INDIAN INSTITUTE OF TECHNOLOGY, BOMBAY
DEPARTMENT OF ELECTRICAL ENGINEERING

FINAL PROJECT REPORT
EE 344 - ELECTRONICS DESIGN LAB

PPG SIGNAL ACQUISITION MODULE

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ABSTRACT

A photoplethysmogram (PPG) is an optically obtained plethysmogram, a volumetric measurement of an organ. With each cardiac cycle the heart pumps blood to the periphery. The change in the volume caused by the blood is detected by illuminating the skin with IR light. We developed and implemented an electronic system to capture and display the PPG signal. We make infrared (IR) light incident on finger tip and measure the reflected IR light using a phototransistor which contains the PPG signal. The raw PPG signal is in the form of current output of the phototransistor, typically [0.2 - 0.4] mA, and we use a current to voltage converter to get the voltage signal. The raw PPG often has a large slowly varying baseline and it needs to be restored to optimally use the available ADC range. We carry out baseline restoration by controlling the bias voltage of the current injector using a microcontroller. We amplify the signal using a fixed value of gain resistor in the current to voltage converter. We also designed an auto-led intensity control to control the LED current and hence the emitted IR light in an effort to make the acquisition module adaptable to users with varying skin colours, motion artifacts etc. Finally we display the PPG signal on an android smartphone by transmitting the PPG signal over bluetooth.

ACKNOWLEDGEMENTS

First of all, we would like to thank *Professor PC Pandey* for being a great advisor. We gained a big deal of knowledge by taking a dip in your pool of prudence and we are very happy for we got a chance to be mentored by you. A huge shout out to you sir.

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CONTENTS

CHAPTER 1 : INTRODUCTION

Related to the measurement of blood flow is the measurement of volume changes in any part of the body that results from pulsations of blood with each heartbeat. Such measurements are useful in the diagnosis of arterial obstructions as well as for pulse wave velocity measurements. Instruments measuring volume changes are called plethysmographs and measurement of these volume changes is called plethysmography. In general, plethysmograph is an instrument that consists of rigid cup or chamber placed over the limb in which volume changes are to be measured. The measurement of blood volumetric changes in the skin perfusion by means of photoplethysmography (PPG) depends on the fact that blood absorbs infrared light more strongly than the remaining skin tissues. PPG uses inexpensive optical sensors which are rugged and needs less maintenance. Since it consumes very less power, it is an ideal ambulatory device.

1.1 MOTIVATION

A portable, easy-to-use PPG recording device will be a boon for patients who have cardiac problems as they can get the PPG reading anytime they want. Also, one more advantage of such a PPG acquisition device which translates to the motivation of working for it is its non-invasive property. PPG signal retaining all its intrinsic properties can be very helpful in cardiovascular diagnosis. The current implementations of PPG Acquisition lose valuable information regarding the properties such as shape and dicrotic wave. The implementation in this project tries to minimize the information lost as it displays the natural waveform with minimal distortion and filtering. The major challenge in developing PPG signal acquisition module is the analog signal processing intricacies involved during the design

1.2 SIGNAL ACQUISITION

In this project, the PPG signal is acquired by using an LED and photo-sensor pair and is used for non-invasive monitoring of the pulsatile component of the peripheral blood flow. The change in volume caused by the pressure pulse is detected by illuminating the skin with IR light from a light-emitting diode (LED) and then measuring the amount of light reflected using a phototransistor. Each cardiac cycle appears as a peak as seen in Fig 1.1.

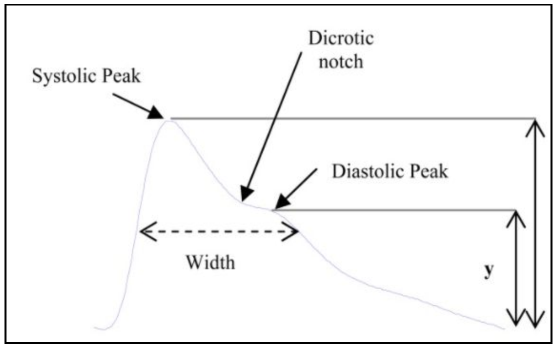

Figure 1.1: PPG Signal Reference waveform

1.3 CLINICAL APPLICATIONS OF PPG

PPG has been applied in many different clinical settings, including clinical physiological monitoring, vascular assessment and autonomic function (vasomotor function and thermoregulation, blood pressure and heart rate variability). The PPG technology can be used in a wide range of non invasive medical applications like measuring oxygen saturation, blood pressure and cardiac output, assessing autonomic function and also detecting peripheral vascular disease [4]. Its most common application is heart rate monitoring. A faithful recording of this signal is of great value in cardiovascular diagnosis by analyzing the waveshape and its timing relation with other physiological signals.

