Faculty of
Electronic Engineering
كلية الهندسة الإلكترونية

HEART-RATE AND RESPIRATION VISUALIZATION USING ARDUINO AND LABVIEW

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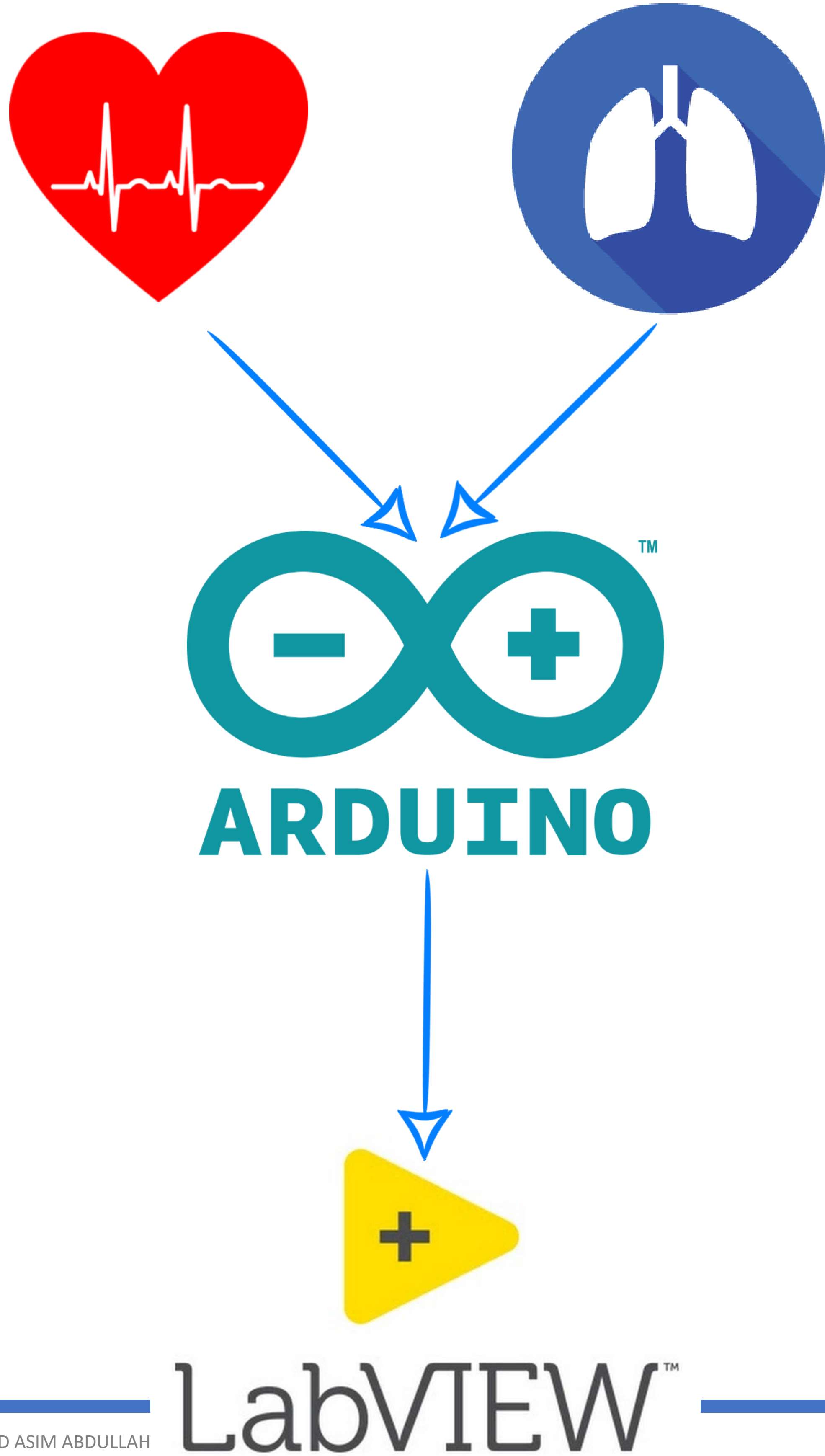
ARDUINO
LabVIEW

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AKNOWLEDGMENT

First and foremost, I would like to thank

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For his support, outstanding guidance and encouragement thought my project.

I would like to thank my family, especially my parents for their encouragement, patience and assistance over the year I am forever indebt to my parents who have always kept me in their prayers.

ABSTRACT

Project Title:

HEART-RATE AND RESPIRATION VISUALIZATION USING ARDUINO AND LABVIEW

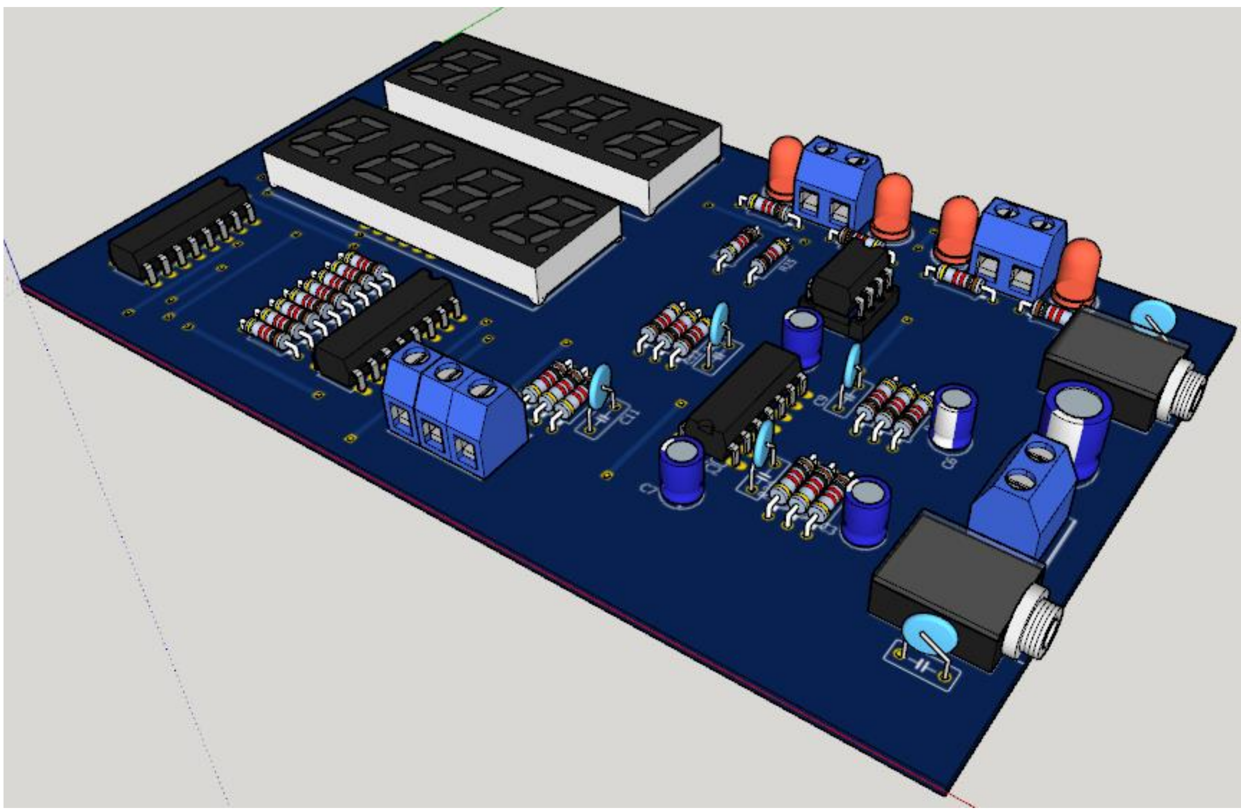


Fig 1. Final product of the project in 3D

Challenge/problems I trying to solve through my project:

In current day many people have irregular heart rate or respiration rate due to many reasons: environment, workplaces, dust or even the unhealthy food.

So, I tried to fined simple and cost-effective way to simply monitor them using low cost hardware and friendly user interface for a PC.

How my project helps/solves the mentioned problems:

By simply attach two devices to the body each one has its own sensor and working principle I can monitor the change in the biomedical signal and visualize it using 7-segment or PC program.

Description of the project:

The device is containing to sensor one for sensing the change in blood flow in veins and arteries through finger tips by emitting red light through skin and receive the light from the other side of the skin by using LDR in voltage divider and measuring the change in voltage which represent the change on the blood flow rate.

The other sensor contents a temperature resistor, which changes its value during the change in temperature of air during breathing.

Taking each signal from the mentioned sensors and filtering them using two stage band pass filters with their constant amplification
the amplification is made by normal op-amps.

The output signal from final stage of each sensor is passed through comparator to extract the actual rate for each respiration and heart pulses.

CONCLUSION

Monitoring heart rate and respiration can be simply done using two cheap and effective sensors (LDR and temperature resistor)

Using Arduino as Data Accusing card and visualize data using LabView as user interface

Collect and store data for comparing or extracting useful information about the patient.

CHAPTER 1

BASICS OF PHOTOPLETHYSMOGRAM:

1- Introduction:

A photoplethysmogram (PPG) is an optically obtained plethysmogram, a volumetric measurement of an organ. A PPG is often obtained by using a pulse oximeter which illuminates the skin and measures changes in light absorption. [1] A conventional pulse oximeter monitors the perfusion of blood to the dermis and subcutaneous tissue of the skin.

Diagram of the layers of human skin

With each cardiac cycle the heart pumps blood to the periphery. Even though this pressure pulse is somewhat damped by the time it reaches the skin, it is enough to distend the arteries and arterioles in the subcutaneous tissue. If the pulse oximeter is attached without compressing the skin, a pressure pulse can also be seen from the venous plexus, as a small secondary peak.

The change in volume caused by the pressure pulse is detected by illuminating the skin with the light from a light-emitting diode (LED) and then measuring the amount of light either transmitted or reflected to a photodiode [2]. Each cardiac cycle appears as a peak, as seen in the figure. Because blood flow to the skin can be modulated by multiple other physiological systems, the PPG can also be used to monitor breathing, hypovolemia, and other circulatory conditions. [3] Additionally, the shape of the PPG waveform differs from subject to subject and varies with the location and manner in which the pulse oximeter is attached.

