Final mini project: EE2301

ee21btech11028

Aim: To build and implement a PPG device for heartbeat and blood pressure.

Apparatus: Breadboard, connecting wires, op-amps(LM358, LM324), resistors, capacitors, phototransistors, MOSFET

Theory: Heart Rate measurement has been done for a long time by manually counting the number of pulses at an exposed artery on the arm for 30 sec or 1 min. Recent digital advancements have implemented heart rate measurement by Photoplethysmography or PPG. It is a technique that measures blood volume by measuring the absorption of light by skin tissue. The changes in blood volume show up as varying illumination levels on a photodetector via reflection/transmission, and heart rate can be measured from the periodicity of the change.

Procedure: (a)

I. Introduction

The project is focused on the design and analysis of a reflection-based PPG circuit using a TCRT5000 phototransistor. Heartbeat directly relates to changes in blood volume in the finger, hence we can capture that change as a voltage waveform using PPG. Proper filtering and processing using FFT can extract the heart-rate value from the periodicity of the waveform. The amplitude of the signal waveform will depend on the reflectance of the finger; hence reflectivity directly affects the amplitude of measurement. Because we are processing using FFT, the amplitude would not matter except for increasing the SNR value.

The reflectance of blood is maximum for the 850-950nm wavelength band i.e., the infrared band. Thus, using IR LED as the source of light would give the best results. Parameters of the finger-like skin color and thickness would affect the readings, and design parameters like pressure applied incident ambient light, and distance of the finger from the detector. It is obvious that signal amplitude would increase with IR LED current and its slope would be a measure of the reflectance of the finger. Our analysis includes measuring the minimum LED current required to obtain reasonable SNR and the effect on the reflectance of skin color.

II. Circuit design

The circuit contains four stages (i) Photodetector, (ii) Filter stage, (iii) Amplification and rectification stage, and (iv) Processing stage. Each stage is shown in the picture below.

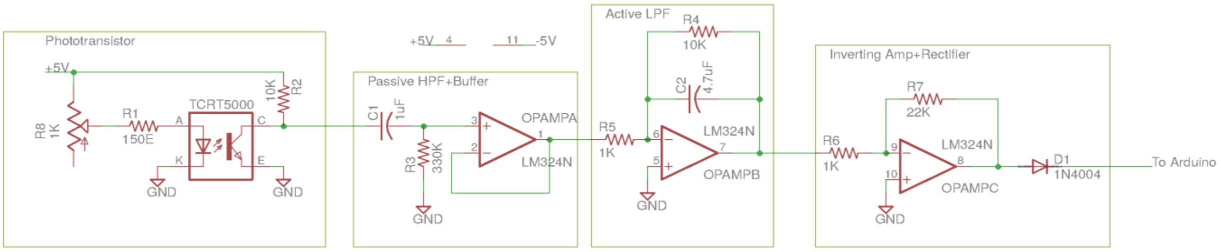
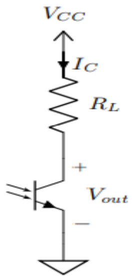


Fig. 1: Left to Right: (A) Photodetector stage (B.1) Passive HPF and Buffer (B.2) Active LPF (C) Amplification and Rectification

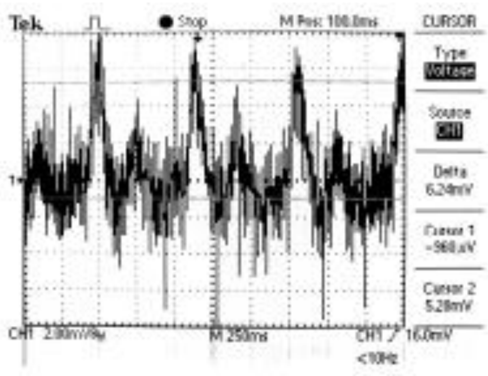
(i) Photodetector

TCRT5000 phototransistor is chosen as a photodetector for the high current transfer ratio of 1mA collector current for 10mA LED current. Also, the packaging is suitable for reflection-based sensing. To keep the transistor in the linear region or active mode for common emitter configuration