The various applications of PPG signal [4] can be summarised in the table 1.1 :

Clinical physiological monitoring	**Vascular Assessment**	**Autonomic function**
● Blood oxygen saturation ● Heart rate ● Blood pressure ● Cardiac output ● respiratory rate	● Arterial disease ● Arterial compliance and ageing ● Endothelial function ● Venous Assessment ● Vasospastic Condition ● Microvascular blood flow and tissue viability.	● Vasomotor function and thermoregulation ● Blood pressure and heart rate variability ● Orthostasis ● Neurology

Table 1.1 : Various applications of PPG Acquisition Setup

CHAPTER 2 : TECHNICAL DESIGN

2.1 REFLECTANCE AND TRANSMITTANCE METHOD

The wearable PPG has two modes - transmission and reflectance. In transmission mode, the light transmitted through the medium is detected by a PD(photodetector) opposite the LED source, while in reflectance mode, the PD detects light that is back-scattered or reflected from tissue, bone and/or blood vessels [5]. Fig 2.1 describes the situation.

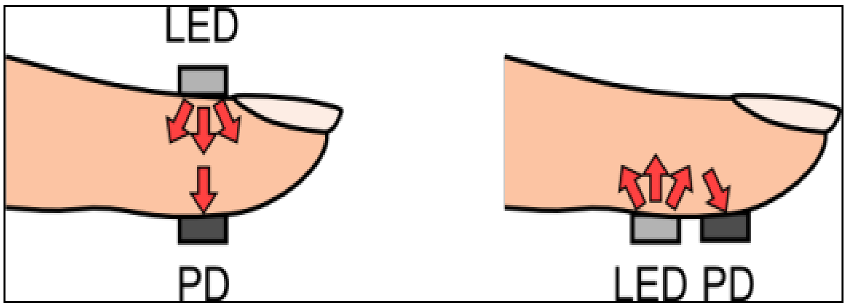

Figure 2.1 : Reflectance and Transmittance with Finger

Reflectance mode eliminates the problems associated with sensor placement. However, reflection-mode PPG is affected by motion artifacts and pressure disturbances. Any movement, such as physical activity, may lead to motion artifacts that may corrupt the PPG signal and limit the measurement accuracy of physiological parameters. Pressure disturbances acting on the LED-photodetector pair, such as the contact force between the PPG sensor and measurement site (skin), can deform the arterial geometry by compression. Thus, in the reflected PPG signal, the AC amplitude may be influenced by the pressure exerted on the skin [5].

Transmission mode is capable of obtaining a relatively good signal. To be effective, the sensor must be located on the body at a site where transmitted light can be readily detected, such as the fingertip, nasal septum, cheek, tongue, or earlobe. Sensor placement on the nasal septum, cheek or tongue is only effective under anesthesia. The fingertip and earlobe are the preferred monitoring positions, however, these sites have limited blood perfusion. Since blood absorbs more light than the surrounding tissue, a reduction in the amount of blood is detected as an increase in the intensity of the detected light [5].

2.2 BLOCK DIAGRAM OF THE PPG SIGNAL ACQUISITION MODULE

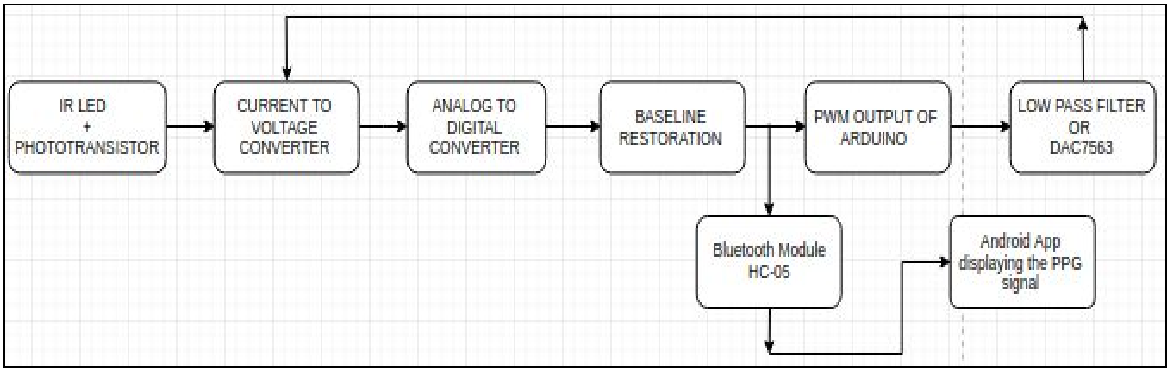

Figure 2.2 : Block Diagram

2.3.1 LED AND PHOTOTRANSISTOR CIRCUIT

The first stage of the circuit involves sensing of the reflected IR light using TCRT5000 which are reflective sensors. They include an infrared emitter and phototransistor in a leaded package which blocks visible light. The current vs voltage characteristics of TCRT5000 IR LED is shown in Fig 2.3.