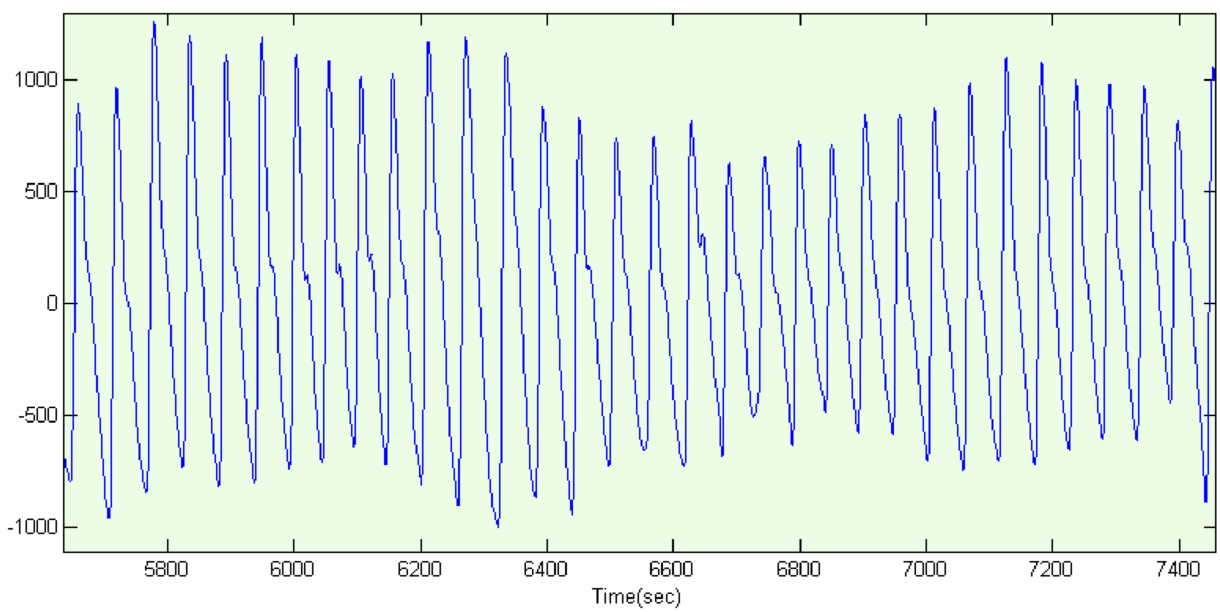


Fig 2. Representative PPG taken from an ear pulse oximeter. Variation in amplitude are from Respiratory Induced Variation.

2-Sites for measuring PPG:

While pulse oximeters are a commonly used medical device, the PPG derived from them is rarely displayed and is nominally only processed to determine heart rate. PPGs can be obtained from transmissive absorption (as at the finger tip) or reflection (as on the forehead).

In outpatient settings, pulse oximeters are commonly worn on the finger. However, in cases of shock, hypothermia, etc. blood flow to the periphery can be reduced, resulting in a PPG without a discernible cardiac pulse. In this case, a PPG can be obtained from a pulse oximeter on the head, with the most common sites being the ear, nasal septum, and forehead.

PPGs can also be obtained from the following parts:

the vagina (vaginal photo plethysmograph).

the clitoris (clitoral photo plethysmograph).

the esophagus.

Motion artifacts have been shown to be a limiting factor preventing accurate readings during exercise and free-living conditions.

3-Monitoring heart rate and cardiac cycle:

Because the skin is so richly perfused, it is relatively easy to detect the pulsatile component of the cardiac cycle. The DC component of the signal is attributable to the bulk absorption of the skin tissue, while the AC component is directly attributable to variation in blood volume in the skin caused by the pressure pulse of the cardiac cycle.

The height of AC component of the photoplethysmogram is proportional to the pulse pressure, the difference between the systolic and diastolic pressure in the arteries. As seen in the figure showing premature ventricular contractions (PVCs), the PPG pulse for the cardiac cycle with the PVC results in lower amplitude blood pressure and a PPG. Ventricular tachycardia and ventricular fibrillation can also be detected.

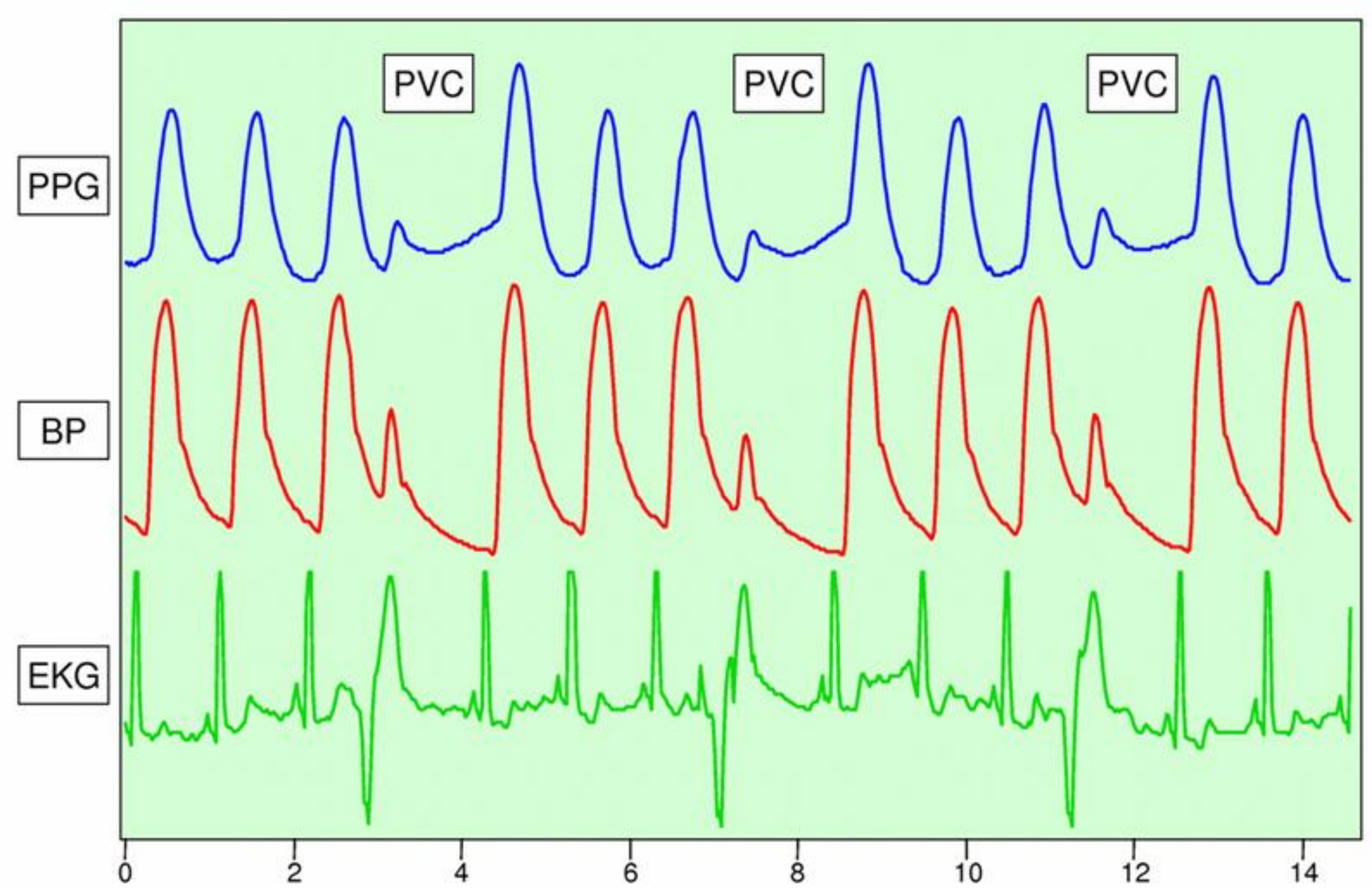


Fig 3. Premature Ventricular Contraction (PVC) can be seen in the PPG just as in the EKG and the Blood Pressure (BP).

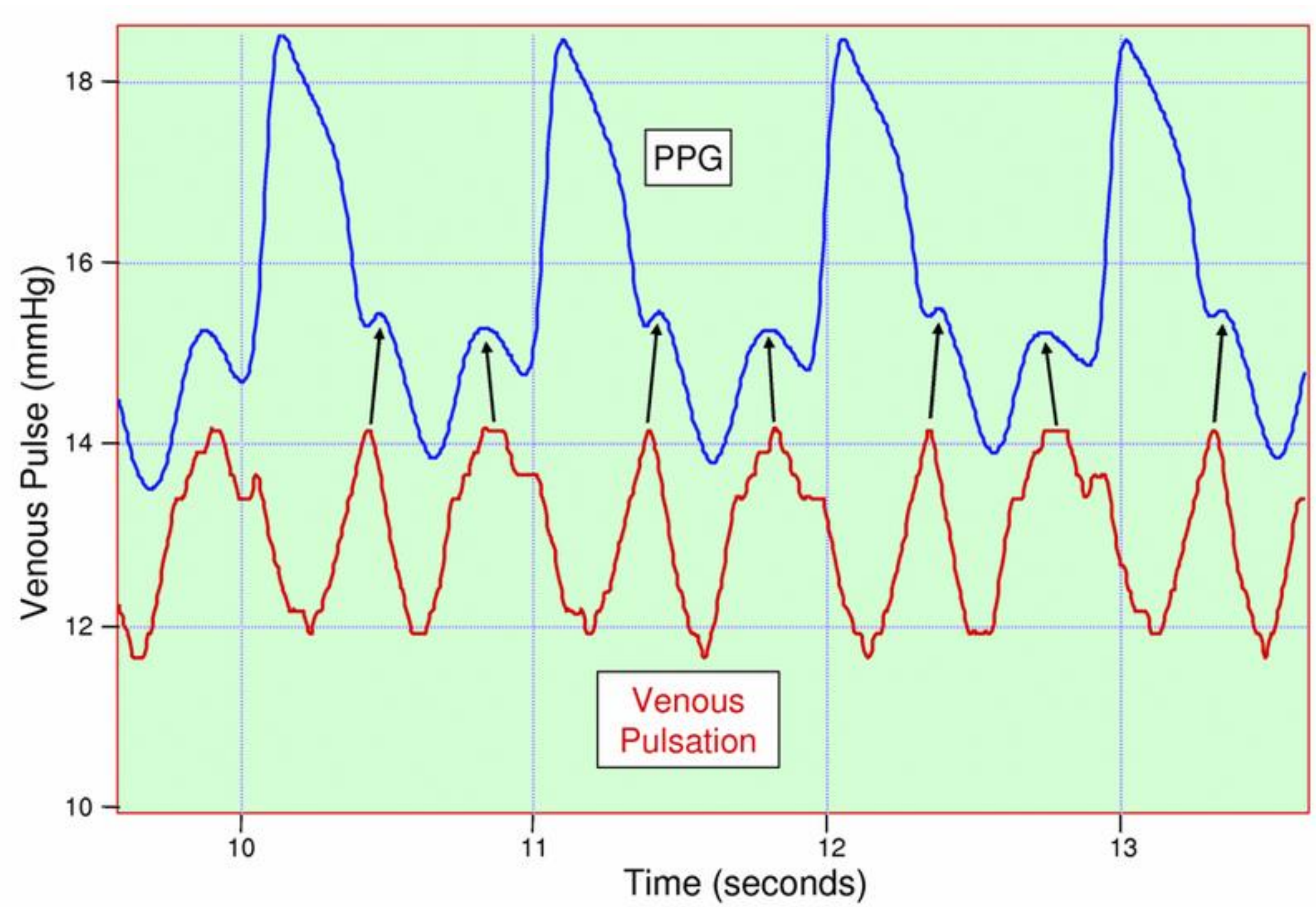
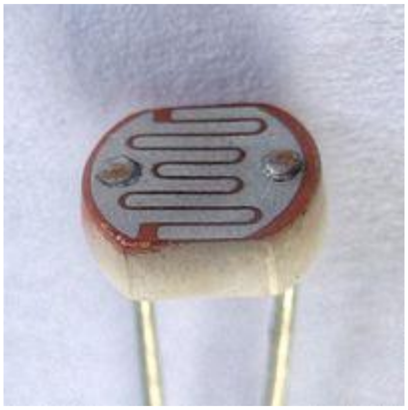