$$V_{CC} > R_L I_C$$



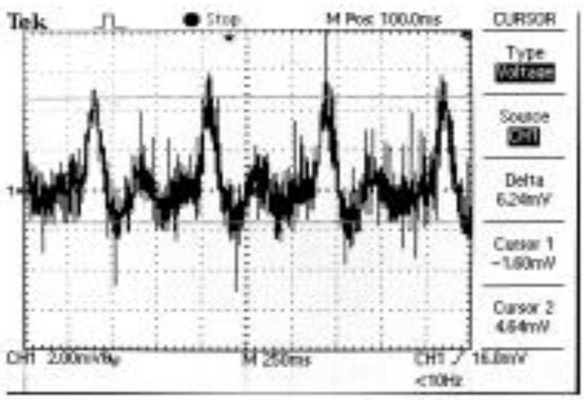
We will have an expected value of IC in a specific range based on incident light. This incident light can be calculated using the Current Transfer plot from the datasheet and an expected value of reflectance. Based on I_C, R_L = 10k is selected to maintain the transistor in active mode. The input impedance of the next stage must be high enough to not alter the output of the transistor. The output of this stage can be seen in the figure below



(ii) Filter Stage

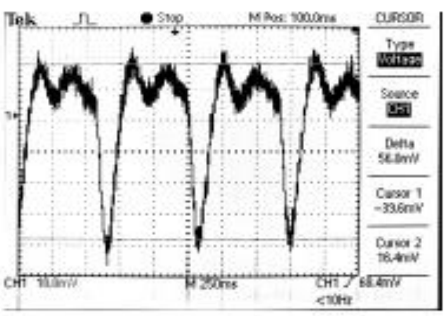
The signal which we want to measure would be in the band of 0.5Hz to 2Hz (30bpm to 120bpm) hence we keep filter corners near these values. Adding a passive HPF right after the phototransistor works due to the high impedance of the HPF. Since we are interested only in the variation of the intensity, we use an HPF to remove the DC value from our signal, which arises due to the constant incident light on the phototransistor (reflecting off the finger and ambient light). Passive HPF would suffice because we do not want to amplify the high-frequency noise at this stage. Output can be seen in the figure below

$$f_{\text{hpf}} = \frac{1}{2\pi X 33O K\Omega X 1\mu F} = 0.483\text{Hz.}$$



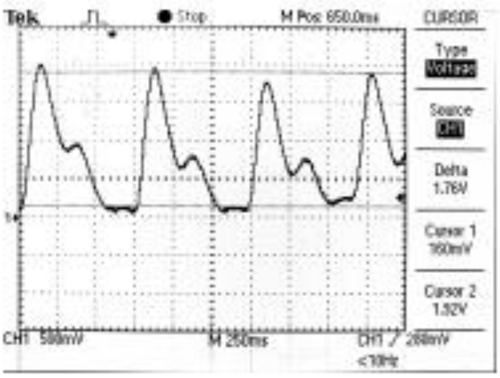
Next is the active LPF stage, which is necessary to remove high-frequency noise and reduce the signal to relevant harmonic and remove all unwanted high-frequency components of the signal. To maintain the high input impedance of this stage, a buffer is added after HPF. This stage has an amplification of 10x so that the next amplification stage would not use very high resistance values. Output can be seen in the figure below.

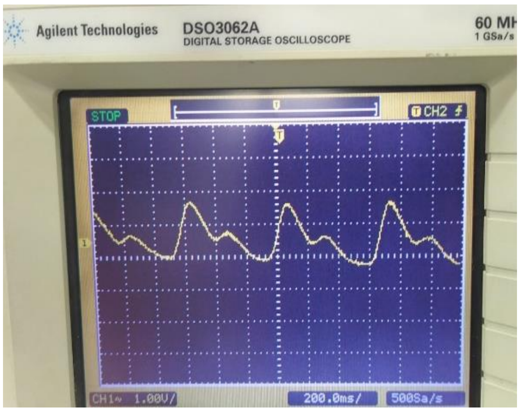
$$f_{\text{lpf}} = \frac{1}{2\pi X 10 K\Omega X 1\mu F} = 3.38\text{HZ.}$$