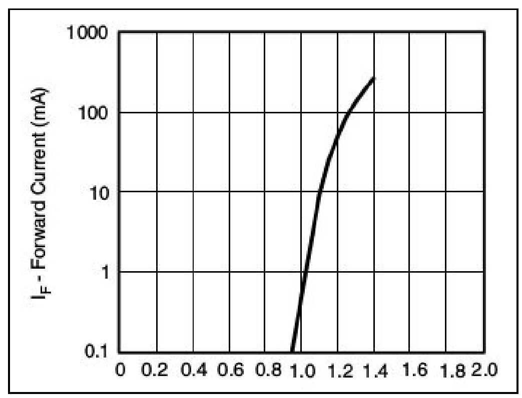

Figure 2.3 :I-V characteristics of TCRT5000

Reason for choosing phototransistor over photodiode for IR detection :

1. Better sensitivity than photodiode
2. High gain of around 50 to 100
3. Much lower level of noise than photodiodes
4. Does not have a good high frequency response i.e bandlimited to around 250 kHz. Though it doesn't matter in case of PPG signal acquisition since frequency of desired signal is < 5 Hz

Working : The current I_L flowing in the LED-phototransistor circuit in Fig 2.4 generates IR light (wavelength ~ 950 nm) which after reflection and attenuation through the finger falls on the phototransistor of TCRT5000. The phototransistor generates current I_C corresponding to the amount of reflected IR light falling on it. In the absence of fingertip, a dark current (approx. 10 nA) flows through the phototransistor. In the final circuit, the current is controlled by the auto-LED controller described in section 2.2.4 .

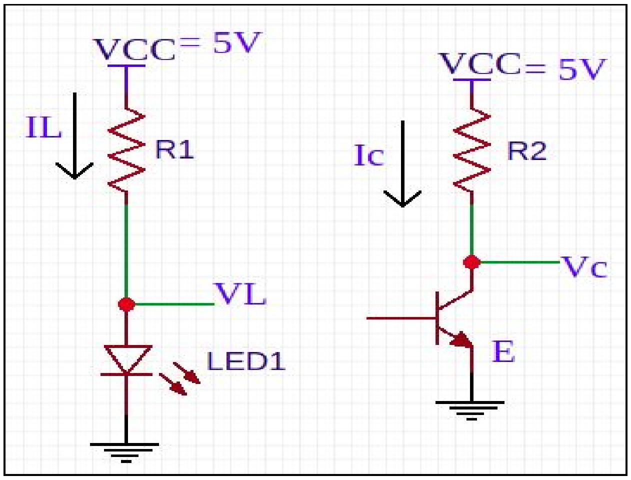

Figure 2.4 : IR LED and PhotoTransistor

2.3.2 CURRENT TO VOLTAGE CONVERTER

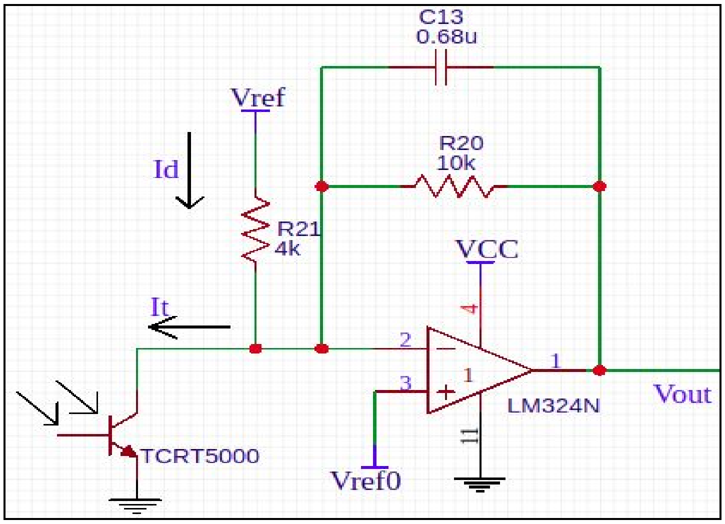

Figure 2.5 : Current to Voltage Converter

The output voltage of the circuit in Fig 2.5 is given by below expression :

$$V_{out} = V_{ref0} + \left(I_t - \frac{V_{ref} - V_{ref0}}{R_{21}}\right) R_{20}$$

$$I_t = I_c + \delta i_c$$

The current I_t generated due to reflected IR radiation has two components : a DC baseline offset I_c and a pulsalite component or the AC component (δi_c). This is followed by a controlled current injector to make sure that the opamp output is not driven into saturation due to the DC component I_c which if passed through the current to voltage converter will amplify to a large extent because of high amplification factor(~ 10^4) and thus will saturate the opamp output V_{out} . What is desired is that only the AC component (δi_c) passes through the current to voltage converter. But because the control of V_{ref} through the arduino to ensure the below condition

$$I_c = \frac{V_{ref} - V_{ref0}}{R_{21}}$$

is not perfect, some small dc component may sometimes pass through the I-V Converter.