Fig 4. Venous pulsations can be clearly seen in this PPG.

CHAPTER 2

HARDWARE AND SOFTWARE

1-LDR(Photoresistor):

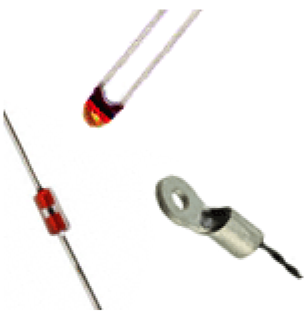


A photoresistor (or light-dependent resistor, LDR, or photo-conductive cell) is a light-controlled variable resistor. The resistance of a photoresistor decreases with increasing incident light intensity; in other words, it exhibits photoconductivity. A photoresistor can be applied in light-sensitive detector circuits, and light-activated and dark-activated switching circuits.

A photoresistor is made of a high resistance semiconductor. In the dark, a photoresistor can have a resistance as high as several megaohms (MΩ), while in the light, a photoresistor can have a resistance as low as a few hundred ohms. If incident light on a photoresistor exceeds a certain frequency, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electrons (and their hole partners) conduct electricity, thereby lowering resistance. The resistance range and sensitivity of a photoresistor can substantially differ among dissimilar devices. Moreover, unique photoresistors may react substantially differently to photons within certain wavelength bands.

A photoelectric device can be either intrinsic or extrinsic. An intrinsic semiconductor has its own charge carriers and is not an efficient semiconductor, for example, silicon. In intrinsic devices the only available electrons are in the valence band, and hence the photon must have enough energy to excite the electron across the entire bandgap. Extrinsic devices have impurities, also called dopants, added whose ground state energy is closer to the conduction band; since the electrons do not have as far to jump, lower energy photons (that is, longer wavelengths and lower frequencies) are sufficient to trigger the device. If a sample of silicon has some of its atoms replaced by phosphorus atoms (impurities), there will be extra electrons available for conduction. This is an example of an extrinsic semiconductor. [4]

2-Thermistor:



A thermistor is a temperature sensitive resistor, they are often used as a temperature sensor. The term thermistor is a contraction of the words “thermal” and “resistor”. All resistors have some dependency on temperature, which is described by their temperature coefficient. In most cases for (fixed or variable) resistors the temperature coefficient is minimized, but in the case of thermistors a high coefficient is achieved. Unlike most other resistors, thermistors usually have negative temperature coefficients (NTC) which means the resistance decreases as the temperature increases. These types are called NTC thermistors. Thermal resistors with a positive temperature coefficient are called PTC thermistors (Positive Temperature Coefficient).

Types and applications:

Thermistors are ceramic semiconductors. In most cases they are composed of metal oxides, which are dried and sintered to obtain the desired form factor. The types of oxides and additives determine their characteristic behavior. For NTC’s cobalt, nickel, iron, copper or manganese are common oxides. For PTC's barium, strontium or lead titanites are commonly used.

NTC thermistor

The NTC type is used when a change in resistance over a wide temperature range is required. They are often used as temperature sensors in the range of -55°C to 200°C, although they can be produced to measure much lower of higher temperatures. Their popularity can be accounted to their quick response, reliability, robustness and low price.

PTC thermistor

The PTC type used when a sudden change in resistance at a certain temperature is required. They exhibit a sudden increase in resistance above a defined temperature, called the switch, transition of "Curie" temperature. The most common switching temperatures are in the range of 60°C to 120°C. They are often used for self-regulating heating elements and self-resetting over-current protection.

1-Arduino Uno Kit:

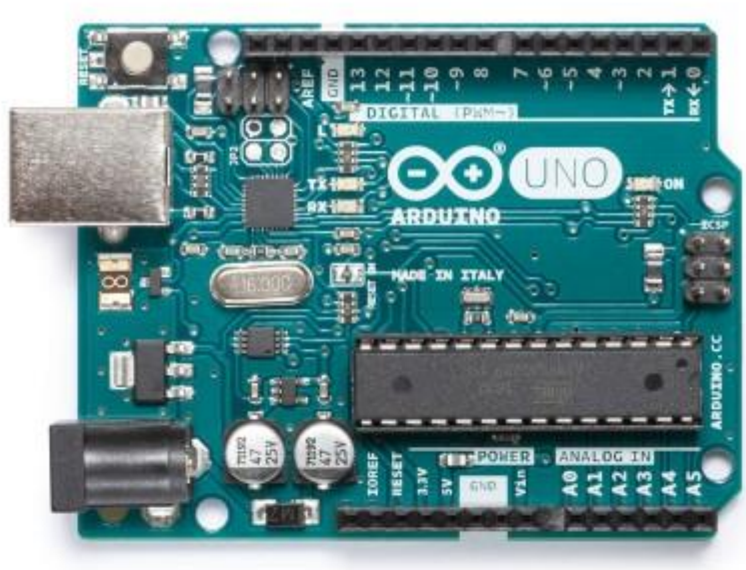


Fig 5. Arduino Uno Board.

The Arduino Uno is a microcontroller board based on the ATmega328 [5]. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Uno differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega8U2 programmed as a USB-to-serial converter.

"Uno" means one in Italian and is named to mark the upcoming release of Arduino 1.0. The Uno and version 1.0 will be the reference versions of Arduino, moving forward. The Uno is the latest in a series of USB Arduino boards, and the reference model for the Arduino platform.

The Arduino Uno can be powered via the USB connection or with an external power supply. The power source is selected automatically. External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector. The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.

The power pins are as follows:

- VIN. The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.

- 5V. The regulated power supply used to power the microcontroller and other components on the board. This can come either from VIN via an on-board regulator or be supplied by USB or another regulated 5V supply.

- 3V3. A 3.3-volt supply generated by the on-board regulator. Maximum current draw is 50 mA.

- GND. Ground pins.

Each of the 14 digital pins on the Uno can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms.

In addition, some pins have specialized functions:

- Serial: 0 (RX) and 1 (TX). Used to receive (RX) and transmit (TX) TTL serial data. These pins are connected to the corresponding pins of the ATmega8U2 USB-to-TTL Serial chip.

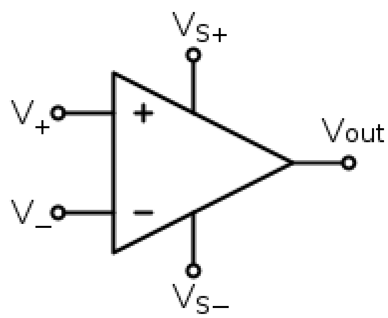
- External Interrupts: 2 and 3. These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.

- PWM: 3, 5, 6, 9, 10, and 11. Provide 8-bit PWM output with the analogWrite() function.

- SPI: 10 (SS), 11 (MOSI), 12 (MISO), 13 (SCK). These pins support SPI communication, which, although provided by the underlying hardware, is not currently included in the Arduino language.

- LED: 13. There is a built-in LED connected to digital pin 13. When the pin is HIGH value, the LED is on, when the pin is LOW, it's off.

3-Operational amplifier:



An operational amplifier (often op-amp or opamp) is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output. [6] In this configuration, an op-amp produces an output potential (relative to circuit ground) that is typically hundreds of thousands of times larger than the potential difference between its input terminals. Operational amplifiers had their origins in analog computers, where they were used to perform mathematical operations in many linear, non-linear, and frequency-dependent circuits.

The popularity of the op-amp as a building block in analog circuits is due to its versatility. By using negative feedback, the characteristics of an op-amp circuit, its gain, input and output impedance, bandwidth etc. are determined by external components and have little dependence on temperature coefficients or manufacturing variations in the op-amp itself.

Op-amps are among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific devices. Many standard IC op-amps cost only a few cents in moderate production volume; however, some integrated or hybrid operational amplifiers with special performance specifications may cost over US$100 in small quantities. [7] Op-amps may be packaged as components or used as elements of more complex integrated circuits.

The op-amp is one type of differential amplifier. Other types of differential amplifier include the fully differential amplifier (similar to the op-amp, but with two outputs), the instrumentation amplifier (usually built from three op-amps), the isolation amplifier (similar to the instrumentation amplifier, but with tolerance to common-mode voltages that would destroy an ordinary op-amp), and negative-feedback amplifier (usually built from one or more op-amps and a resistive feedback network).

4-Passive filters:

Passive implementations of linear filters are based on combinations of resistors (R), inductors (L) and capacitors (C). These types are collectively known as passive filters, because they do not depend upon an external power supply and/or they do not contain active components such as transistors.

Inductors block high-frequency signals and conduct low-frequency signals, while capacitors do the reverse. A filter in which the signal passes through an inductor, or in which a capacitor provides a path to ground, presents less attenuation to low-frequency signals than high-frequency signals and is therefore a low-pass filter. If the signal passes through a capacitor, or has a path to ground through an inductor, then the filter presents less attenuation to high-frequency signals than low-frequency signals and therefore is a high-pass filter. Resistors on their own have no frequency-selective properties but are added to inductors and capacitors to determine the time-constants of the circuit, and therefore the frequencies to which it responds.

