required control voltage to set led current.

- DAC2 provides an input to the difference amplifier stage for DC removal from signals.

2.4 Leds

It is important to select good leds for illumination, following factors ensure good signal response:

- Narrow view angle for less dispersion and deeper penetration into skin.

- Rectangular package in clear lens so that finger can rest comfortably.

- High radiant power.

I didn't get new leds and worked with generic 3mm/5mm ir led in circular clear package and a red led in diffused package. This caused the R ratio to not be correct. As a healthy individual, i was getting readings of R to be around 0.6 while it should be around 0.4. So I had to use a scaling factor to adjust the algorithm. A comment has been added in the program code regarding this.

A suitable choice can be Vishay Semiconductor's VSMD66694.
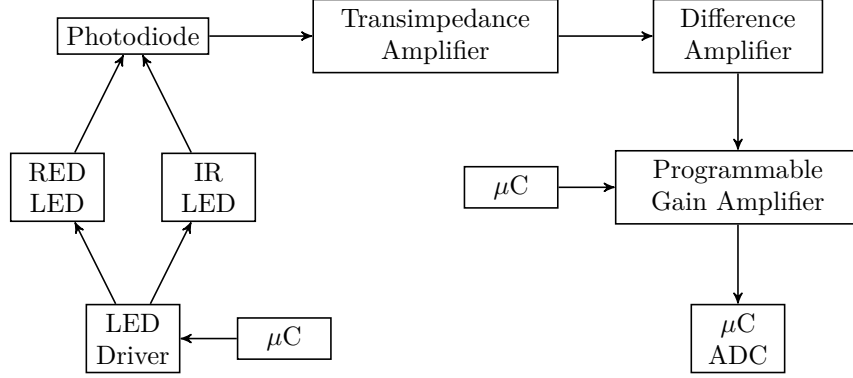
3   Circuit Design

Figure 8: System Block Diagram

Referring the Block diagram, subsections are divided below that show the circuit and corresponding oscilloscope trace outputs.

3.1   Front End

3.1.1   Transimpedance Stage

Photodiode's current is needed to be converted to a proportional voltage so that ultimately the microcontoller can convert the voltage to a digital value using an ADC for calculation of SpO_2. A simple Transimpedance Amplifier configuration was used to achieve this:
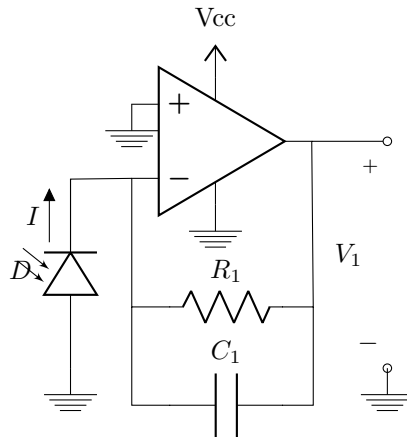
As per led's intensity, if a current of $10\mu A$ is produced in the photodiode, and R = 100KΩ, according to Ohm's law, $V_1 = 1$ V. Capacitor

9

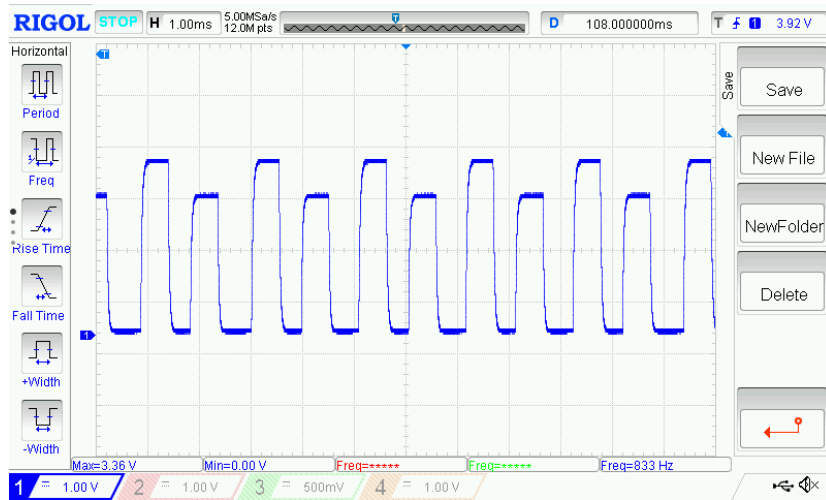is used for low-pass filtering of the pulse. Cut off frequency would be:

$$F_c = \frac{1}{2\pi R_1 C_1} \tag{5}$$

If R_1=576KΩ, $C_1 = 33$pF,

$$F_c \approx 8.3\,\text{kHz}$$
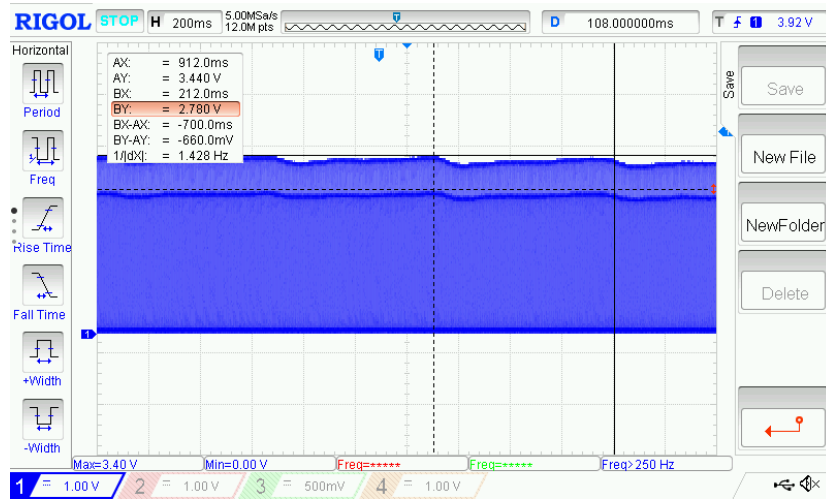
(a) V_1

(b) V_1 zoomed in

Figure 9: V_1 Oscilloscope trace (Red & IR pulsed sequentially)