2.3.3 BASELINE RESTORATION

Most bio-signal waveforms have a baseline along with the desired signal component. The baseline drifts over a large range compared to the excursion (pk-pk value) of the signal component. To make effective use of the input dynamic range of the signal acquisition setup, the baseline should be restored, at least partly, by removing the offset drift before digitisation of the signal [1]. Digital-signal-processing-based methods have been used for correction of baseline drift, but these can be used only after the digitisation of the signal. Generally, the spectra of the drift are overlapped with that of the signal, making it difficult to restore the baseline drift by high pass filtering the signal [1].

In the I-V converter circuit of Fig. 2.5, V_{ref} has been controlled to eliminate the DC offset current in order to restore the baseline and ensure that the signal remains constrained in the desired range. An algorithm has been implemented to restore the baseline based on *requirement basis* which is explained in section 3.3.

2.3.4 AUTO LED INTENSITY CONTROL

Different people have varying skin colour, finger shapes as well as the pressure one puts on the phototransistor which leads to varying pk-pk value of current flowing through phototransistor. To account for that, an LED current controller has been designed which will control the amount of current and hence the light emitted from the LED by varying the current I_L in Fig. 2.6. Based on the value read by the microcontroller, it decides the current I_L by varying the PWM pin D8->SDI (Serial Data Input). The output V_{out} is fed to a buffer so that the op-amp is able to supply current I_L. The range of V_{out} achieved was [0 - 4.8 V] by giving [0 - 255] at the D8 pin of arduino.

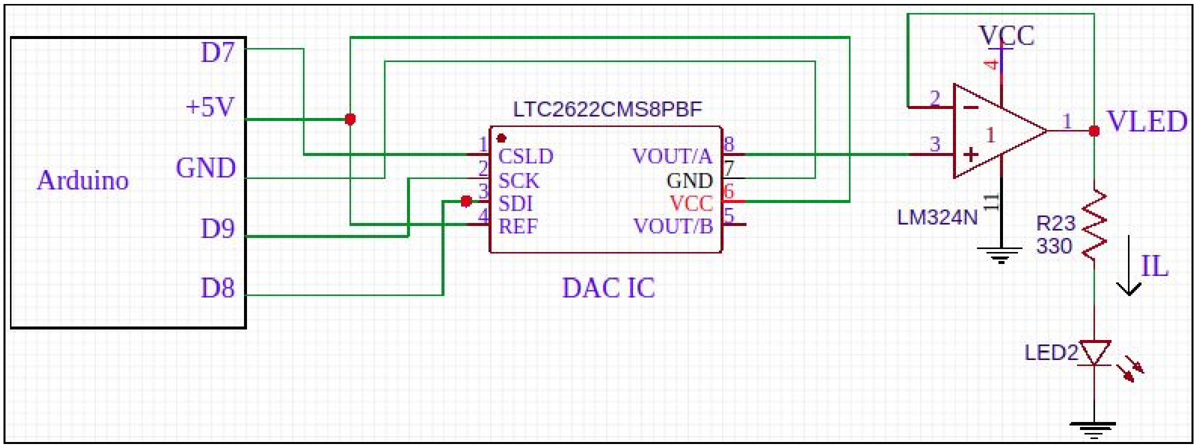

Figure 2.6 : Auto LED Intensity control

Pseudo Code :

1. Read the adc signal in the microcontroller
2. Find the maximum and minimum value of the signal in a window of 80 samples(chosen empirically). Thus the pk-pk value of signal, *amp = (maximum_value - minimum_value)*
3. Based on the value of amp, a linear mapping from "amp" to V_{LED} was done.

$amp = 0.5\ V$ mapped to $V_{LED} = 5\ V$

$amp = 1.5\ V$ mapped to $V_{LED} = 4\ V$

$$V_{LED} = 5 - (amp - 0.5)$$

2.2.5 LOW PASS FILTER FOR PWM SIGNAL FROM ARDUINO

In Fig. 2.5, V_{ref} is controlled using the PWM output of the microcontroller. The PWM signal from arduino is a square shaped pulse of 500 Hz but V_{ref} has to be a constant DC voltage. To convert this to a DC voltage, a 4^{th} order low pass filter has been designed. The filter which we implemented is a cascade of a second order LPF and two first order RC LPF. After this filtering, the filter output is passed through a buffer to erase out the impedance and limited current problem of the low pass filter. The cut off frequency of the filter is around 2.5 Hz. The output of the low pass filter shows around 40-60 mV peak to peak voltage which is fine since the PPG signal pk-pk range after amplification is around 1V.

