Heart Rate Measurement using PPG

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***Abstract*—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 [1]. It is a technique which 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 periodicity of the change.**

I. Introduction

Our project has focused on design and analysis of a reflection based PPG circuit using TCRT5000 phototransistor. Heart beat 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 form the periodicty of the waveform.

The amplitude of signal waveform will depend on the reflectance of the finger, hence reflectivity directly affects the amplitude of measurement. Because we are processing using FFT, amplitude would not matter except for increasing SNR value. reflectance of blood is maximum for 850-950nm [2] wavelength band i.e. the infrared band. Thus using IR LED as source of light would give best results.

Parameters of the finger like skin-color and thickness would affect the readings, and also design parameters like pressure applied, incident ambient light, distance of finger from 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 minimum LED current required to obtain reasonable SNR, and also the effect on reflectance of skin color.

II. Circuit Design

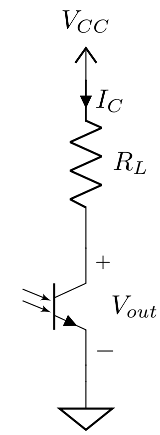
The circuit contains four stages (i) Photodetector, (ii) Filter stage, (iii) Amplification and rectification stage, (iv) Processing stage. Each stage is shown in Figure 1.

A. Photodetector

TCRT5000 photo-transistor is chosen as photo-detector for high current transfer ratio of 1mA collector current for 10mA LED current [3]. Also the packaging is suitable for reflection-based sensing. To keep the transistor in linear region or Active Mode for common emitter configuration [4]

$$V_{\mathrm{CC}} > R_L I_C$$

We will have an expected value of I_C in a specific range based on incident light. This incident light can be calculated using the Current Transfer plot from datasheet [3] and an expected value of reflectance. Based on I_C, R_L = 10k is selected to maintain transistor in active mode. The input impedance of the next stage has to be high enough to not alter the output of the transistor Output of this stage can be seen in Figure 3



B. 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 photo-transistor works due to the high impedance of the HPF. Since we are interested only in the variation of the intensity, we use a HPF to remove DC value from our signal, which arises due to the constant incident light on the photo-transistor (reflecting off the finger and also 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 Figure 4

$$f_{HPF} = \frac{1}{2\pi \times 330K\Omega \times 1\mu F} = 0.483Hz$$

Next is active LPF stage, which is necessary to remove high-frequency noise and also reduce the signal to relevant harmonic and remove all unwanted high-frequency components of the signal. To maintain highinput impedance of this stage, a buffer is added after HPF .This stage has amplification of 10x so that the next amplification stage would not use very high resistance values. Output can be seen in Figure 5

$$f_{LPF} = \frac{1}{2\pi \times 10K\Omega \times 1\mu F} = 3.38Hz$$

C. 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 Figure 6

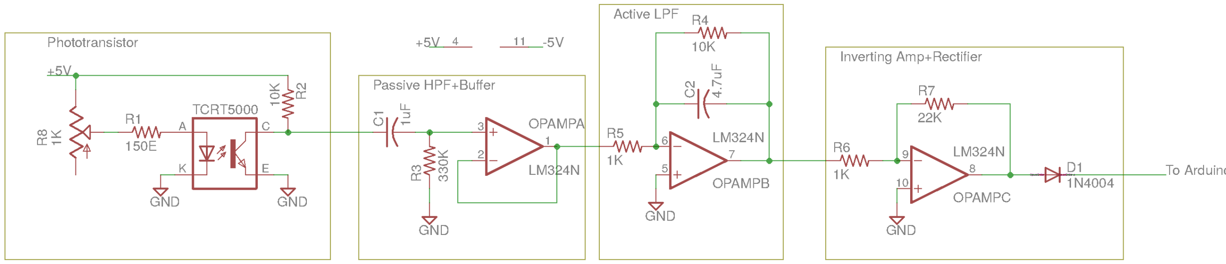


Fig. 1: Left to Right: (A) Photodetector stage (B.1) Passive HPF and Buffer (B.2) Active LPF (C) Amplification and Rectification