Since LEDs are pulse on-off at a fast rate sequentially the pulse would look like a square wave. We need to use a pulse frequency less than $1/10^{\text{th}}$ of this cut-off to pulse the LEDs so that the square wave with all its high-frequency components is clearly visible and not filtered out.

$$F_p = 500\,\text{Hz}$$

It can be seen in traces, 2 PPG signals are observable, riding on a DC level. Higher amplitude one is a result of ir led pulsing, while lower amplitude is from red led. Since the peaks correspond to heart rate, in this case as per trace, it measures out to be 1.42/sec or 85BPM. Individual pulses which construct the signal can be seen in Figure 9b. Amplitude of detected red signal is lower than ir and that is due to:

- Higher intensity of ir led due to higher ir current.

- Photodiode's red sensitivity is 80% of ir sensitivity.

- Ir penetrates into skin deeper than red, hence a better ir response is visible at photodiode[2].

Hence to obtain a suitable response, it is important to increase led intensity until it reaches a required level so that the PPG signal has a higher amplitude.

3.1.2 Difference Amplifier

PPG signal needs to be amplified to a suitable level so that full scale ADC range can be utilized to better digitize the signal. Right now, amplitude of PPG signal is quite low and DC level is higher. We are not bothered by the DC anymore, μC can read it and store for R value calculation, we only need to amplify the AC part which is an envelope of the signal. Direct amplification would lead to gain of the DC level as well, as the required signal is riding on top of it. This will saturate the opamp and amplification level range will be quite low.

If we can subtract the DC level from entire signal, only AC would remain which can be easily amplified further at higher levels. A Difference amplifier along with a 8bit Digital to analog converter (DAC) generating the DC cancellation signal can be used here. Since red and ir have different levels, separate DC levels are generated by DAC in sync with the pulsed frequency.
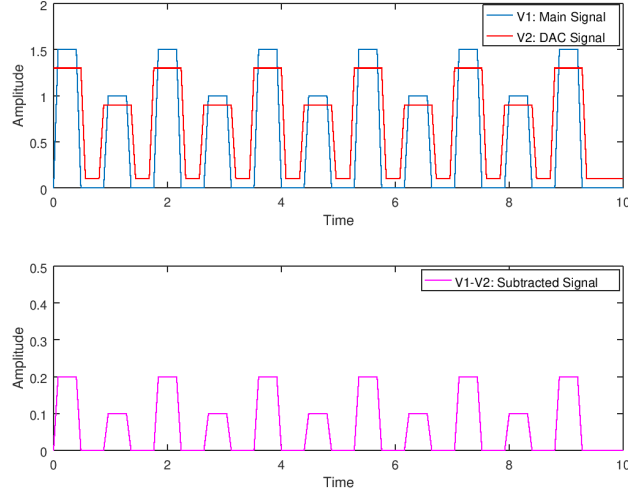
Figure 10: Effect of Difference Amplifier

As shown in Figure 10 a plot generated in Octave demonstrates subtraction of required signal and diff signal. This difference can then be amplified further. Pulse width of diff signal is slightly larger than required signal so that there are no spikes on edges in output signal. Also the lower level of diff signal is slightly above 0V to allow the difference to always be negative in low states and since negative supply is grounded, output would be 0V here.
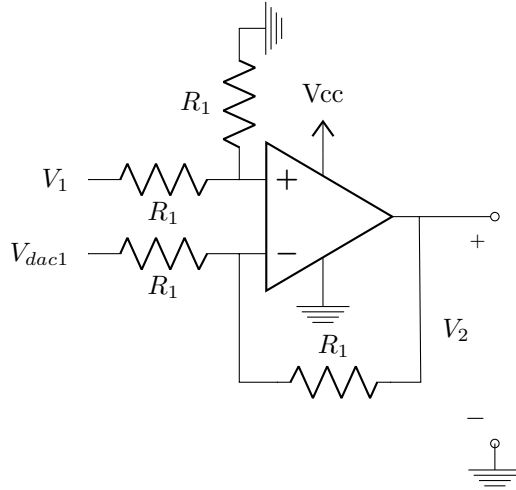
$$V_2 = \frac{R_1}{R_1}(V_1 - V_{dac1})$$

For $R_1 = 10K$,

$$V_2 \approx V_1 - V_{dac1}$$

3.1.3   Programmable Gain Amplifier

It becomes necessary to amplify the signal as skin tone, improper finger contact with sensor or any skin pigmentation[3] can cause attenuation in signal leading to low amplitudes. This stage provides selectable variable gain which can be set by microcontroller.