The inductors and capacitors are the reactive elements of the filter. The number of elements determines the order of the filter. In this context, an LC tuned circuit being used in a band-pass or band-stop filter is considered a single element even though it consists of two components.

At high frequencies (above about 100 megahertz), sometimes the inductors consist of single loops or strips of sheet metal, and the capacitors consist of adjacent strips of metal. These inductive or capacitive pieces of metal are called stubs.

The simplest passive filters, RC and RL filters, include only one reactive element, except hybrid LC filter which is characterized by inductance and capacitance integrated in one element.

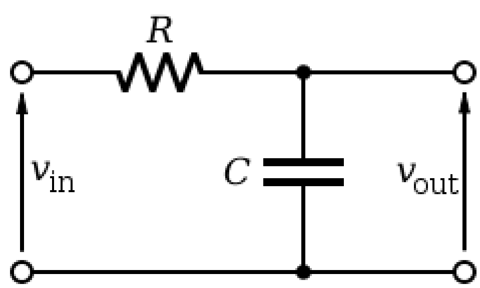


Fig 6. A low-pass electronic filter realized by an RC circuit

4-Active filters:

An active filter is a type of analog circuit implementing an electronic filter using active components, typically an amplifier. Amplifiers included in a filter design can be used to improve the cost, performance and predictability of a filter. [8]

An amplifier prevents the load impedance of the following stage from affecting the characteristics of the filter. An active filter can have complex poles and zeros without using a bulky or expensive inductor. The shape of the response, the Q (quality factor), and the tuned frequency can often be set with inexpensive variable resistors. In some active filter circuits, one parameter can be adjusted without affecting the others. [8]

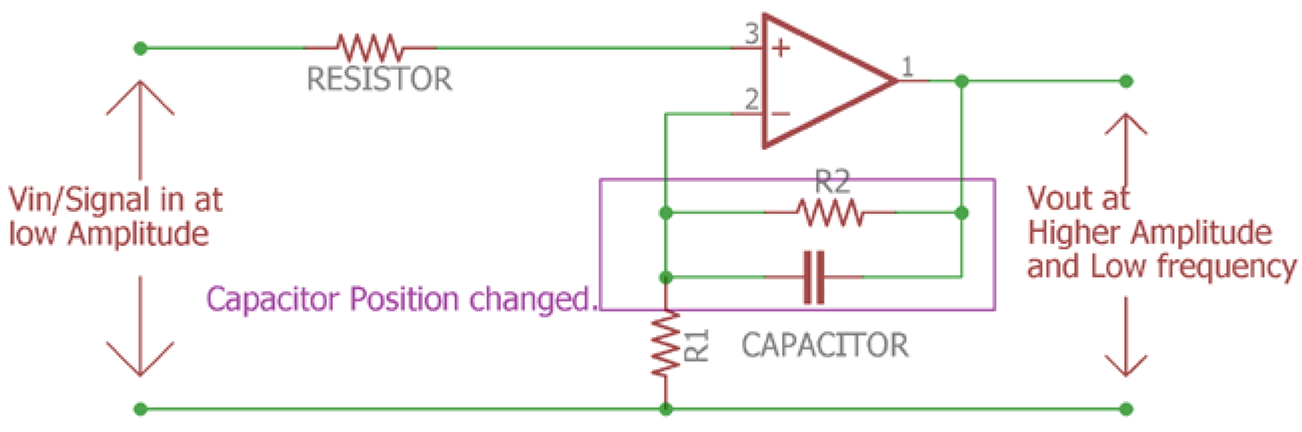
Using active elements has some limitations. Basic filter design equations neglect the finite bandwidth of amplifiers. Available active devices have limited bandwidth, so they are often impractical at high frequencies. Amplifiers consume power and inject noise into a system. Certain circuit topologies may be impractical if no DC path is provided for bias current to the amplifier elements. Power handling capability is limited by the amplifier stages. [9]

5-Non-inverting and Inverting Amplifier Filter Circuit:

[10] This active low pass filter circuit shown in the beginning also has one limitation. **Its stability can be compromised if the signal source impedance changed.** E.g. decrease or increase.

A standard design practice could improve the stability, removing the capacitor from input and connecting it **parallel with op-amp second feedback resistor**.

Here is the circuit **Non-Inverting Active Low Pass Filter-**

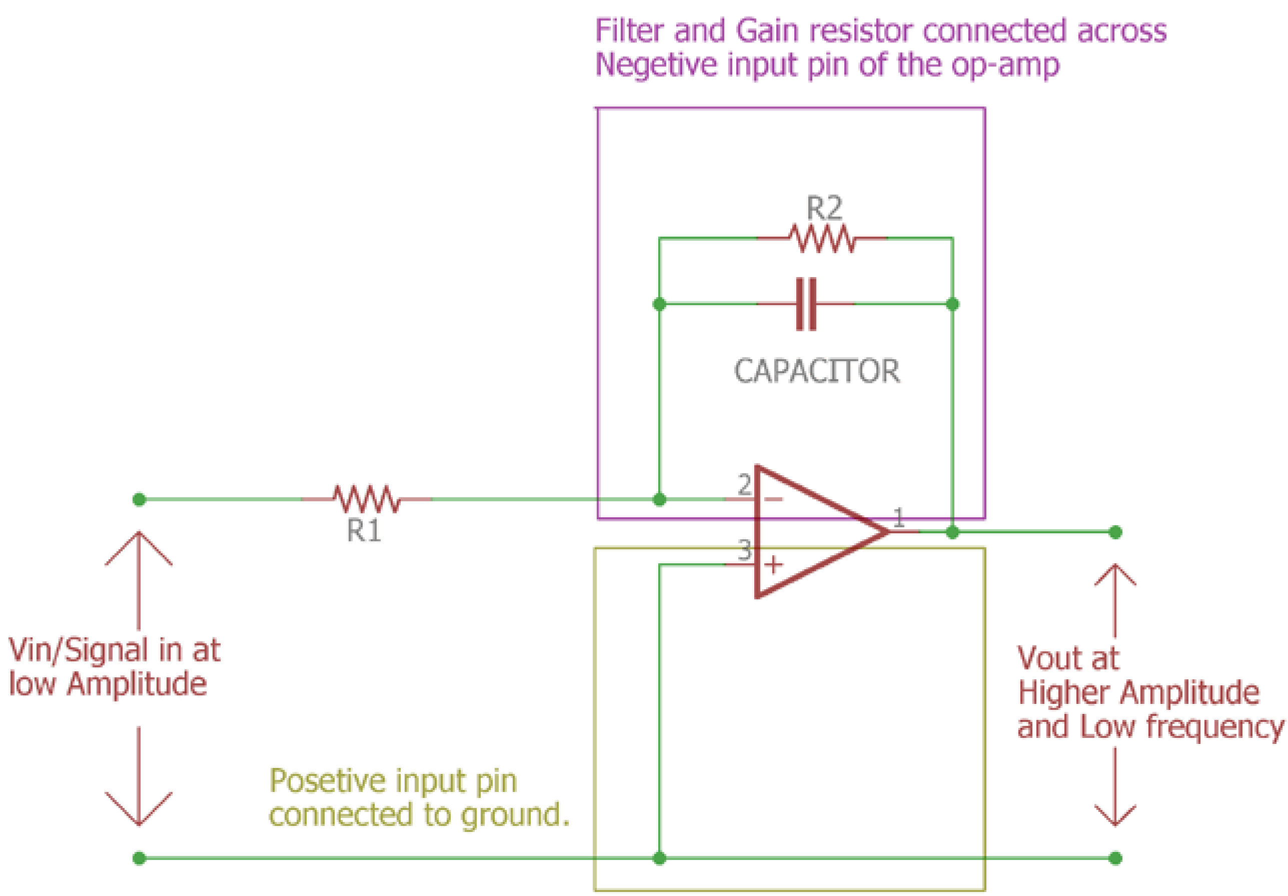


Active Low Pass Filter

In this figure, if we compare this with the circuitry described in the beginning, we can see that the **capacitor position is altered for impedance related stability**. In this configuration the external impedance makes no effect on the capacitors reactance, **thus the stability improved**.

On the same configuration if we want to invert the output signal then we can choose the inverting-signal configuration of the op-amp and could connect the filter with that inverted op-amp.

Here is the circuitry implementation of **inverted active low pass filter**:-



Active Low Pass Filter - Inverted Configuration

It is an active low pass filter in inverted configuration. **The op-amp is connected inversely**. In the previous section the input was connected across op-amp's positive input pin and the op-amp negative pin is used to make the feedback circuitry. Here the circuitry inverted. Positive input connected with ground reference and the capacitor and feedback resistor connected across op-amp negative input pin. This is called **inverted op-amp configuration and the output signal will be inverted than the input signal**.

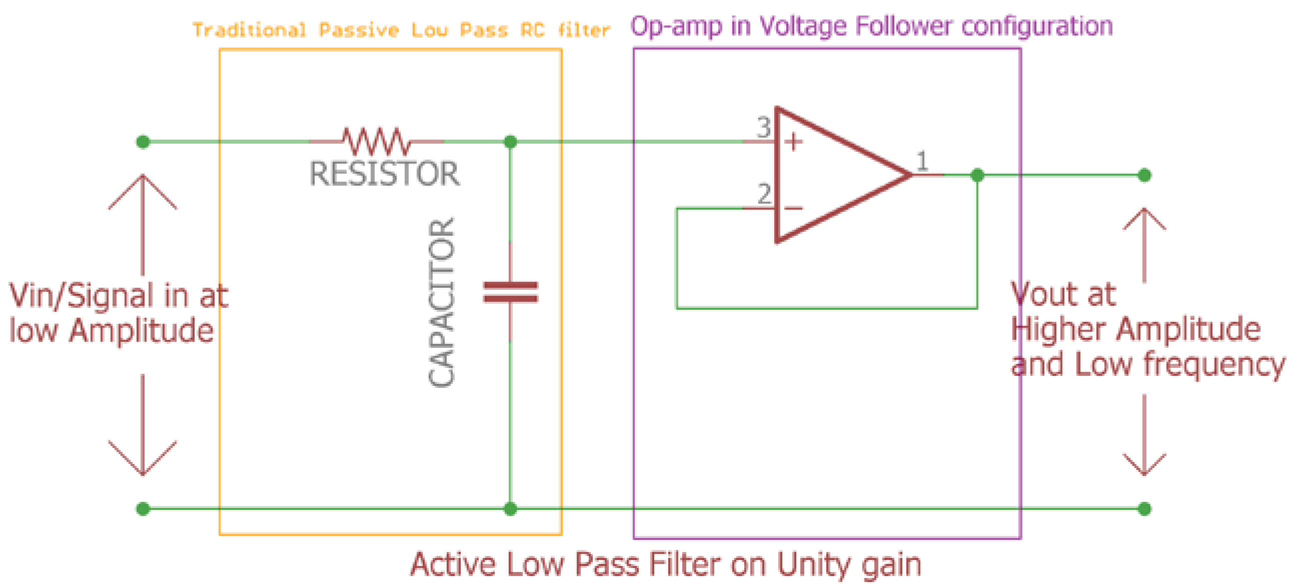
Unity Gain or Voltage Follower Active Low Pass Filter:

Till now the circuitry described here is used for voltage gain and post-amplification purpose.