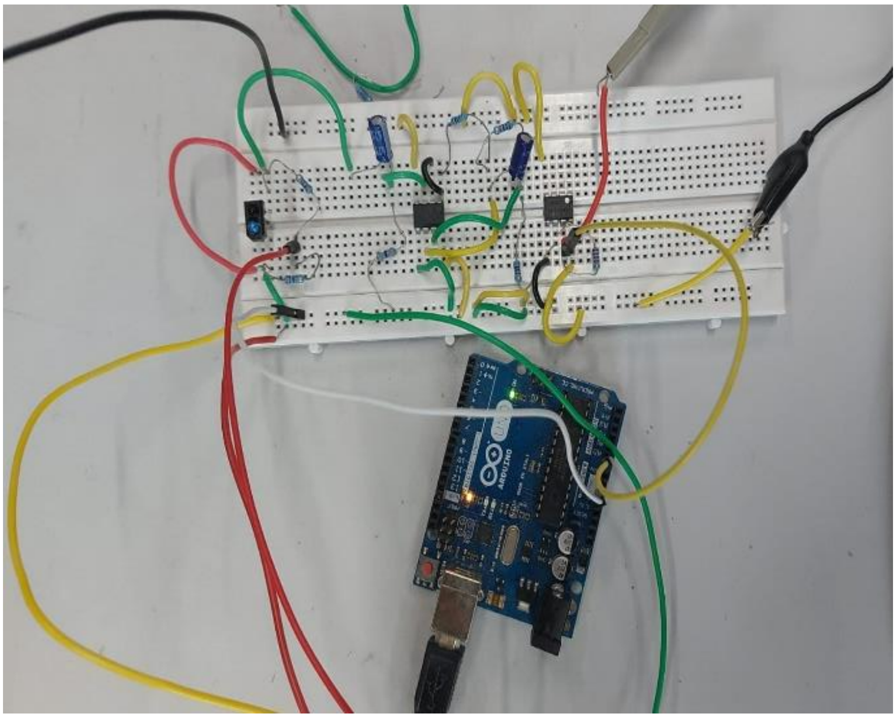
(iii)Amplification and Rectification

The final output to be processed by a microprocessor will have to be in a reasonable voltage range of 0-3.3V or 0-5V. For that, we have added an inverting amplifier of 22x gain followed by a diode to rectify the negative voltages of the final waveform. Output can be seen in the figure below.





Snap of the circuit:



(iv) Processing in Arduino: The processing stage requires sampling the waveform using an ADC and taking the FFT of enough samples to give a peak in the 0.5-2Hz range. The accuracy of the FFT calculation will depend on our sampling duration. We have used a sampling frequency of 16Hz and have taken samples for 16 seconds, giving a sample length of 128. A larger sampling duration would give us greater accuracy because our signal is of very low frequency. It is normal for heart-rate measurements to last 15 to 30 seconds.

The algorithm is a simple 3-step process that loops forever

1) Collect Ns number of samples at Fs frequency.

2) Compute FFT of Ns samples, and pass the values in 0.5 - 2 Hz frequency range to the PC

3)Plot the FFT and mark the magnitude peak

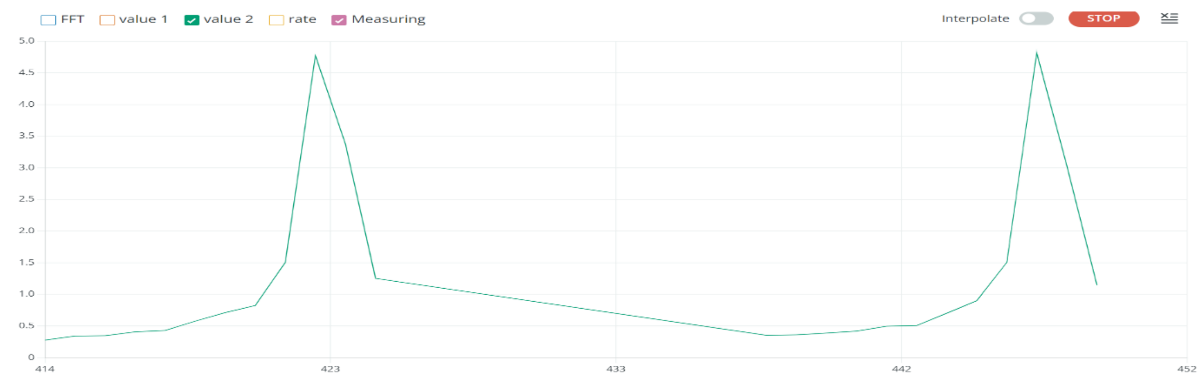
Observed readings:

```
Measuring:-
.
.
.
.
.
.
.
.

FFT:-
0.500000 4.8312
0.625000 7.2046
0.750000 4.3012
0.875000 2.3901
1.000000 6.2365
1.125000 2.8979
1.250000 1.6988
1.375000 3.1327
1.500000 1.4311
1.625000 7.9629
1.750000 1.5068
1.875000 2.2144

Heart rate:97.500
time delay
0.12
Systolic pressure: 106.90
Diastolic pressure: 67.28
```