μC would determine what level of further amplification is required and drive the respective pin high so that resistor value would get selected.
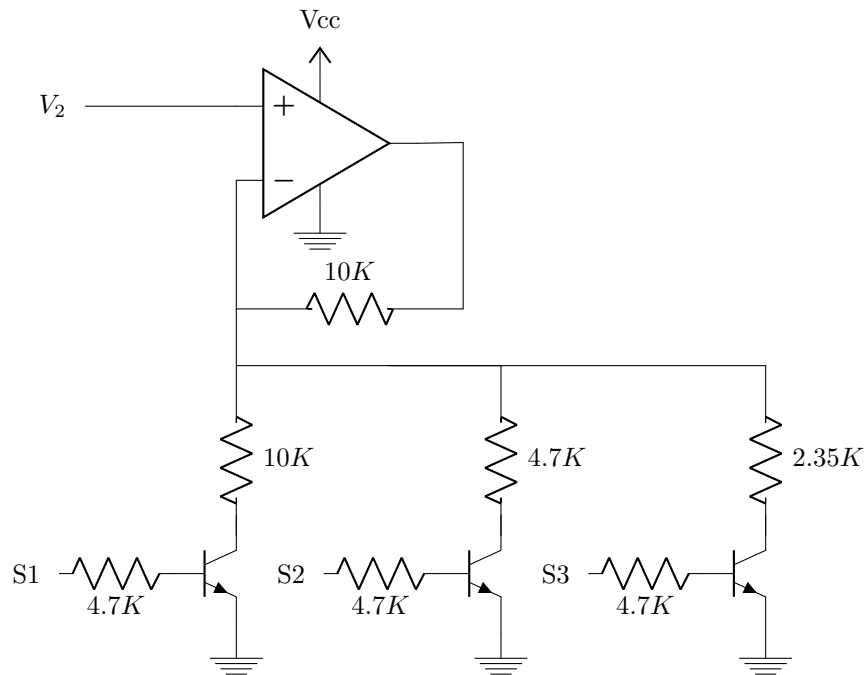
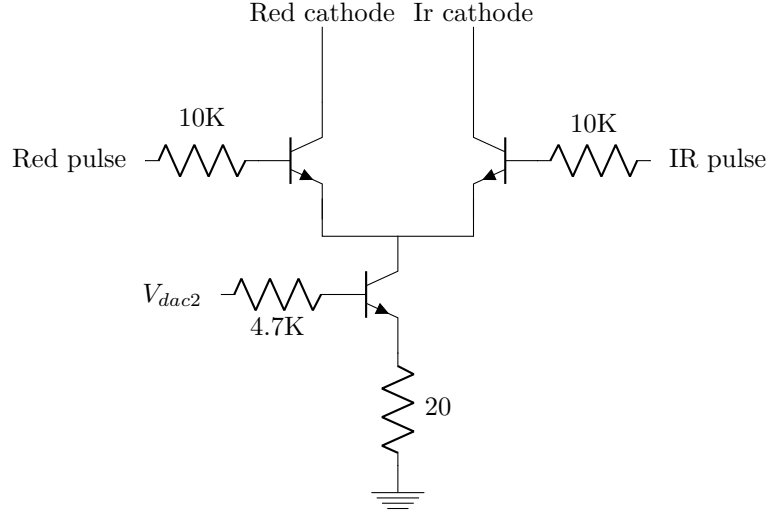
| Switch	Gain
all off	1
S1	2
S2	3
S1+S2	4
S3	5
S1+S3	6
S2+S3	7

3.2 LED Driver

As discussed previously, the detected signal levels can be very low after I to V stage. LED Driver needs to increase current to the leds as required. Following circuit is used as a voltage controlled current source, voltage is set by the DAC as instructed by the μC.


Leds get activated by a single bridge configuration, whenever red/ir pulse is active, corresponding red/ir leds get active (led anodes connected to Vcc). Amount of current would depend on V_{dac2} & R_1.

V_{dac2} is also set individually for red and ir as per the pulsed frequency. If intensity is not sufficient for signal detection, it is necessary to increase V_{dac2}. μC would determine the thresholds and modulate the control voltage accordingly.