We can make it using a unity gain amplifier, that means the output amplitude or gain will be same as input: **1x**. **Vin = Vout.**

Not to mention, it is also an op-amp configuration which often described as voltage follower configuration where the op-amp created the exact replica of the input signal.

Let's see the circuit design and how to **configure the op-amp as voltage follower and make the unity gain active low pass filter**: -



In this image, the feedback resistors of the op-amp are removed. Instead of the resistor the negative input pin of the op-amp connected directly with the output op-amp. This op-amp configuration is called as **Voltage follower configuration**. The gain is 1x. It is a unity gain active low pass filter. It will produce exact replica of the input signal.

Practical example with Calculation:

We will design a circuitry of active low pass filter in non-inverting op-amp configuration.

Specifications: -

1. **Input Impedance 10kohms**
2. **Gain will be 10x**
3. **Cutoff frequency will be 320Hz**

Let's calculate the value first before making the circuitry: -

Amplifier Gain (DC amplitude) (Af) = (1+R3/R2)

(Af) = (1+R3/R2)

Af = **10**

R2= **1k** (We need to select one value; we selected **R2 as 1k** for reducing the complexity of the calculation).

By putting the value together, we get (10) = (1+R3/1)

We calculated the value of the **third resistor is 9k**.

Now we need to calculate the value of the resistor according to the cut-off frequency. As active low pass filter and the passive low pass filter works on the same way the frequency cut-off formula is same as before.

Let's check the value of the capacitor if the cut-off frequency is 320Hz, we selected the value of the resistor is **4.7k**.

$fc = 1 / 2\pi RC$

By putting all value together, we get: -

$$320 = \frac{1}{2 * \pi * 4.7 * 1000 * C}$$

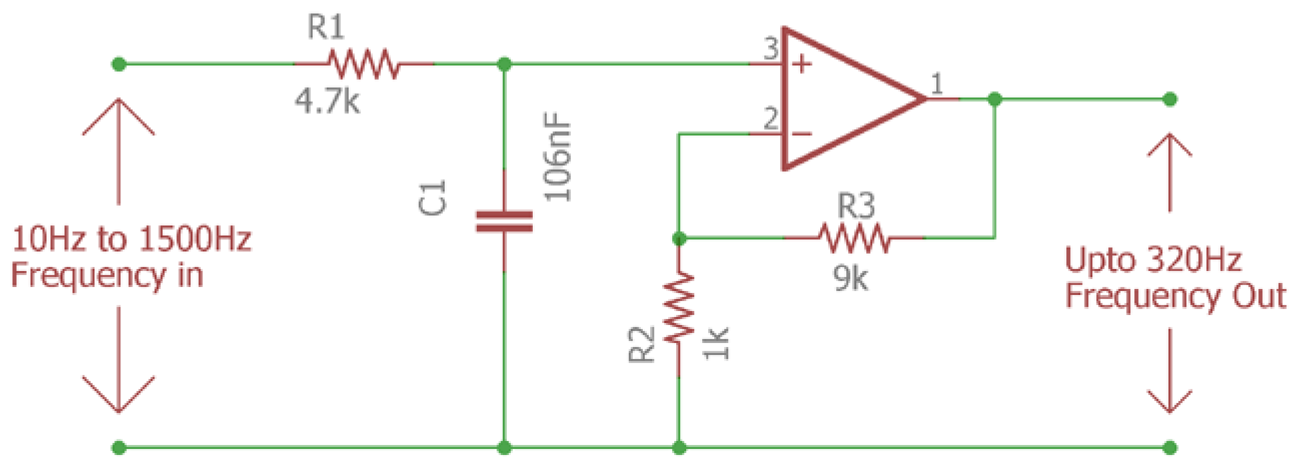
By solving this equitation, we get the value of the **capacitor is 106nF approximately**.

Next step is to calculate gain. The formula of the gain is same as passive low pass filter. The formula of gain or magnitude in dB is as follows: -

20log(Af)

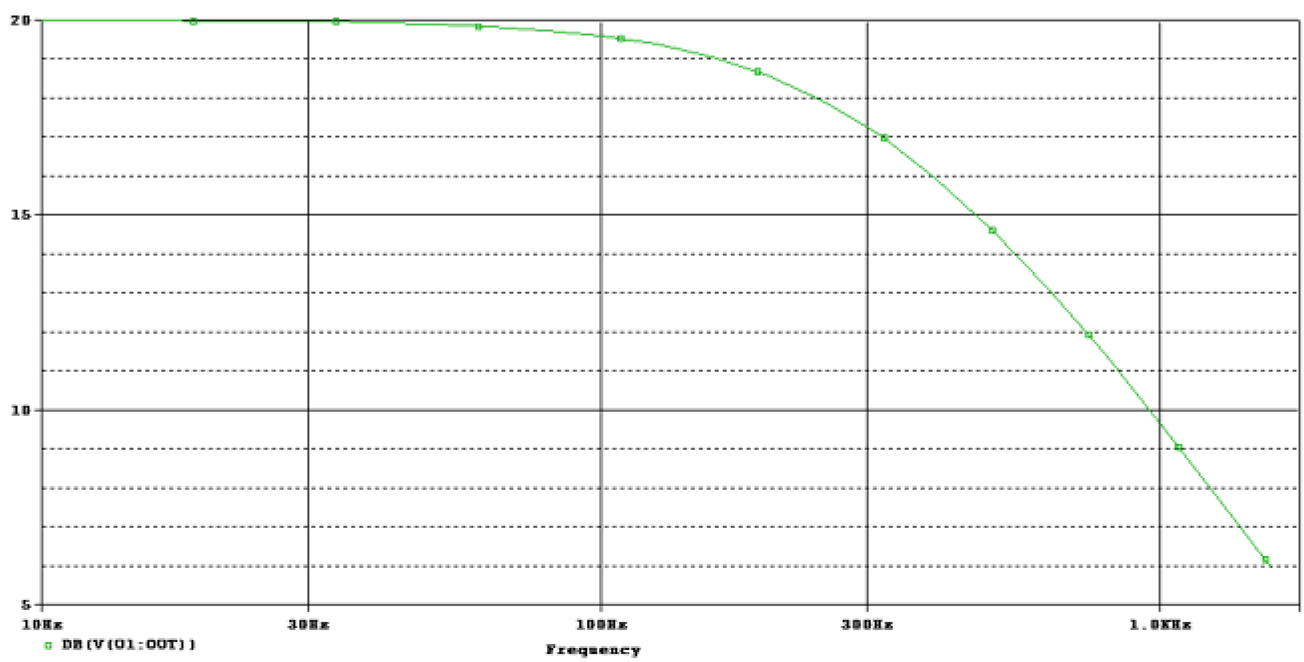
As the gain of the op-amp is 10x the magnitude in dB is 20log (10). **This is 20dB**.

Now as we already calculated the values now it is the time to construct the circuit. Let's add all together and build the circuit: -



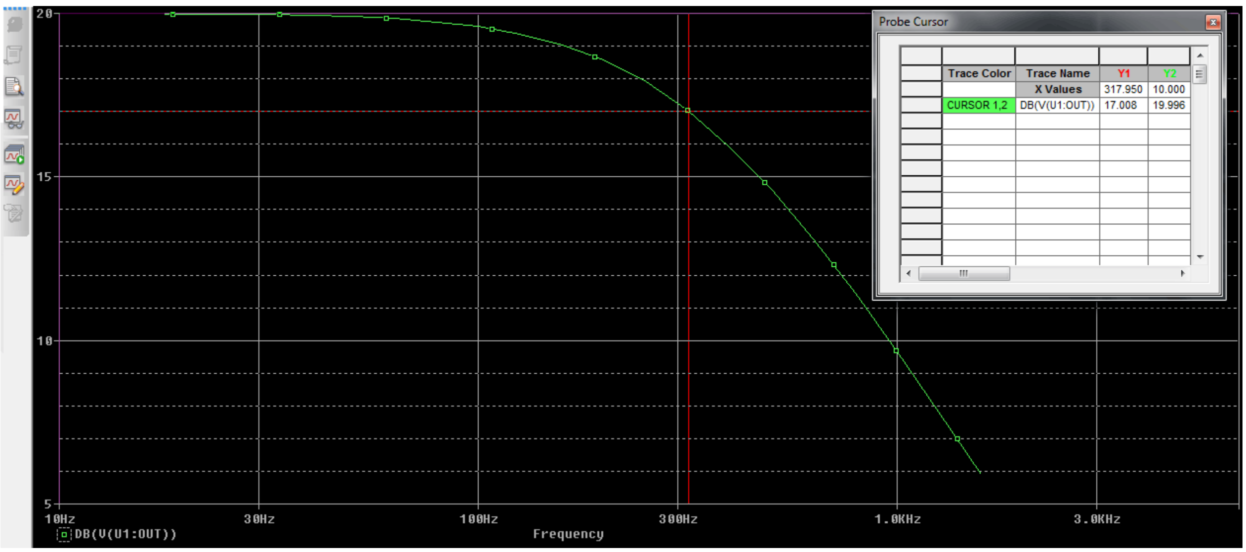
Active Low Pass Filter with 320Hz cutoff Frequency

We constructed the circuit based on the values calculated before. We will provide **10Hz to 1500Hz**frequency and **10 points per decade** at the input of the active low pass filter and will investigate further to see whether the cutoff frequency is 320Hz or not at the output of the amplifier.



This is **the frequency response curve**. The green line is started from 10Hz to 1500Hz as the input signal is supplied for that range of frequency only.

As we know that the corner frequency will be always at -3dB from the Maximum gain magnitude. Here the gain is 20dB. So, if we find out the -3dB point will get the exact frequency where the filter stops the higher frequencies.