Gain of second order LPF = $1 + \frac{R8}{R5} = 1 + \frac{0.47}{4.7} = 1.1$

Cut-off Frequency of second order LPF = $\frac{1}{2\pi RC} = \frac{1}{2\pi * 820k\Omega * 0.47\mu F} = 2.59$ Hz

Cut-off Frequency of first order LPF = $\frac{1}{2\pi RC} = \frac{1}{2\pi * 820k\Omega * 0.47\mu F} = 2.59$ Hz

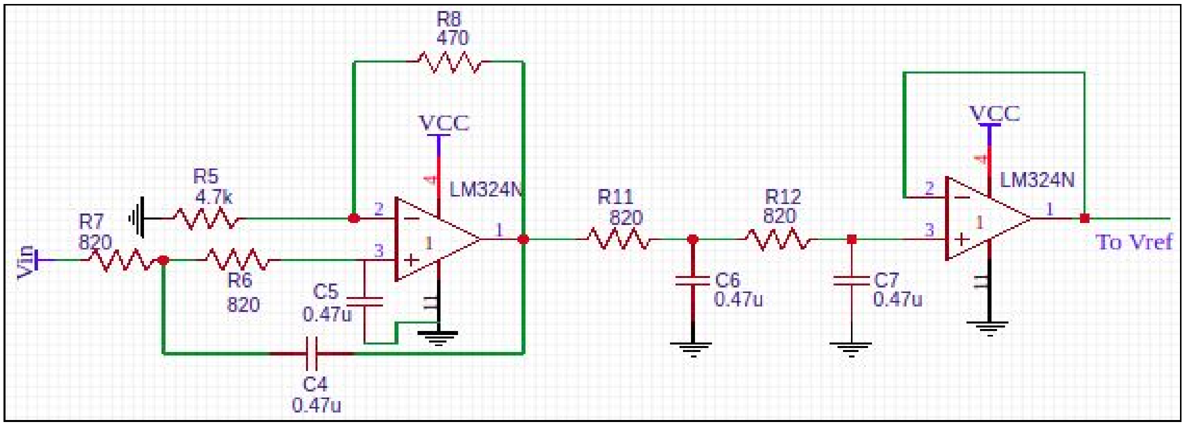

Figure 2.7 : Complete Low Pass Filter

2.3.6 DECOUPLING CAPACITORS TO REMOVE NOISE FROM POWER SUPPLY

For reducing the noise in the DC voltage coming from the power supply, decoupling capacitors of values 100µF, 0.1µF and 0.1µF has been used. The job of decoupling capacitor is to suppress high-frequency noise in power supply signals. They take tiny voltage ripples, which could otherwise be harmful to delicate ICs, out of the voltage supply. Though it was found out that there wasn't much difference in the noise level of the power supply before and after this addition, and the voltage was approximately (5 ± 0.04) V. Fig 2.8 provides the circuit for decoupling capacitors.