Shown below is final output after the PGA stage. The gained up PPG signal is clearly visible for both red and ir which is at a suitable level for ADC capture and usage in algorithms for calculations.
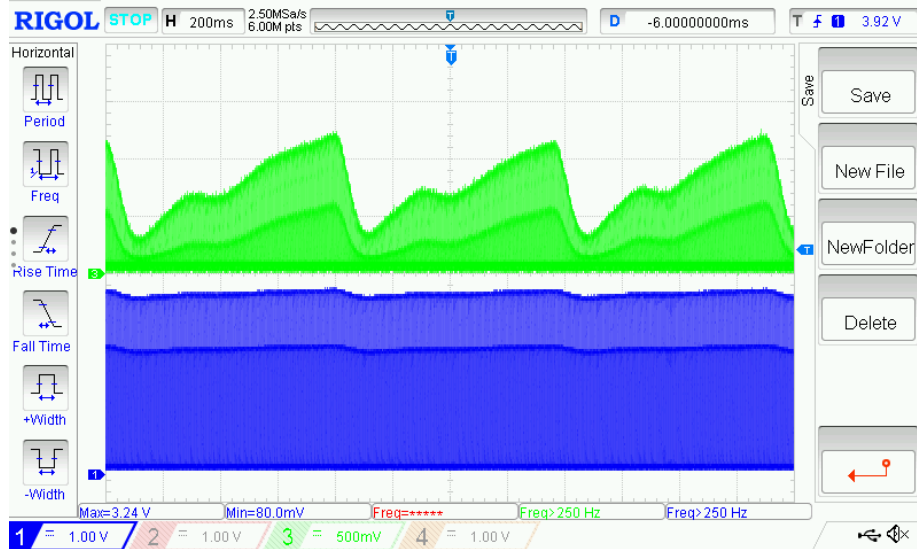
(a) Final output - green, V_1 - blue
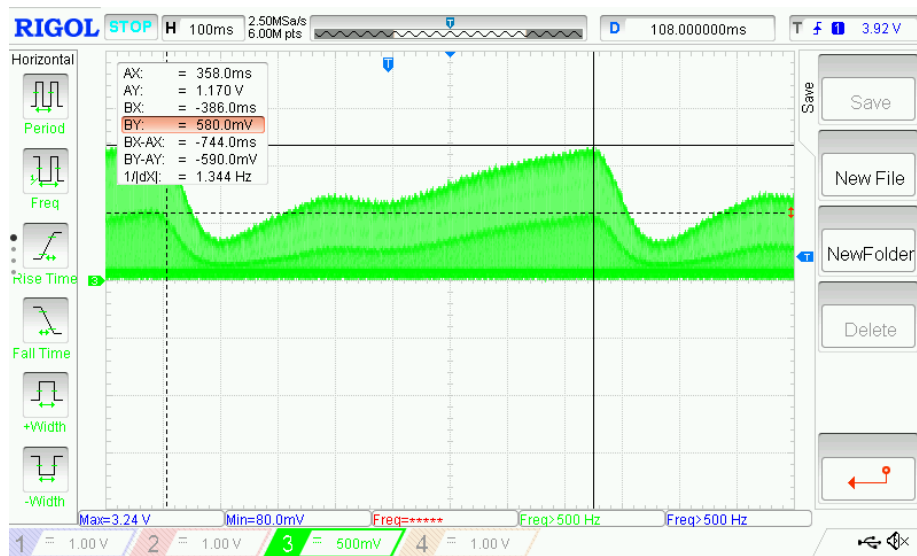
(b) Final output measurement