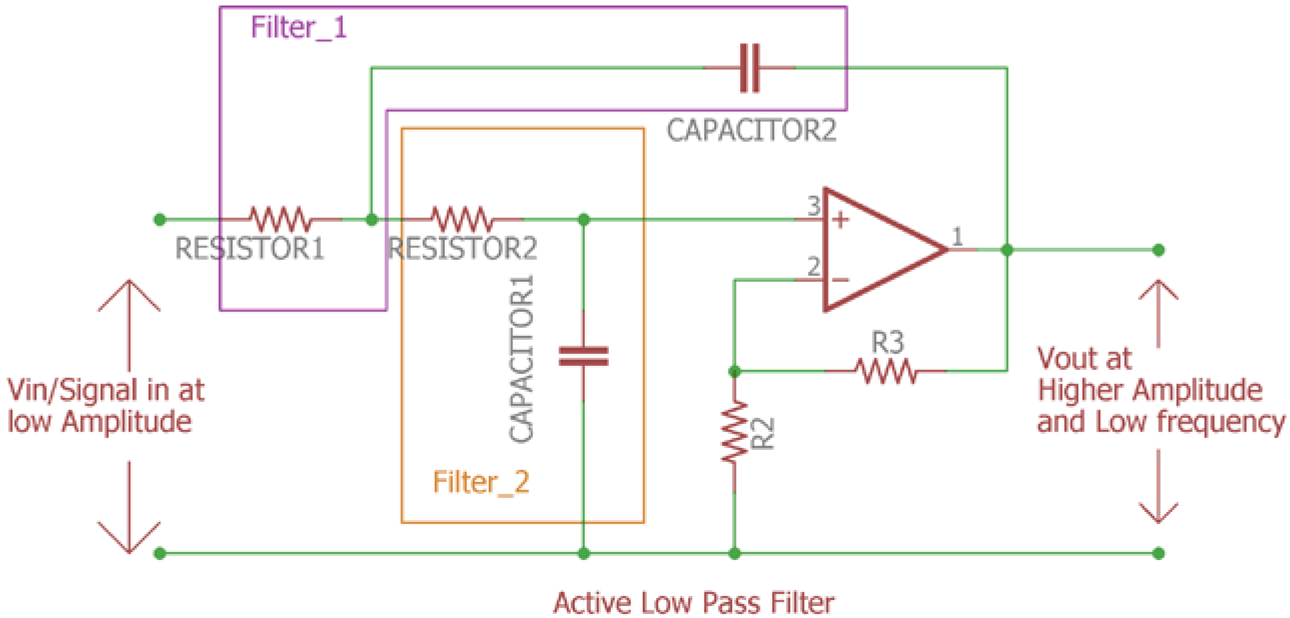
We set the cursor at the **17 dB as (20dB-3dB = 17dB)** the corner frequency and get **317.950Hz or 318Hz** which is close to the **320Hz**.

We can change the capacitor value to the generic one as **100nF** and not mention the corner frequency will also affected by few Hz.

Second Order Active Low Pass Filter:

It's possible to add more filters across one op-amp like second order active low pass filter. In such case just like the passive filter, extra RC filter is added.

Let’s see how the **second order filter circuit** is constructed.



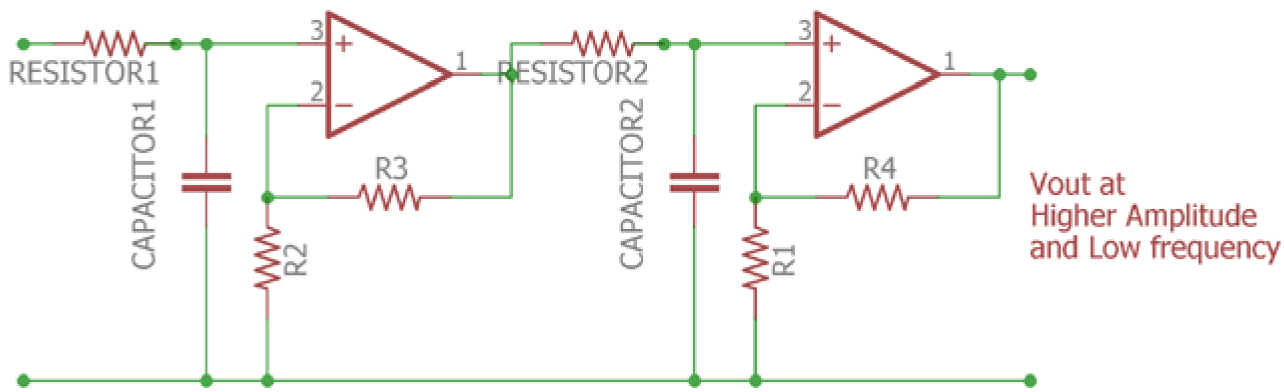
This is the Second order filter. In the above figure we can clearly see the two filters added together. This is the second order filter. It is a widely used filter and industrial application is Amplifier, Musical system circuitry before the Power Amplification.

As you can see there is one op-amp. The voltage gain is same as previously stated using two resistors. (Af) = (1+R3/R2)

The cut-off frequency is

$$fc = \frac{1}{\sqrt{R_1 C_1 R_2 C_2}}$$

One interesting thing to remember **if we want to add more op-amp which consist first order filters the gain will be multiplied by each individual**. Confused? May be a schematic will help us.



Active Low Pass Filter at op-amp cascading

The more the op-amp added the more gain is multiplied. See the above figure, in this image two op-amp cascaded with individual op-amp. In this circuit the Cascaded op amp, If the first one is having 10x gain and the second one is for 5x gain then the total gain will be 5 x 10 = 50x gain.

So, the magnitude of the cascaded op-amp low pass filter circuit in case of two op-amp is: -

dB = 20log (50)

By solving this equation, it is 34dB. So, the gain of cascading op-amp low pass filter gain formula is

TdB = 20log(Af1*Af2*Af3*......Afn)

Where TdB = Total Magnitude

This is how Active low pass filter is constructed. On the next tutorial, we will see how Active high pass filter can be constructed. But before the next tutorial let's see what the applications of Active low pass filter are:

Applications

Active Low pass filter can be used at multiple places where passive low pass filter cannot be used due to the limitation about gain or amplification procedure. Apart from that the active low pass filter can be used in following places: -

Low pass filter is widely used circuit in electronics.

Here are few applications of Active Low Pass Filter: -

1. Bass equalization before Power amplification
2. Video related filters.
3. Oscilloscope
4. Music control system and Bass frequency modulation as well as before woofer and high bass audio speakers for bass out.
5. Function Generator to provide variable low frequency out at different voltage level.
6. Changing the frequency shape at different wave from.

CHAPTER 2

HRR Counter Schematic:

1-Signal Processing

The circuit board consists of 2 sections.

Section 1:

is responsible for taking the input from the sensor and filtering it then amplify the signal before sending it to the microcontroller (Arduino UNO)**.**

Using two channels for input (CH1 & CH2)

Filtration process:

Using two stage active filters and passive filters to band pass the desired frequency which in this case is from 0.7 hz to 3.4 hz**.**

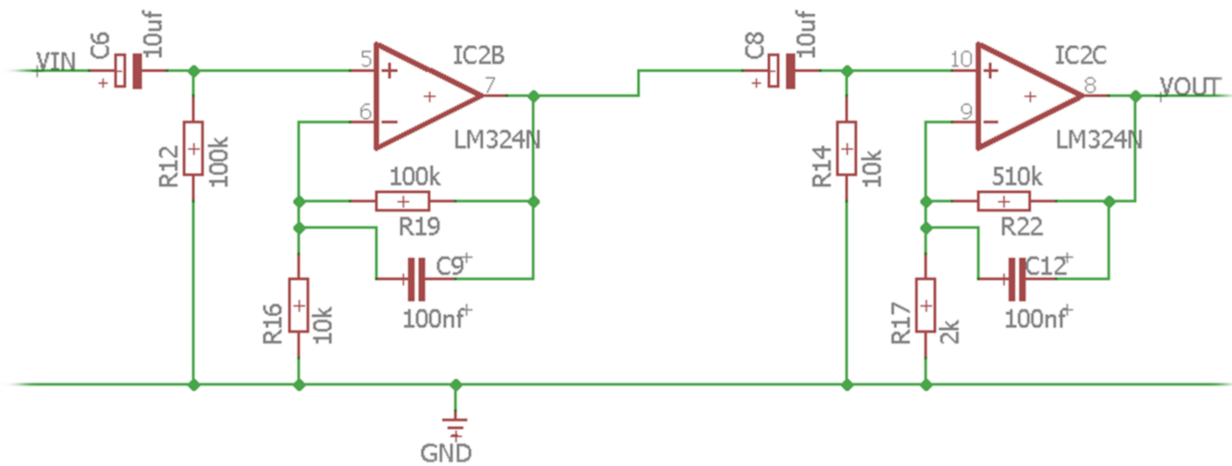


Fig 7. Two stage filters (EaglePCB).

First, I used RC passive high pass filter with cut-off frequency of 159.155mHZ. (calculated from previous chapter of filters)

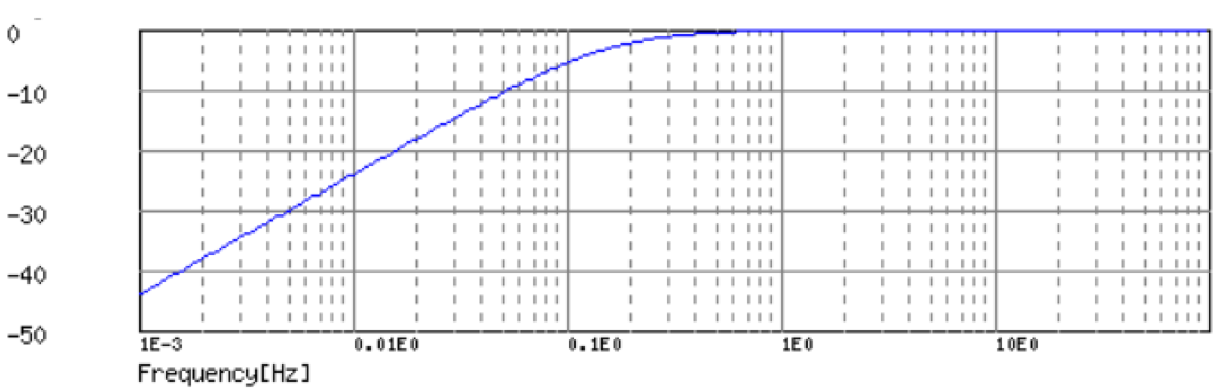


Fig 8. Frequncy response for 1'st stage High-pass RC filter.