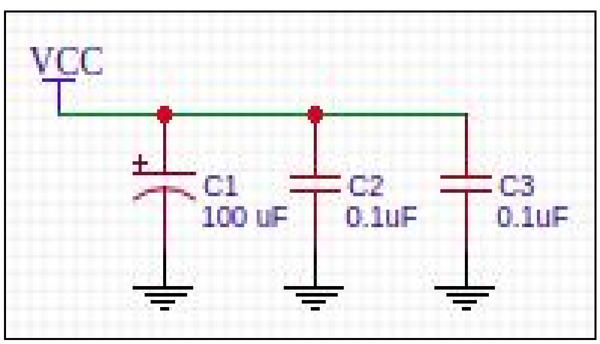

Figure 2.8 : Decoupling Capacitors

Complete Circuit Design

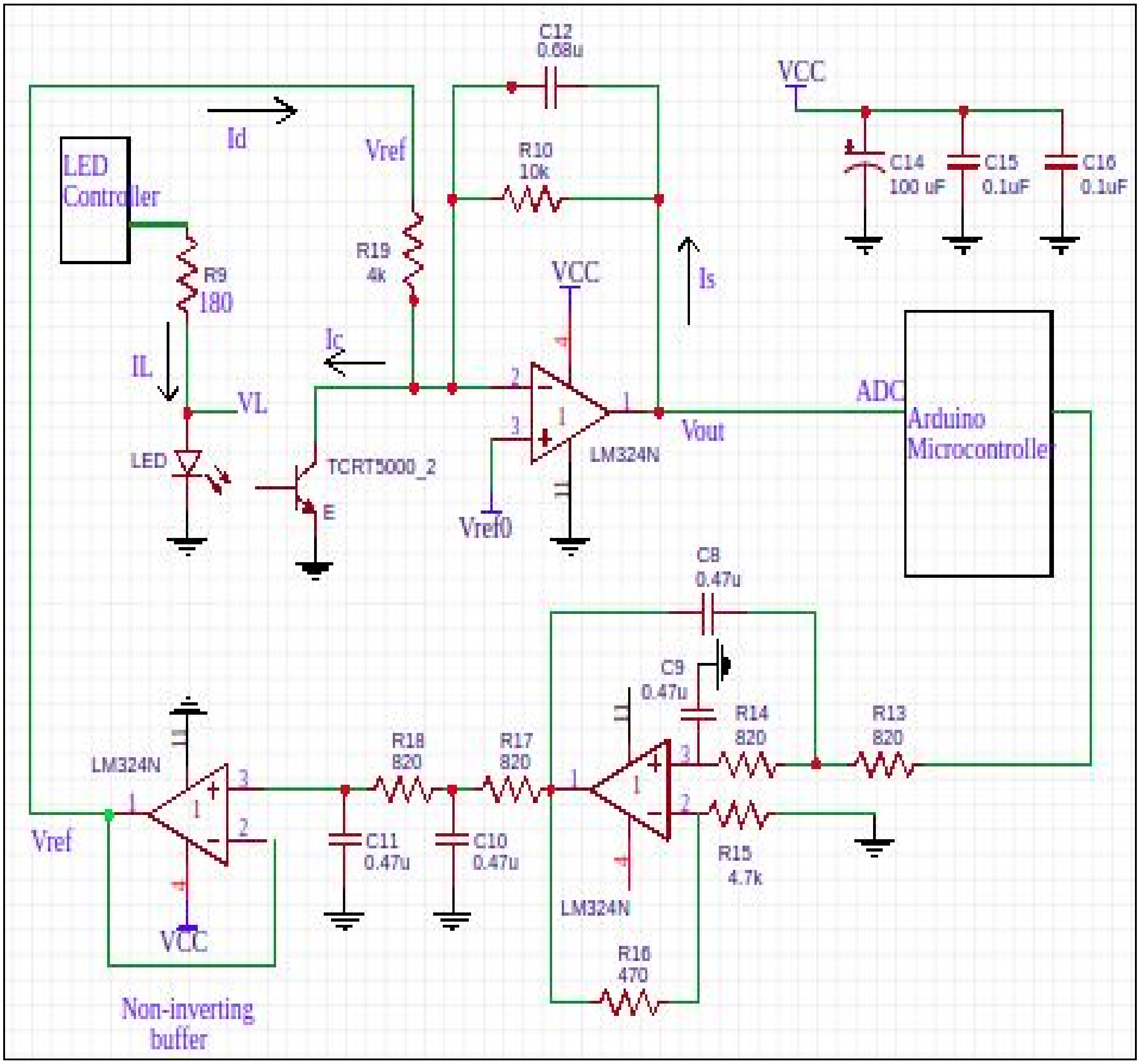

Figure 2.9 : Final Complete Circuit

CHAPTER 3 : PROJECT IMPLEMENTATION

3.1 Experimental Observations of LED-phototransistor + I/V Converter Circuits

3.1.1 Table 3.1 - Testing of LED Circuit in Fig 2.4 : Maximum current allowed in the TCRT5000 LED = 60 mA. Operating current range I_L in our circuit < 20 mA (suggested).

R1 (in Ω)	I_L(in mA)	V_L (in V)
180	20.8	1.24
150	24.9	1.26
120	31	1.28
100	37.2	1.28
80	57	1.34
47	80	1.25

3.1.2 Table 3.2 - Testing of Phototransistor Circuit in Fig 2.4 :

Vc (in V)	Ic (in mA)	R2 (in KΩ)
4.99	0.48	0.15
4.65	0.42	10
4.26	0.27	18
3.3	0.10	47
0.88	0.047	100

3.1.3 Table 3.3 - Testing of Sensor and I-V converter circuit in Fig 3.1 : Without the finger the current I_C is directed according to Vref and op-amp circuit. But on putting the finger, the phototransistor acts as a current source and provides current based on the IR light falling on it.

V_{ref} (in V)	Ic (on placing finger)(in mA)	Ic (without finger)(in mA)
3.74	0.42	3.67
3.21	0.42	3.60
3.07	0.42	3.45
2.53	0.42	2.96
1.42	0.42	1.82
0.44	0.42	0.83