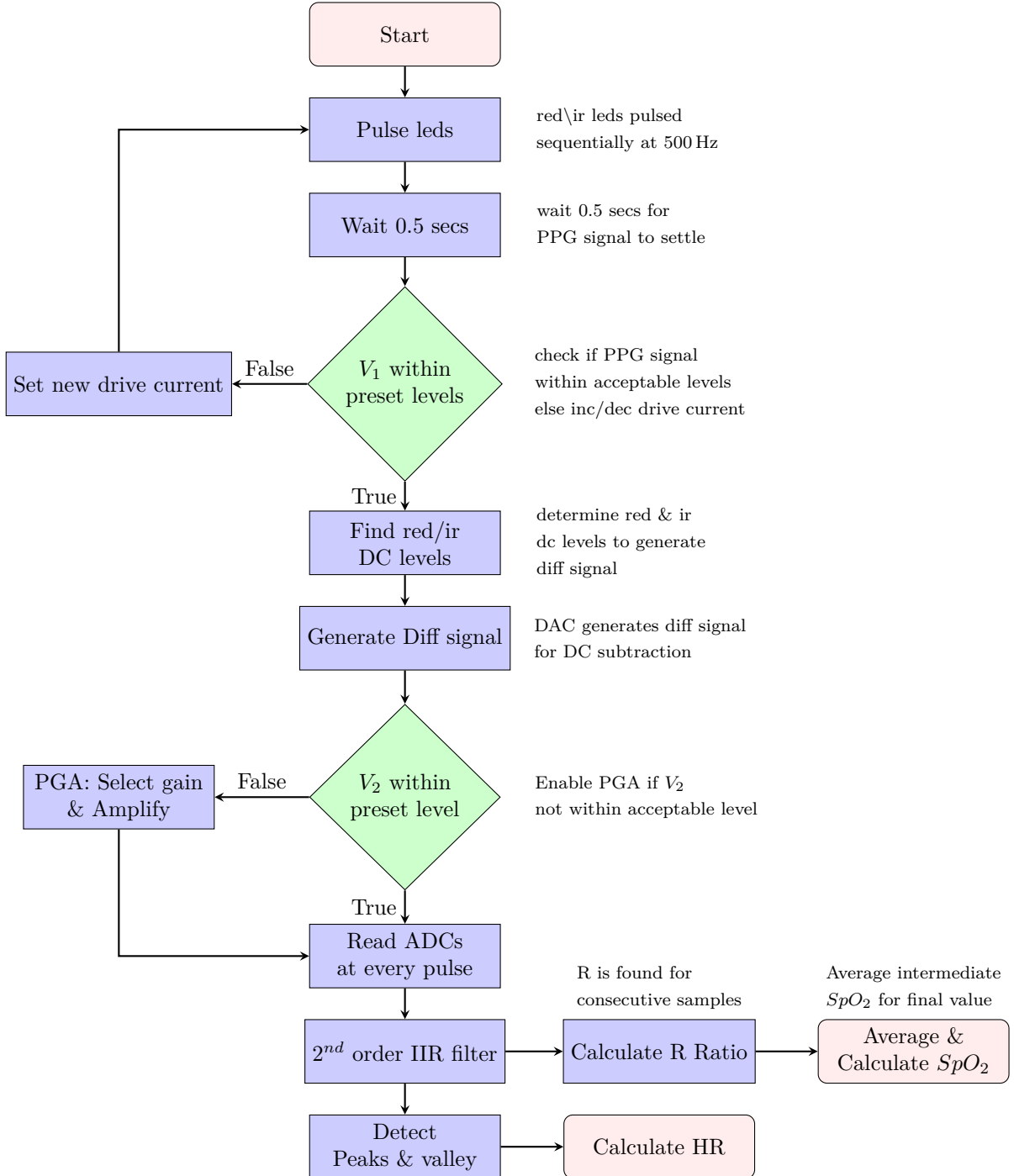Figure 11: Final output

15

4 Algorithm

Figure 12: Program Flow

4.1 IIR Filter

ADC read samples can have little noise spikes which if passed directly to peak-valley detect function will lead to a lot of false detection and every peak-valley will not be captured accurately. A 2nd order IIR filter is sufficient to smooth out the spikes before starting with estimations. Below is a 2nd order IIR transfer function as difference equation:

$$y_i = b_1 * x_i + b_2 * x_{i-2} - a_2 * y_{i-1} + b_3 * x_{i-1} - a_3 * y_{i-2}$$

where,

y_i: current output

x_{i-1}: previous input

y_{i-1}: previous output

y_{i-2}: output previous to y_{i-1}

x_i: current input
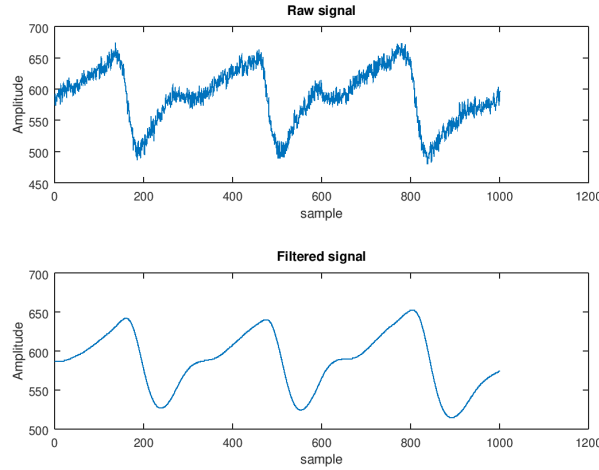
x_{i-2}: input previous to x_{i-1}

Figure 13: 2nd order butterworth IIR filter

Octave's *butter* function[2] was used to get the transfer function coefficients for a low pass configuration. Sampling frequency of 500Hz and a cut-off 3.3Hz (for max HR of 200) was used. Calculated below are the coefficient values:

---

[2]https://octave.sourceforge.io/signal/function/butter.html

$a_2 = -1.94137, a_3 = 0.94304$

$b_1 = b_3 = 4.1762e - 04$

$b_2 = 8.3523e - 04$

To visualize filter's performance, a raw signal was captured from ADC, filter equation was implemented and applied on the input signal in Octave. As seen in Figure 13 filter is quite effective in suppressing noise and produces a smooth output[3].

4.2   Heart Rate

HR is calculated using mountaineer's method for peak detection (MMPD) in photoplethysmographic signals[4].

In this method, slope is calculated for every sample and as slope changes from positive to negative, sample will corresponding to a peak. Similarly a slope change from negative to positive would be a valley. A count for positive or negative consecutive slopes is also taken and compared with a preset value which updates with every detected peak to improve the robustness of the algorithm. A timer running would store peak timings and time difference between consecutive peaks would correspond to the heart rate. Shown below is a visualization of the algorithm ran on a sample set. Peaks & valleys are captured quite accurately.
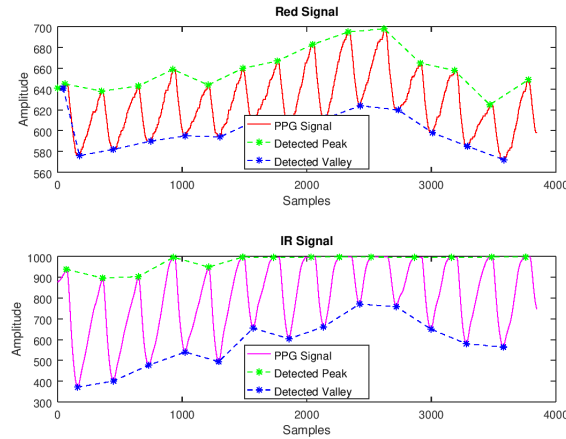

Figure 14: HR Algorithm applied to sample data

---

[3]Only a 1st order filter was implemented in actual program as it worked "just fine", but it is much better to have a 2nd order filter for suitable filtering performance.

18

4.3 SpO₂ Calculation

As discussed previously in equation (4):

$$R = \frac{V_{p2} - V_{l2}}{DC_2} / \frac{V_{p1} - V_{l1}}{DC_1}$$

We don't want to use signal's actual peak and valleys for R calculation as that is dependent on heart rate and any averaging of values on top of that would delay the final SpO₂% which we intend to obtain. Hence a weight averaging method is used[9], where instantaneous SpO₂% is calculated for neighboring samples and averaged together. This ensure multiple instantaneous values are obtained which can be averaged to obtain a final value. Following steps are performed in order:
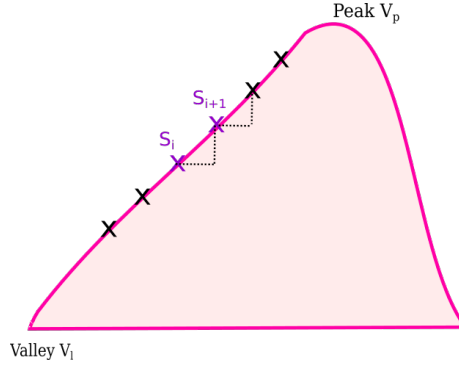