Then I used active low-pass filter to band bass the signal frequency. Using the mentioned equations, the cut-off frequency is about 16 hz. With pre-amplification of 20 dB (or 10 V/V).

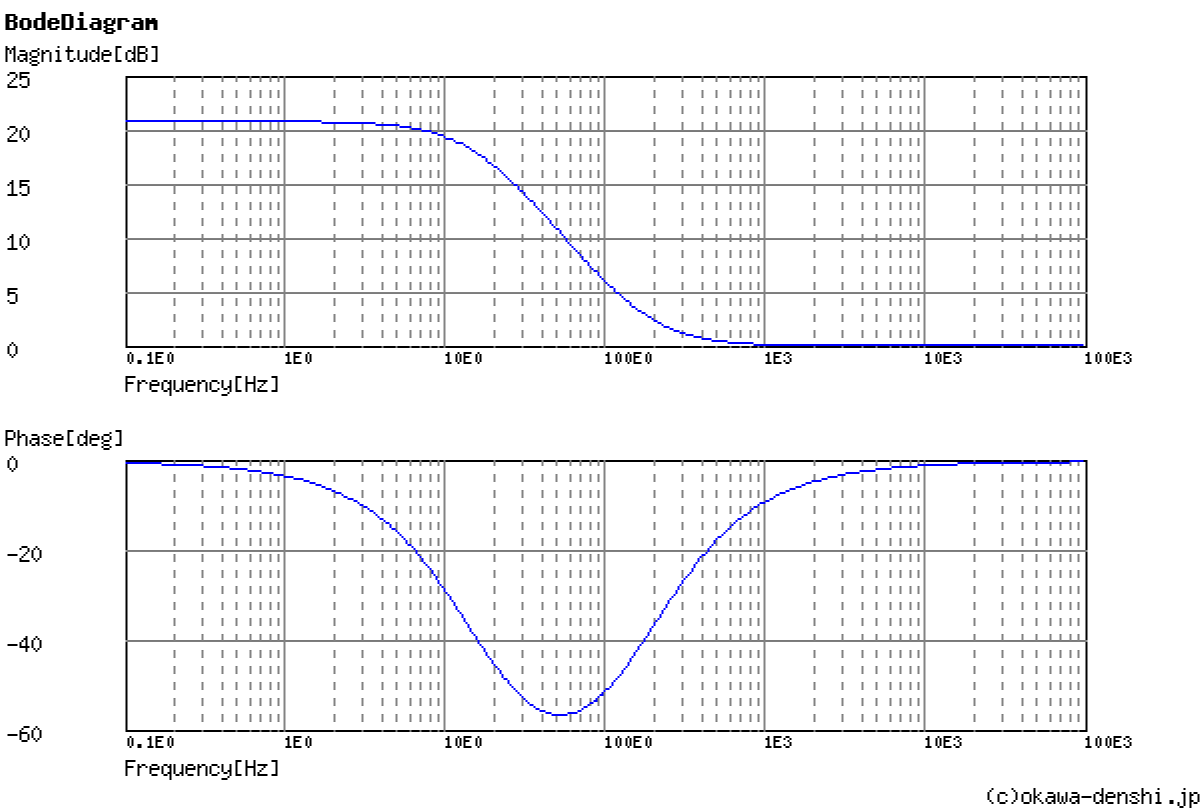


Fig 9. Frequncy response for 1’st stage Low-pass Active filter.

For the Second stage filter, I used another High-Pass RC filter with different configuration to get smoother signal with cut-off frequency of 1.59 HZ. (calculated from previous chapter for filters).

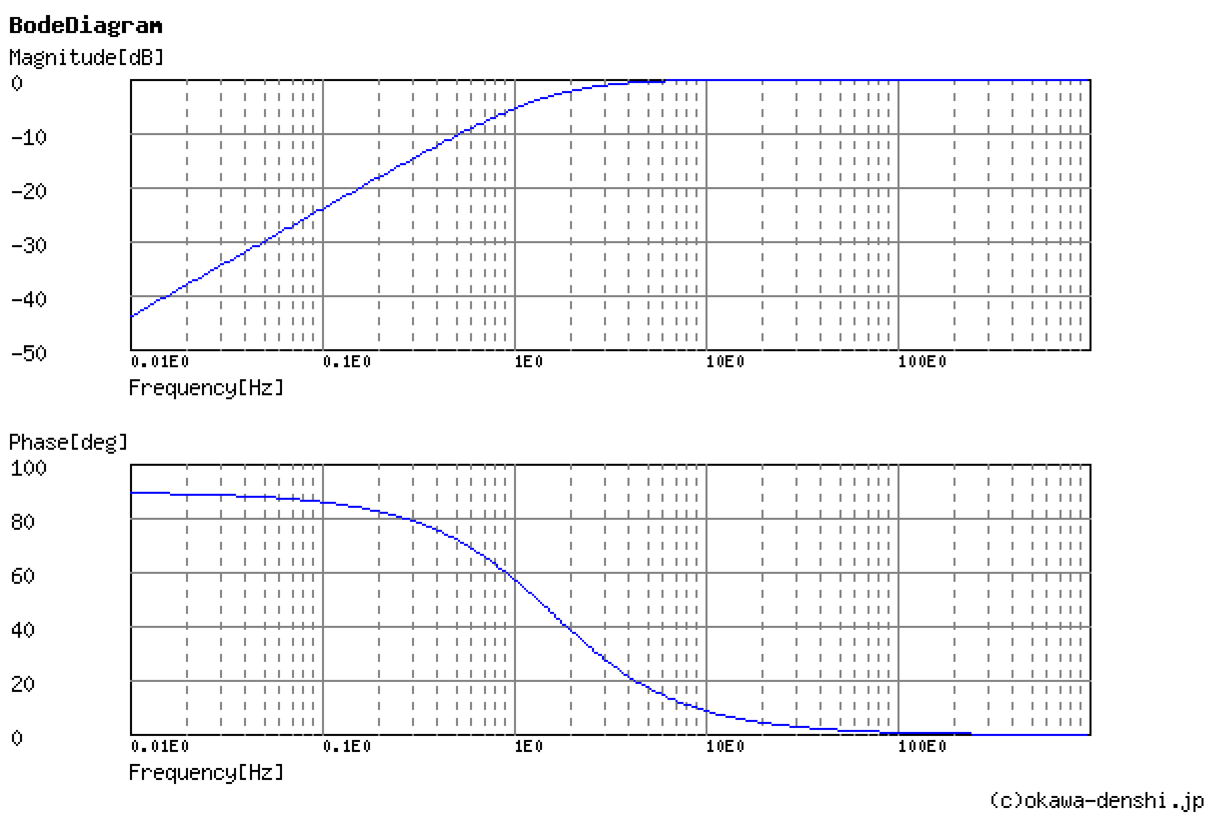


Fig 10. Frequncy response for 2’nd stage High-pass RC filter.

Followed by active low-pass filter to band bass the signal frequency. Using the mentioned equations, the cut-off frequency is about 3.12 hz (calculated from previous chapter for filters). With pre-amplification of 48 dB (or 255 V/V).

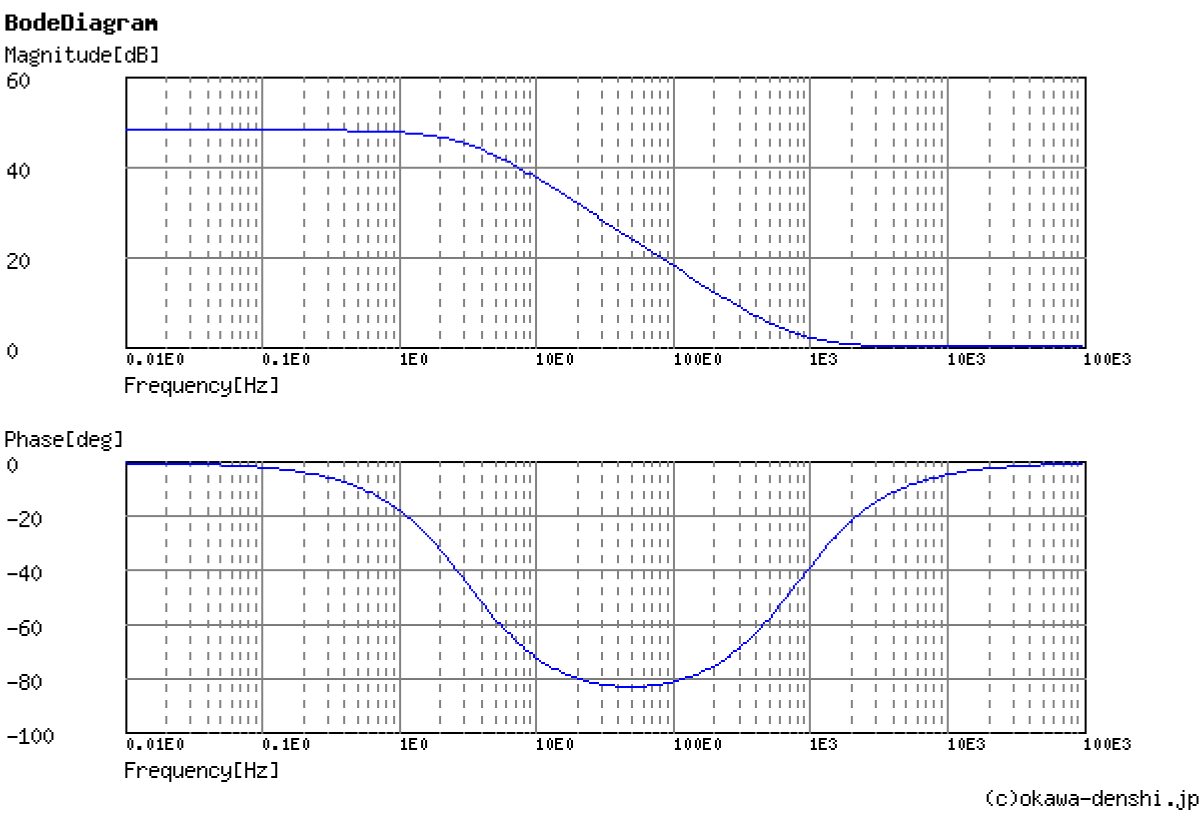
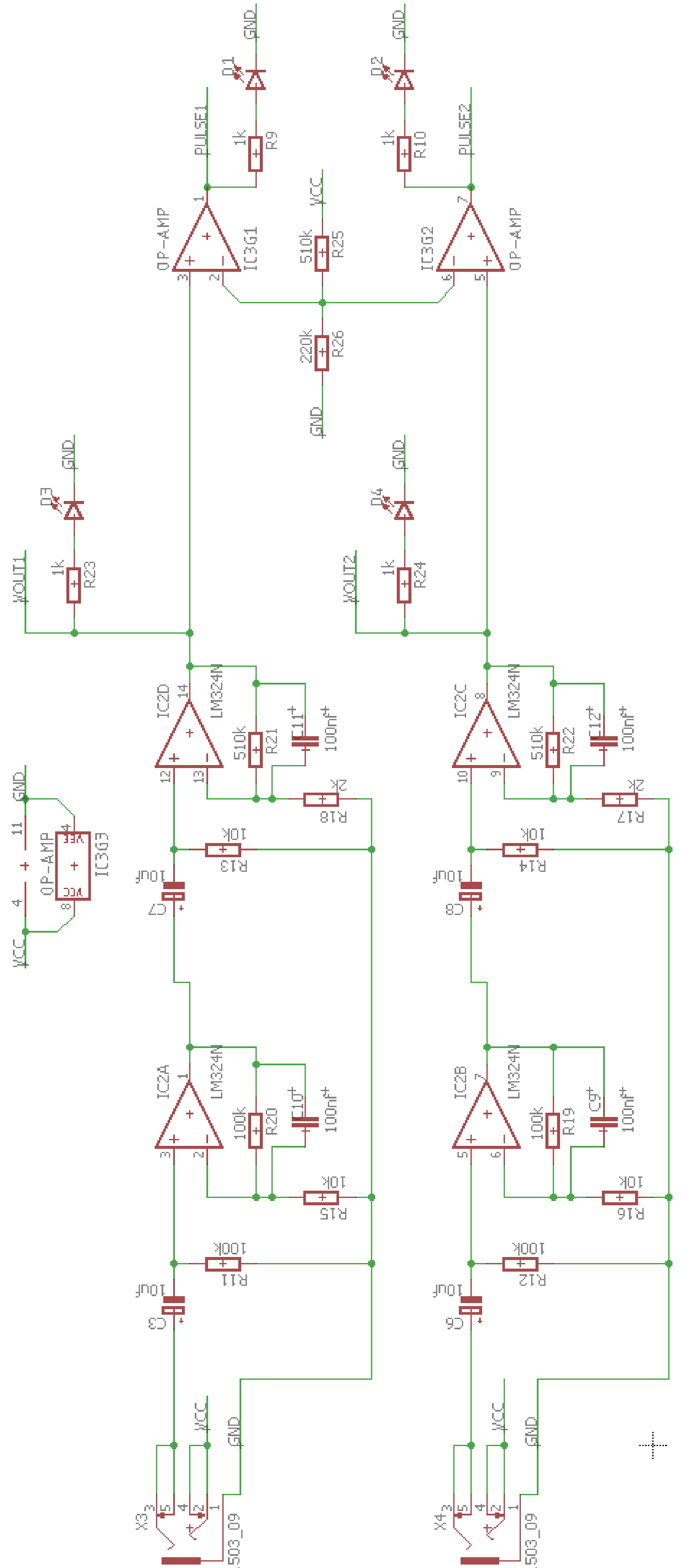