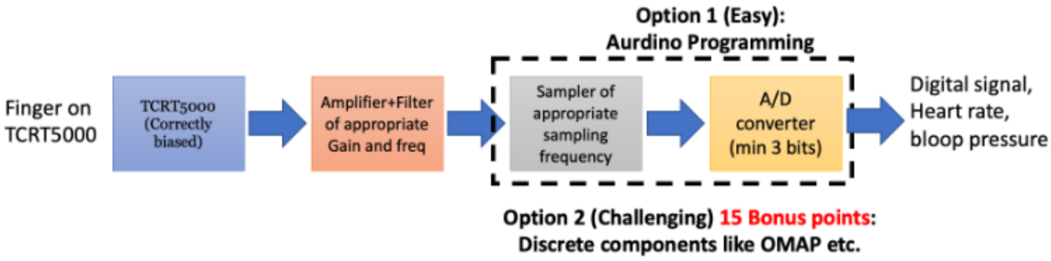
```
Measuring:-
.
.
.
.
.
.
.
.

FFT:-
0.500000 3.0801
0.625000 2.9413
0.750000 1.3504
0.875000 1.6361
1.000000 0.4924
1.125000 0.5663
1.250000 0.7618
1.375000 4.7982
1.500000 5.3342
1.625000 0.4912
1.750000 1.9144
1.875000 1.4408

Heart rate:90.000
time delay
0.50
Systolic pressure: 121.18
Diastolic pressure: 68.67
```

Snaps of serial plotter:

FFT plot from Arduino:

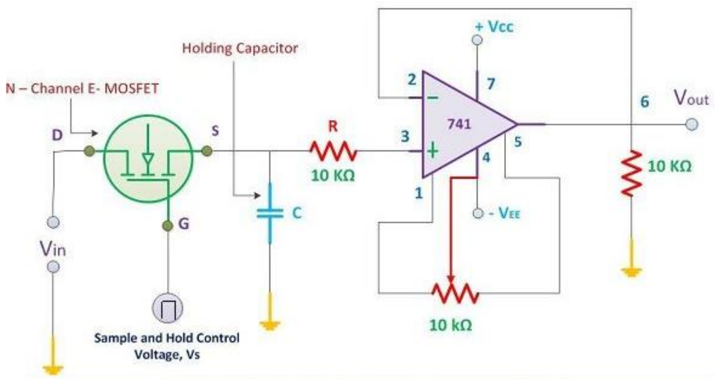


(b) The above can be done in another way by replacing the Arduino programming part by building the sampler and A/D converter (at least 3 bits) using discrete components OPAMPs etc.



The output obtained in **(a)** was rectified by using the diode which then will be sampled. Then the formed is passed through a 3-bit A/D converter which is then encoded by using Arduino. Note that here the function of Arduino is just encoding unlike in **(a)**

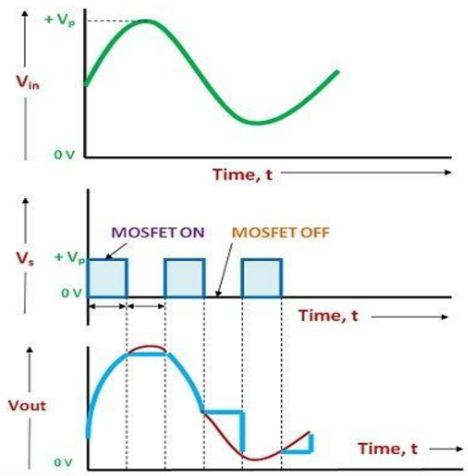
Sample and hold circuit: The working of the sample and hold circuit can be easily understood with the help of the working of its components. The main components that a sample and hold circuit involves are an N-channel Enhancement type MOSFET, a capacitor to store and hold the electric charge, and a high-precision operational amplifier.