Figure 15: Selecting samples for instantaneous SpO₂

1. Find R between consecutive samples of red and ir signals: S_{i+1} & S_i.

$$R = \frac{S_{i_2+1} - S_{i2}}{DC_2} / \frac{S_{i_1+1} - S_{i1}}{DC_1}$$

   Find SpO₂ with this R value which can obtained using a typical relationship curve equation as shown in Figure 4:

$$SpO_2 = -25 * R + 110;$$

2. Assign a weight to this SpO₂ based on the current average. If this instantaneous SpO₂ is lower than average, assign a lower weight. If nearer to average, assign a higher weight.

3. Once weights are assigned for 20 samples, calculate a weighted average. Store this weighted average.

19

4. Restart at step 1 and perform 10 such iterations.

5. After 10 iterations, average the calculated weighted averages in each iteration. This becomes the final SpO_2. Update this value with the current SpO_2 average which is used for assigning weights.

A detailed explanation of this algorithm is in - Pulse Oximetry: Analysis of Theory, Technology and Practise[9]

Finally, an OLED display is refreshed every 5 secs with SpO_2% & HR value.

5   PCB & Enclosure

5.1   PCB

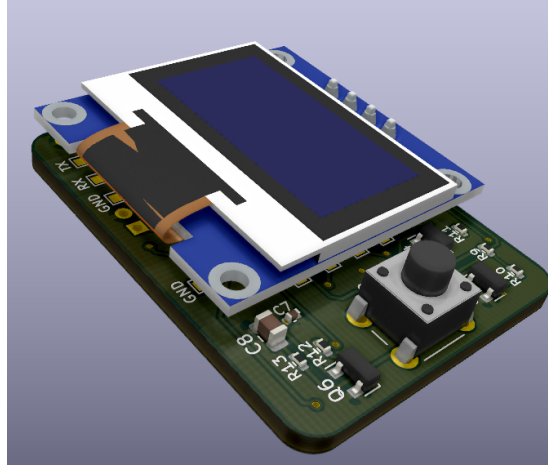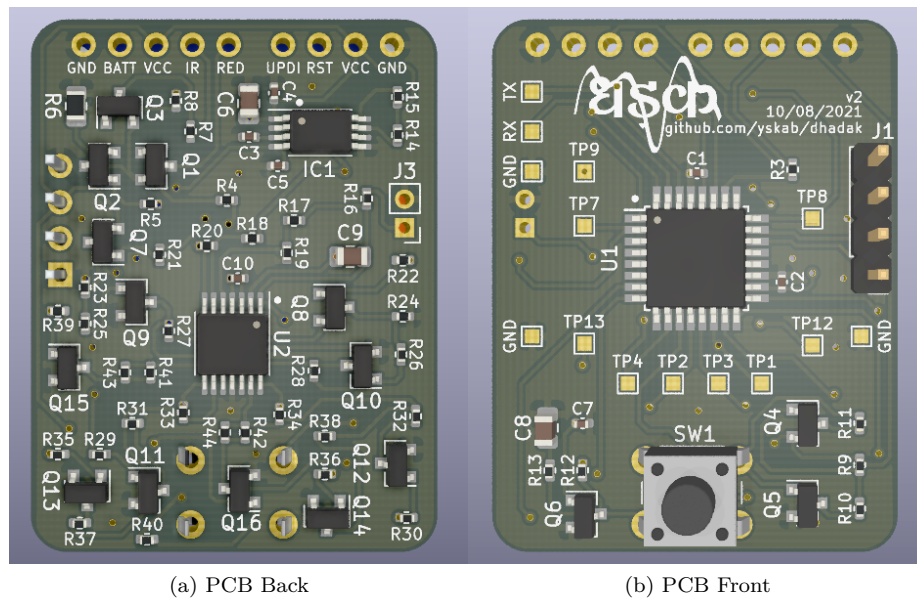Figure 16: Completed PCB

(a) PCB Back   (b) PCB Front

Figure 17: PCB Images

PCB Design was completed on 2 layers with most of the components placed on the back side so that they can be re-flowed easily on a dosa pan. All components on front side are to be hand soldered.

- Design also includes a soft latch power on/off switch circuit to easily operate the device.

- A programming header was also added to program the μC via UPDI interface.

- Connection headers were added to connect the leds, battery & photodiode which will be present on bottom compartment of enclosure.

- Header to attach OLED Display.

Sufficient test points were added on front side for easy access to probe and view the signals on oscilloscope.

To keep the PCB size equivalent to that of the OLED display module, 0402 size resistors/capacitors were used.

5.2 Enclosure

Enclosure was designed taking reference from a typical Oximeter which has display & PCB on top, a finger insert below and a bottom part with battery compartment.
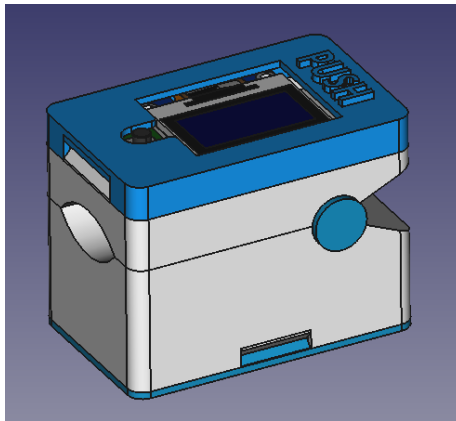

Figure 18: Completed Enclosure

A reflective setup was implemented with photodiode on top base and pulse leds in bottom compartment.