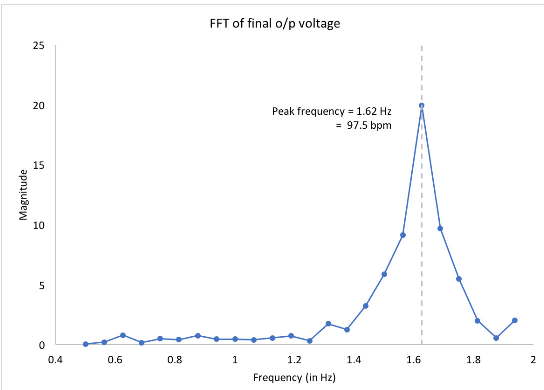


Fig. 2: FFT plot from Arduino.

D. *Processing in Arduino*

The processing stage requires sampling the waveform using an ADC and taking FFT of enough samples to give a peak in 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 sample length of 256.

$$F_s = 16Hz$$

$$t_s = 16s$$

$$\Delta f = \frac{F_s}{N_s} = \frac{F_s}{F_s t_s} = 1/t_s = 1/16Hz$$

A larger sampling duration would give use greater accuracy, because of 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 which loops forever

- Collect N_s number of samples at F_s frequency.
- Compute FFT of N_s samples, and pass the values in 0.5 - 2 Hz frequency range to the PC
- Plot the FFT and mark the magnitude peak.

Better processing methods could be employed to decrease the processing time using dedicated FFT hardware and DSP processors, but for our prototype Arduino is sufficient. The FFT plot generated by arduino can be seen in Figure 2.

III. Experimental Results

A. *Dependence on LED current*

In Figure 7 we can see a very linear dependence of output signal amplitude with the input LED current. This signal is taken after filtering stages at output of LPF (also adjusted for gain of 1x). We can use this plot to choose an LED current based on desired output voltage. The degradation after 15.3mA occurs due to saturation of photo-transistor and leaving Active Region. The plot stays linear for low current values.

B. *Choice of LED current based on SNR*

SNR analysis in Figure 9 shows that we may be able to go till 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 wide range of values of LED current to choose from, depending on what signal amplitude we would want at the filter output.

C. *Reflectance dependence on skin color*

In Figure 8 we have plots for fingers of multiple different skin color. 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 significant change in amplitude based on the pressure applied by the finger. To maintain a constant pressure, we have used a Velcro belt to secure the finger with the photo-detector. 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 photo-detector, 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.

IV. Conclusion

Our experiments and results show that Heart Rate measurement can be done with very low IR LED current and the dependence of output amplitude is linear with the LED current. This helps us in designing LED circuit 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. FFT method also