Practical Circuit of Sample and Hold Circuit

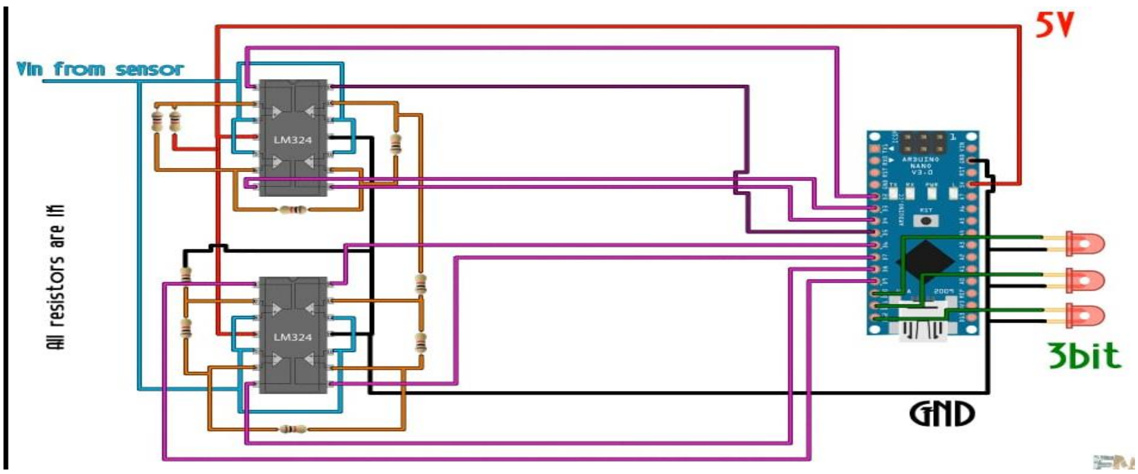
The N-channel Enhancement MOSFET will be used as a switching element. The input voltage is applied through its drain terminal and the control voltage will be applied through its gate terminal. When the positive pulse of the control voltage is applied, the MOSFET will be switched to the ON state. And it acts as a closed switch. On the contrary, when the control voltage is zero then the MOSFET will be switched to the OFF state and acts as the open switch.

When the MOSFET acts as a closed switch, then the analog signal applied to it through the drain terminal will be fed to the capacitor. The capacitor will then charge to its peak value. When the MOSFET switch is opened, then the capacitor stops charging. Due to the high-impedance operational amplifier connected at the end of the circuit, the capacitor will experience high impedance due to this it cannot get discharged.

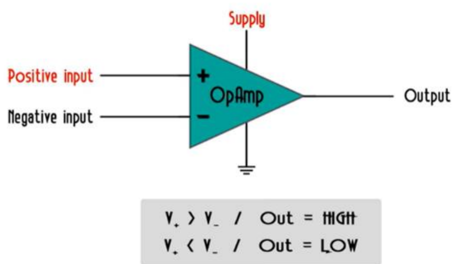


Input and Output Waveforms of Practical Sample and Hold Circuit

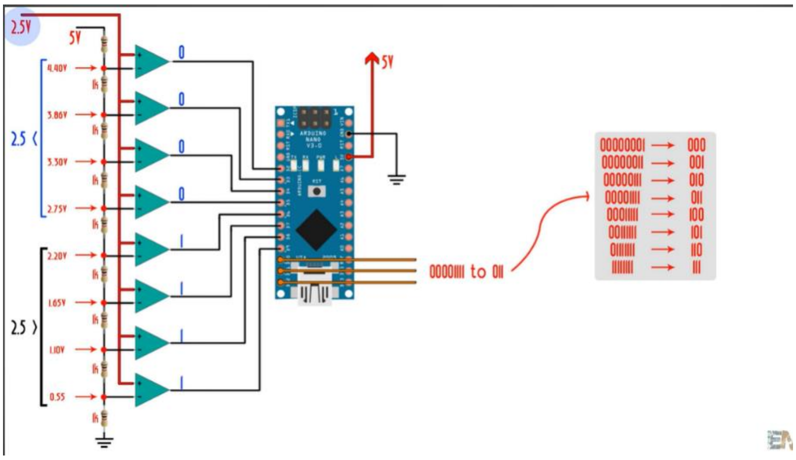
3-bit A/D convertor: Flash ADC circuits basically have a bunch of operational amplifiers. It consists of voltage dividers and an encoder. The reference voltage is applied along with the result of **(a)** due to which it operates in comparator configuration. The Arduino here which acts as encoder reads the all the inputs from comparators and give binary output.