Securing finger is an important part as any wobble or improper contact would lead to degradation in signal quality and calculated parameters. To achieve a firm pressure onto the finger which would hold it stable in place, a safety pin was used (removing the clip part) in the rotation mechanism.

(a) Photodiode compartment

(b) Spacers for pcb

Figure 19: Top Base

(a) Battery compartment

(b) Led compartment
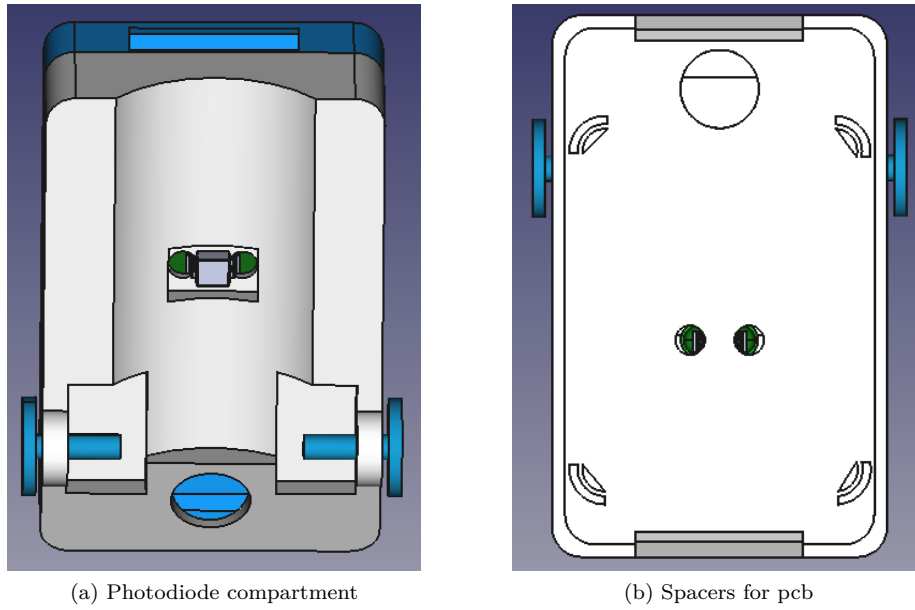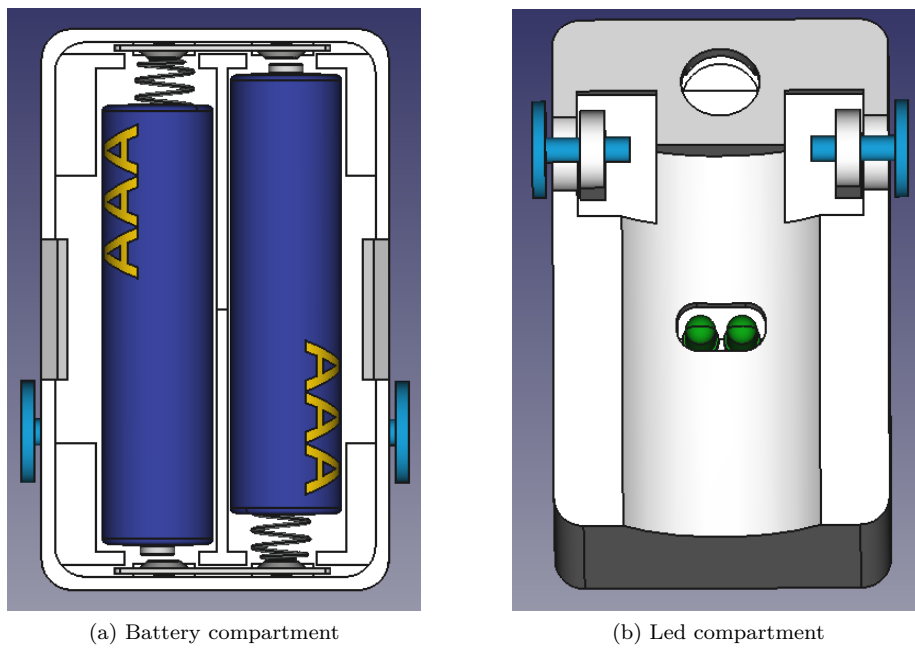
Figure 20: Bottom Base

In idle position, pin would be in natural non-extended state hence both base parts would be closed. When a finger is inserted, lid needs