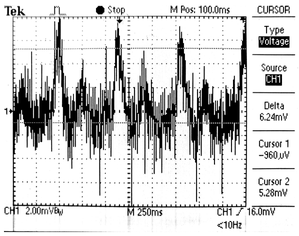


Fig. 3: Phototransistor output

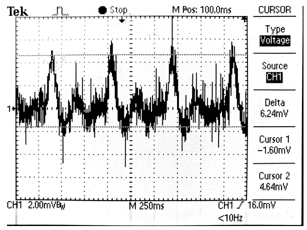


Fig. 4: After HPF

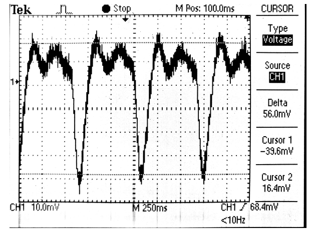


Fig. 5: After LPF, 10x Gain

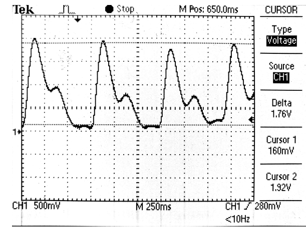


Fig. 6: Final rectified output

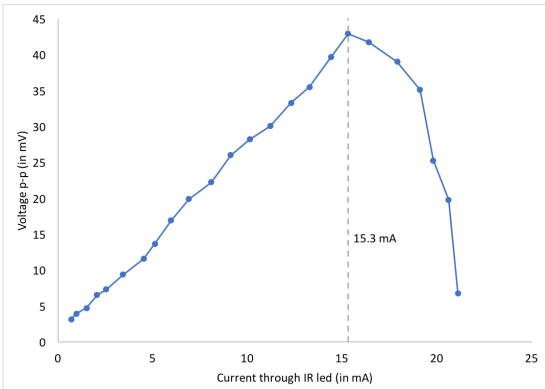


Fig. 7: Signal amplitude vs. IR LED current

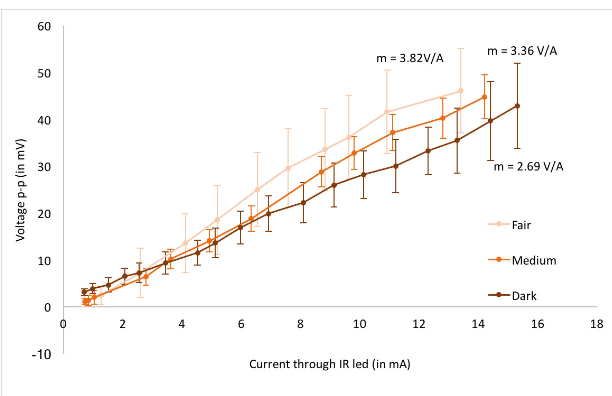
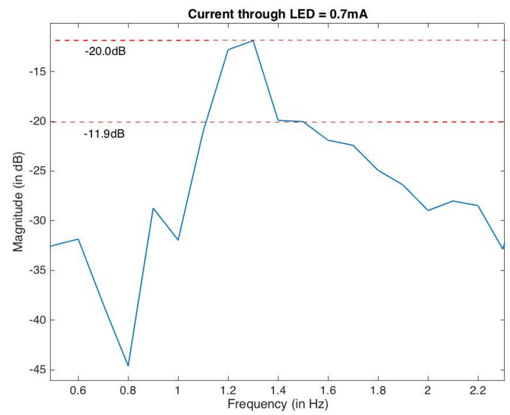
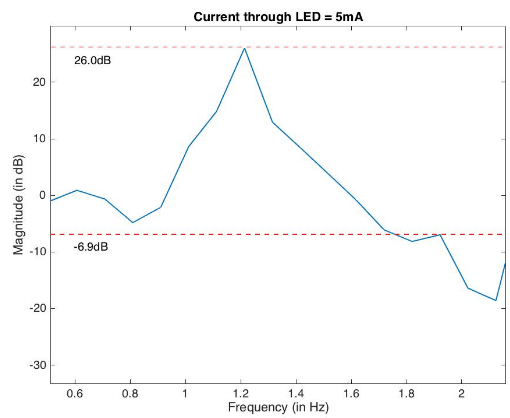


Fig. 8: Skin color dependence



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



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

Fig. 9: Signal and Noise level on FFT plot

gives us dependence of accuracy on sampling time, which means measuring for longer time would give us more accuracy.

We faced implementation challange of pressure variation leading to varying output amplitude. For production designing, care should be taken to make sensor touch finger lightly and not press, and also to maintain fixed distance and not be affected by finger movement.

Work Distribution

- Meet: Filter design, Arduino and python plotter code, Circuit schematic, Report
- Pulkit: Filter design, Sensor circuit design, Circuit implementation and layout, Plots and presentation

Supporting Material

- Demo Video: https://youtu.be/cB5uzFoALTA
- Code: https://github.com/udiboy1209/heart-rate-monitor

References

[1] https://en.wikipedia.org/wiki/Photoplethysmogram
[2] Bosschaart, N., Edelman, G. J., Aalders, M. C. G., van Leeuwen, T. G., & Faber, D. J. (2014). A literature review and novel theoretical approach on the optical properties of whole blood. Lasers in Medical Science, 29(2), 453479. http://doi.org/10.1007/s10103-013-1446-7
[3] https://www.vishay.com/docs/83760/tcrt5000.pdf
[4] Phototransistor design Application Note: https://www.fairchildsemi.com/application-notes/AN/AN-3005.pdf