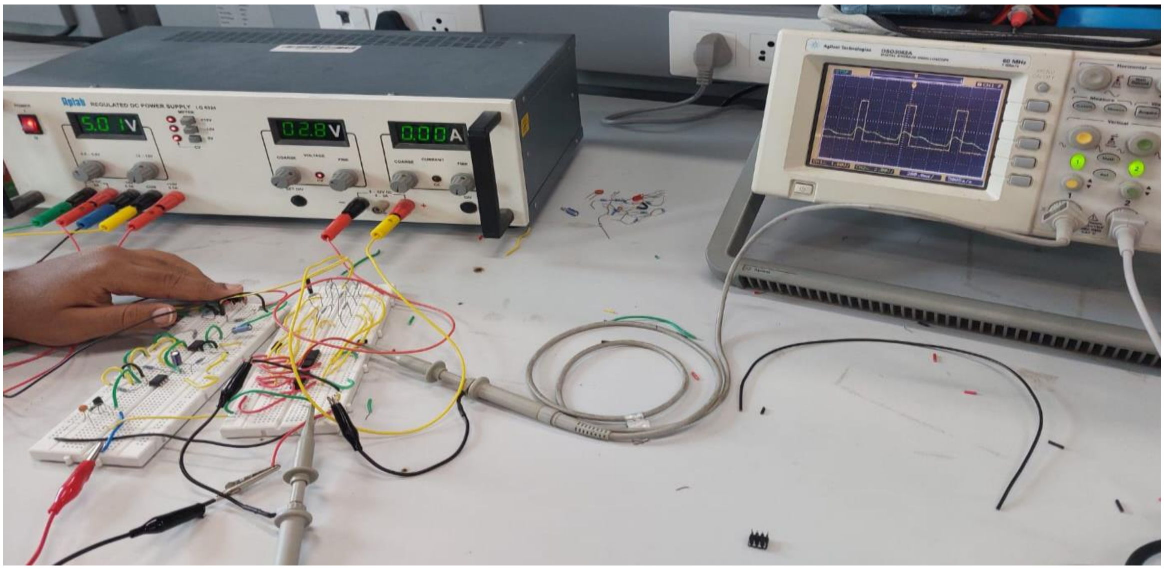
comparator configuration

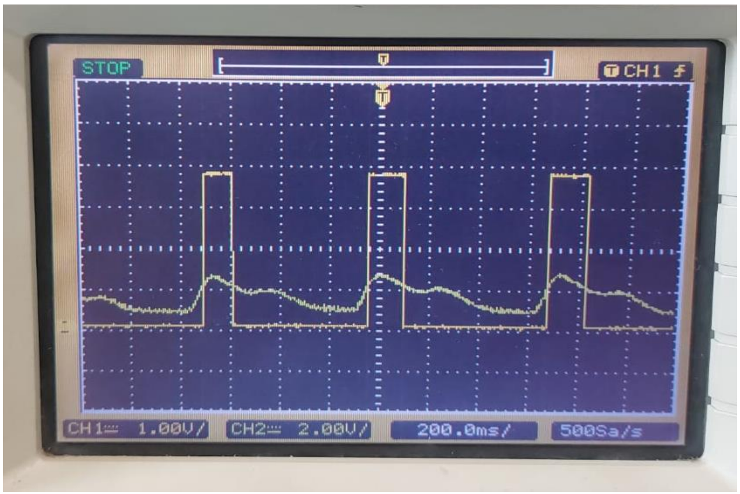


Schematic of how ADC works: Let the reference voltage be 5V. The voltage we need to measure be 2.5V.