(a) Safety pin   (b) Side view of pin

Figure 21: Pin mounted in bottom base
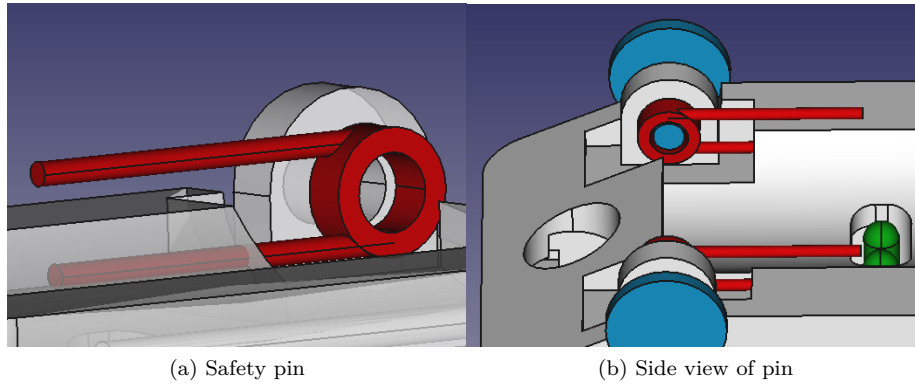
to go up via the rotational mechanism as that is the only path to accommodate the finger. This would cause the upper part connected with pin to push down on finger which would lead to a firm grip to form ensuring good contact with photodiode and led.
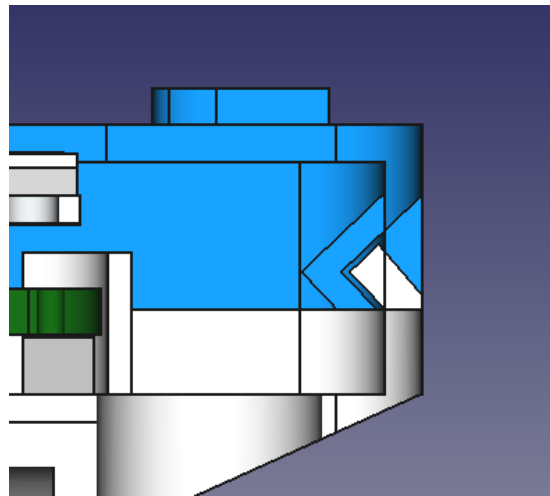

Figure 22: Snap fit cross-section

Snap fit elements were implemented making it easier to fit and remove the cover parts whenever required.

6 References

[1] Hartmann Vera, Liu Haipeng. *Quantitative Comparison of Photoplethysmographic Waveform Characteristics: Effect of Measurement Site* Frontiers in Physiology , vol 10 (2019) `https://www.frontiersin.org/article/10.3389/fphys.2019.00198`

[2] Ash, Caerwyn et al. *Effect of wavelength and beam width on penetration in light-tissue interaction using computational methods.* Lasers in medical science vol. 32,8 (2017): 1909-1918. `https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5653719/`

[3] Feiner, John R. MD, Severinghaus. *Dark Skin Decreases the Accuracy of Pulse Oximeters at Low Oxygen Saturation* December 2007 - Volume 105 - Issue 6 - p S18-S23 `https://journals.lww.com/anesthesia-analgesia/Fulltext/2007/12001/Dark_Skin_Decreases_the_Accuracy_of_Pulse.4.aspx`

[4] ArgÃijello-Prada, Erick Javier. *The mountaineer's method for peak detection in photoplethysmographic signals.* Revista Facultad De Ingenieria-universidad De Antioquia 2018 (2019): 42-50 `https://api.semanticscholar.org/CorpusID:116767900`

[5] Santiago Lopez, Freescale Semiconductor. *Pulse Oximeter Fundamentals and Design* Document Number: AN4327, Rev. 2, 11/2012 `https://www.nxp.com/docs/en/application-note/AN4327.pdf`

[6] Praveen Aroul, Texas Instruments. *Miniaturized Pulse Oximeter Reference Design* UserâĂŹs Guide and Test Report TIDA-00311 `https://www.ti.com/lit/pdf/tidu542`

[7] Zhang Feng, Microchip Technology Inc. *Pulse Oximeter Design Using MicrochipâĂŹs Analog Devices and dsPICÂő Digital Signal Controllers (DSCs)* AN1525, 04/28/2015 `http://ww1.microchip.com/downloads/en/Appnotes/00001525B.pdf`

[8] Dr. Neil Townsend, Department of Engineering Science, University of Oxford. *C3B Medical Electronics Lecture Notes* `https://www.robots.ox.ac.uk/~neil/teaching/lectures/med_elec/notes6.pdf`

[9] Michael W. Wukitsch, BA,Michael T. Petterson. *Pulse Oximetry: Analysis of Theory,Technology and Practice* `https://doi.org/10.1007/BF01617328`

7 Closing Comments

I referred the listed documents extensively throughout the process specifically [5], [6], [7], [8], [9] to close gaps in my understanding and to improve/revisit the design.

Completing this project taught me lot of things from a design perspective and a lot of respect for the products that I use on daily basis considering the amount of iterations something must have went through and enormous number of checks/edge cases to ensure it works just right.

For me, this project took close to 7 months for completion, considering I worked 20hrs/week on average. I made 3 iterations in total during this timeline, documented is the 3rd version. There are still a lot of improvements i can think of hence a shortcomings/recommended improvements page is added to project directory where i have listed all further improvements or current issues which can be worked on. I wouldn't want to progress these anymore as somewhere i feel the initial goal with which i started off has met:

- Making something from scratch(at least a suitable prototype) and documenting the entire project in 2 different languages.

- A YouTube Vlog of the project.

I hadn't done any of this in the past hence this project required me to change myself to accomplish it. Most important lessons that i have learned from this journey are:

- Never let something which appears difficult or out of reach contemplate your decision to work on it. You know nothing so everything is going to be difficult to understand but it shouldn't become a filter for choosing what to work on.

- Consistency. There were many issues with design that I found on weekends which later got resolved in the next weekend only because there was consistency and I was involved with the problem on a daily basis performing new workarounds every day.

I would end this document now. If you have any suggestions or comments, you can reach me out on Twitter @yskabhijeet.