*Above tables are Experimental data

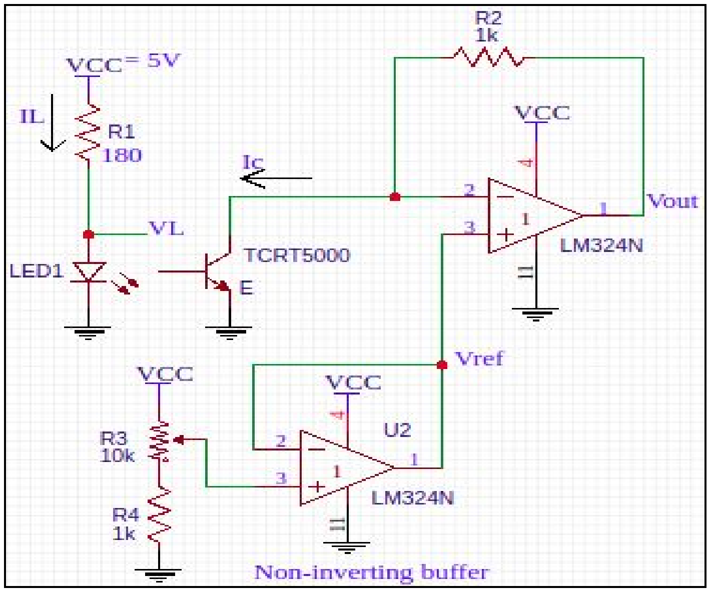

Figure 3.1 : Sensor + I-V converter circuit

3.2 Plot of Input vs Output characteristics of 4th order LPF in Fig. 2.7

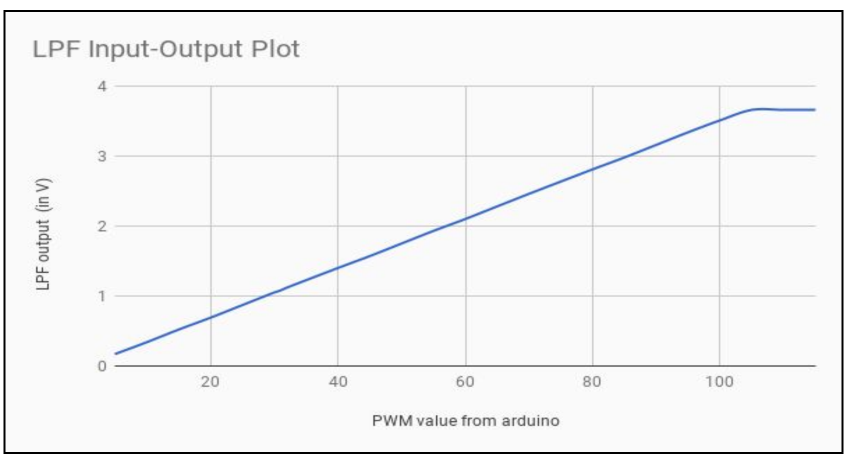

Figure 3.2: LPF Input-Output characteristics

3.3 BASELINE RESTORATION

To detect whether the op-amp output is saturated, we read the absolute value of the signal and check for how many sample values the output is in saturation. The pseudo code for the same is detailed next :

Pseudo code :

1. read the adc value in microcontroller = val (say)
2. If (val > 170)   then   countup = countup + 1
   else if (val < 10)   then   countdown = countdown + 1

   If (countup > 10)   then $V_{ref} = V_{ref} + 1$
   else if (countdown > 10)   then $V_{ref} = V_{ref} - 1$

** V_{ref} in Fig. 2.5

We came up with an upper and a lower bound for the signal range based on the output range of the op-amp. When the signal goes out of the bounds, we instruct the Vref to change accordingly. If the signal is saturated at *saturation_min_value* (nearly 0.04 ~ 6 in LM324N) for a certain number of samples,the PWM output is decreased such that the current supplied by the Vref branch compensates for the DC offset in the photo-transistor current and vice-versa for the case when the signal is saturated at *saturation-max-value* (nearly 3.8 V ~ 192 in LM324N)

3.4 BLUETOOTH TRANSMISSION OF SIGNAL

For transmission of PPG data, bluetooth module HC-05 has been used. It transmits data taken from arduino to an Android App called Bluetooth Graphics which plots the PPG waveform. The sampling frequency of the bluetooth receiver is limited by the sampling frequency of ADC of the microcontroller. We used interrupts in arduino for sampling the signal and were able to control the sampling frequency of the ADC.
Maximum ADC sampling frequency achieved using interrupts = 6421 Hz