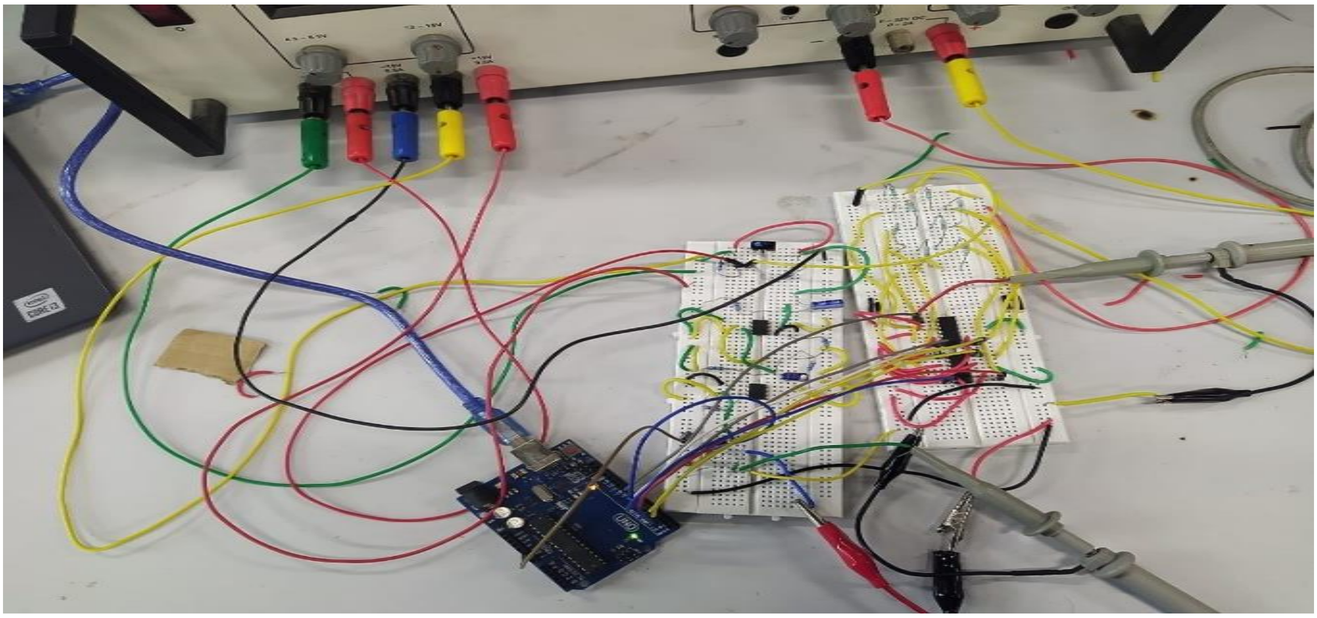


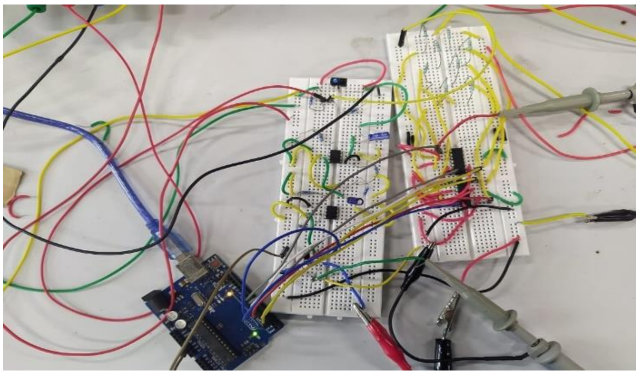
Snap of the circuit: A/D convertor along with sampled heartbeat output





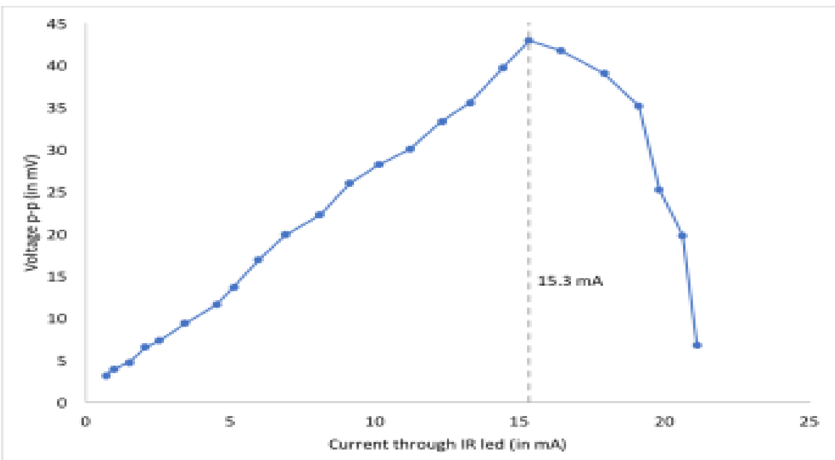
The video of A/D conversion by taking samples after rectifying the signal is attached with the report



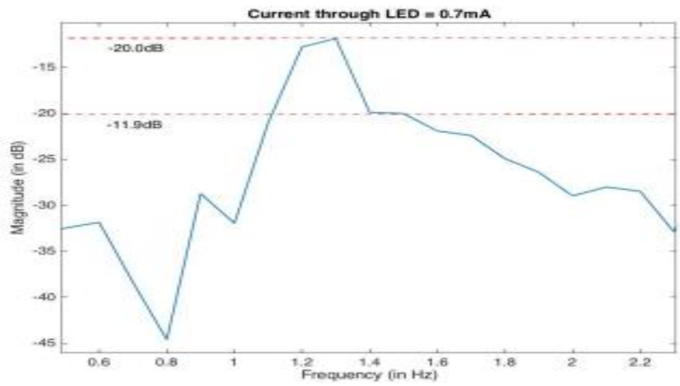


Observations:

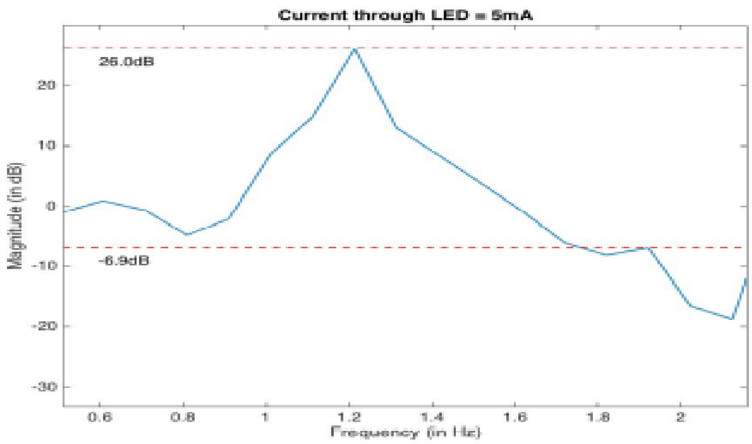
A. Dependence on LED current: We can see a very linear dependence of output signal amplitude with the input LED current. This signal is taken after filtering stages at the output of LPF (also adjusted for a gain of 1x). We can use this plot to choose an LED current based on the desired output voltage. The degradation after 15.3mA occurs due to the saturation of the phototransistor and leaving Active Region. The plot stays linear for low current values.



B. Choice of LED current based on SNR: SNR analysis in the picture below shows that we may be able to go to a current as low as 0.7mA. At 5mA we get a good SNR of 32.9dB. Using lower current values in LED will lead to lower power consumption and illuminate the finger with lower intensity light which will have lesser long-term ill-effects. SNR analysis also shows that we have a wide range of values of LED current to choose from, depending on what signal amplitude we would want at the filter output.

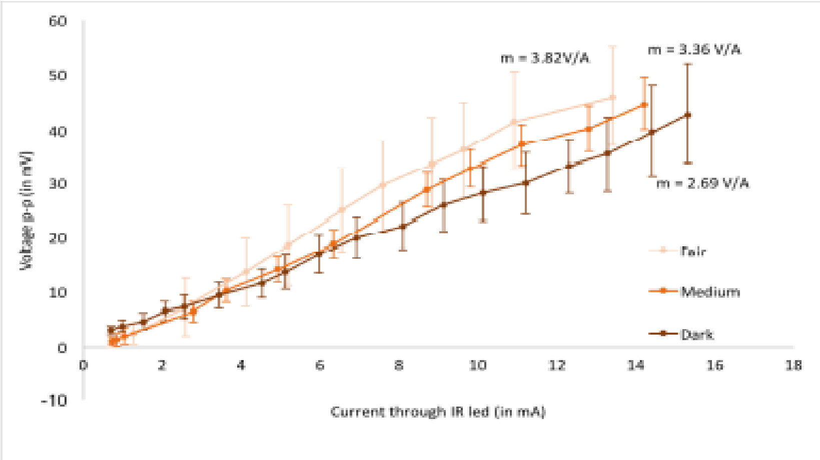


(a) IR Current = 0.7mA, SNR = 8.1dB



(b) IR Current = 5mA, SNR = 32.9dB

C. Reflectance dependence on skin color: In the picture below, we have plots for fingers of multiple different skin colors. We see a slight dependence of the slope of the plot on skin color as expected. But there is no significant change for small current values of 5mA or so ($\Delta V \approx 5mV$ at $I = 5mA$). While conducting the experiment, we observed a significant change in amplitude based on the pressure applied by the finger. To maintain constant pressure, we used a Velcro belt to secure the finger with the photodetector. While we observed the dependence on pressure, it was not possible to measure the pressure to obtain a specification. In the design of the casing for the photodetector, care should be taken to not press too hard onto the finger and make it touch slightly, while also maintaining firm contact at fixed distance.



Conclusion: The experiments and results show that Heart Rate measurement can be done with a very low IR LED current and the dependence of output amplitude is linear with the LED current. This helps us in designing LED circuits based on desired output signal amplitude. We also see a slight dependence of the reflectance (sensitivity of signal amplitude) on skin color. It shows that if we select low current values the effect of skin color on output amplitude would be small. The FFT method also gives us dependence of accuracy on sampling time, which means measuring for a longer time would give us more accuracy. We faced the implementation challenge of pressure variation leading to varying output amplitude. For production design, care should be taken to make the sensor touch the finger lightly and not press, and so to maintain fixed distance and not be affected by finger movement.