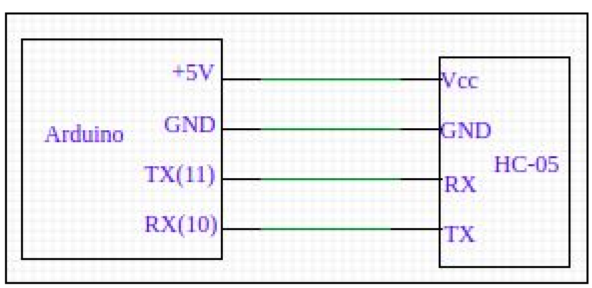

Figure 3.3: Bluetooth-Arduino Interfacing

CHAPTER 4 : RESULTS AND EVALUATION

Figure 4.1 : PPG Signal with low pk-pk (~ 31 mV) on oscilloscope

Figure 4.2 : PPG signal amplified to pk-pk ~ 1V on oscilloscope

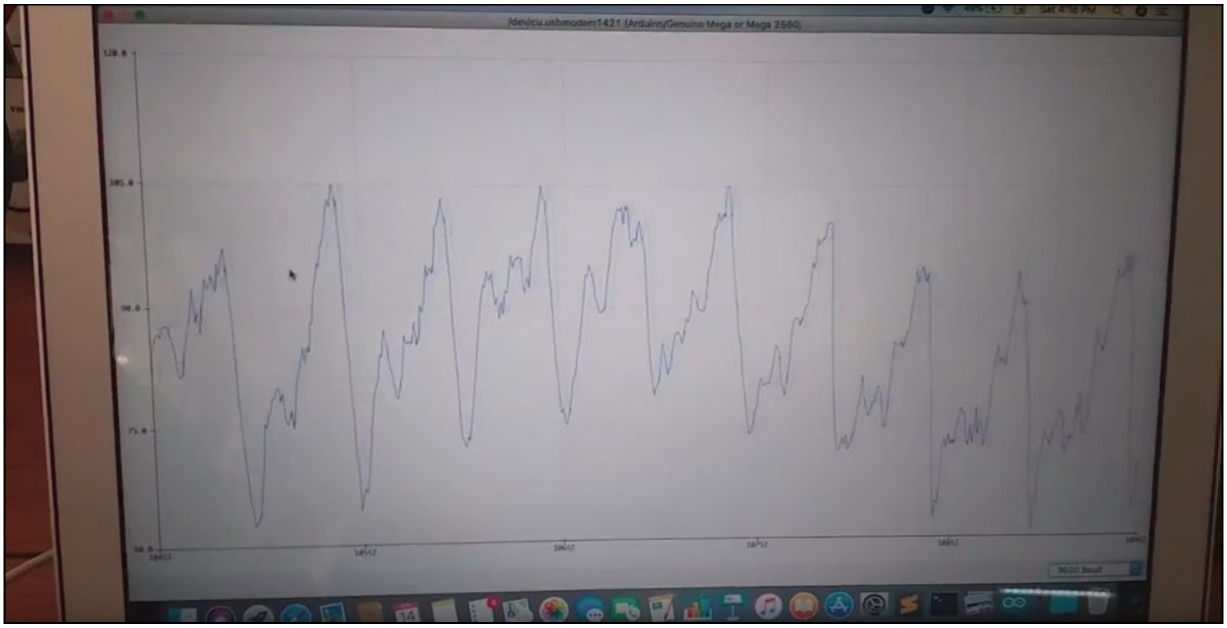

Figure 4.3 : PPG Signal with pk-pk (> 1V) on arduino serial plotter

The above displayed PPG waveform is what we get as the final output of our module on a arduino serial plotter and is sampled at a frequency of 114 Hz. We also displayed the PPG signal on the android app but unfortunately we don’t have pictures of the same.

The PPG signal is quite unstable and any kind of motion artifacts for example head motion without any hand motion while keeping your finger still over the phototransistor introduces some distortion in the waveform shape of the signal.

CHAPTER 5 : CONCLUSIONS

Thus we achieved our aim (not fully) of developing a PPG signal acquisition module which can provide the true PPG signal with low noise and minimal amount of filtering. The circuitry of the module is low-cost and easy to use. The signal was amplified to a reasonable level of around 1.5 V pk-pk value while maintaining the actual waveform of the signal intact. We were able to transmit the PPG signal via bluetooth and displayed the PPG signal on mobile app named "Bluetooth Terminal/Graphics" which can be downloaded from Google Play Store.

Final Devices, Components and IC's Used in the project :

1. TCRT5000 reflective optical Infrared Sensor
2. LM324N Operational Amplifier
3. LTC2622 12-bit DAC IC
4. Arduino Mega Microcontroller (through Arduino Nano would have served the same purpose)
5. HC-05 Bluetooth Module
6. Android Smartphone
7. Basic Components - Resistors, Capacitors, Breadboard etc.

SUGGESTIONS FOR FUTURE WORK:

1. **Auto-Ranging of PPG signal**: The signal amplitude depends on various external factors like skin color, ambient conditions and other factors. In order to compensate for the aforementioned, we need to control the equivalent resistor value R_{20} connected between the output and the non-inverting terminal of the opamp in Fig. 2.5. It is this resistor which controls the amplitude of the output signal and analog switches can be used to control the value of the resistor. But while testing analog switches we observed that analog switches add a lot of noise to the signal.

2. Developing a portable and wearable hand device which can be worn such that the LED-phototransistor pair can be attached to a finger and the circuitry on the dorsal side (back of hand-palm).

3. Developing a **transmittance based PPG Acquisition device** since the transmittance based device will suffer less from motion artifacts [5]. While the reflection based PPG device which we developed suffered from motion artifacts.

4. **Using green light** as the emitter in place of infrared light because it has much greater absorptivity for both oxyhaemoglobin and deoxyhaemoglobin compared to infrared light. Therefore, the change in reflected green light is greater than that in reflected infrared light when blood pulses through the skin, resulting in a better SNR ratio for green light source compared to infrared light source [5].

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