Fig 11. Frequncy response for 2'nd stage Low-pass Active filter.


GND
D1
1k
R9
PULSE1
D2
1k
R10
PULSE2
VCC
OP-AMP
IC3G1
510k
R25
IC3G2
220k
R26
D3
1k
R23
VOUT1
D4
1k
R24
VOUT2
IC2D
LM324N
510k
R21
C11
100nF
2K
R18
10K
R13
10uF
C7
IC2C
R22
C12
R17
R14
C8
IC3G3
VCC
VEE
IC2A
100k
R20
C10
R15
100K
R11
C3
IC2B
R19
C9
R16
R12
C6
X3
X4
1503_09

1-Display

Using 8-digit 7segment (4digit+4digit) to display the data for each channel (CH1 & CH2).

8 digit requires many output pins from Arduino (which doesn't have enough for driving them), So I used a shift Register IC (74HC595) [11].

Displaying data to 7segment is suspended due to the lake of time.

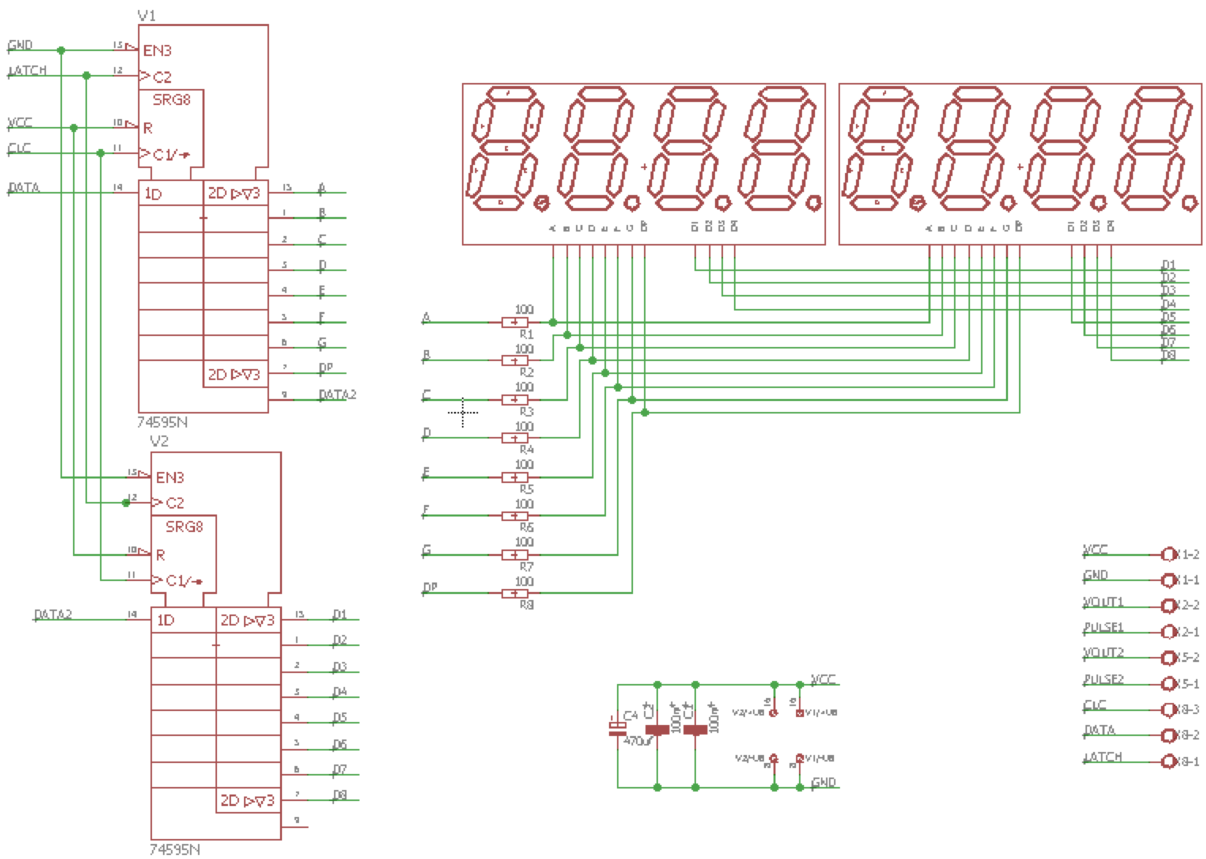


Fig 12. 7Segment schematic and I/O pins (EaglePCB).

8-digits are divided into two 4-digits. 4-digits for each channel.

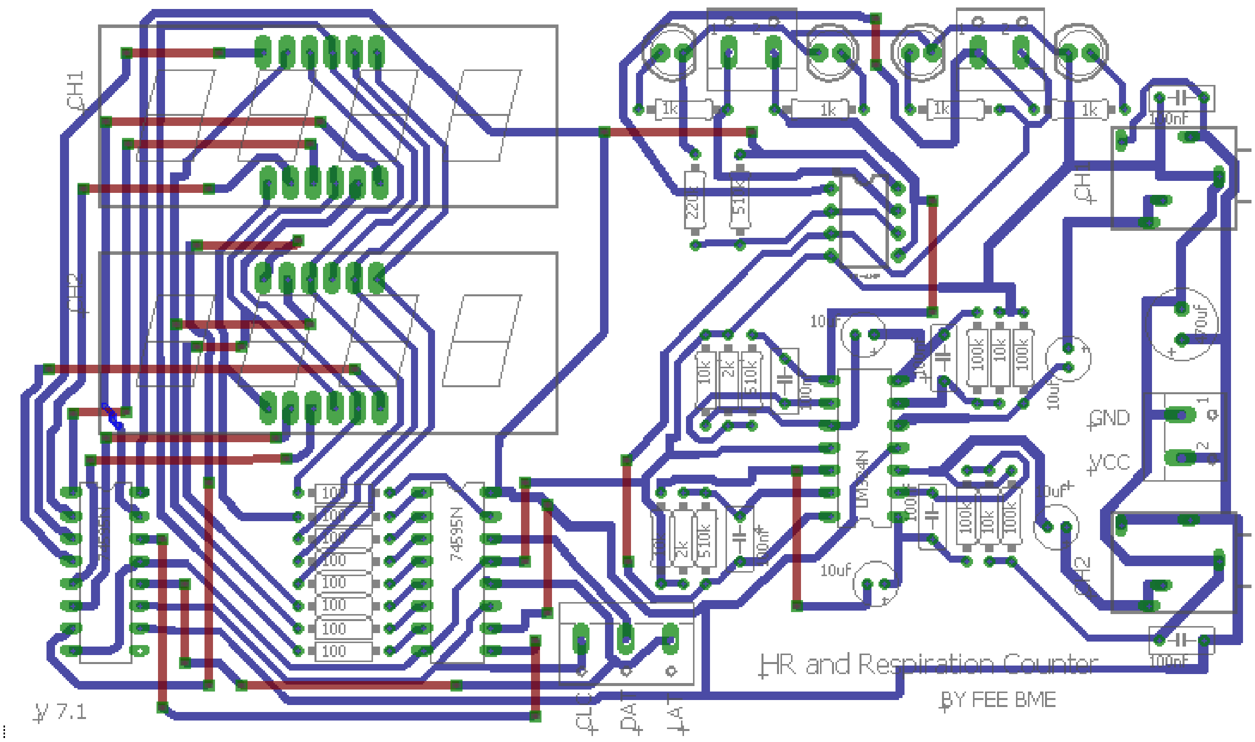


Fig 13. Final PCB Layout (EaglePCB).

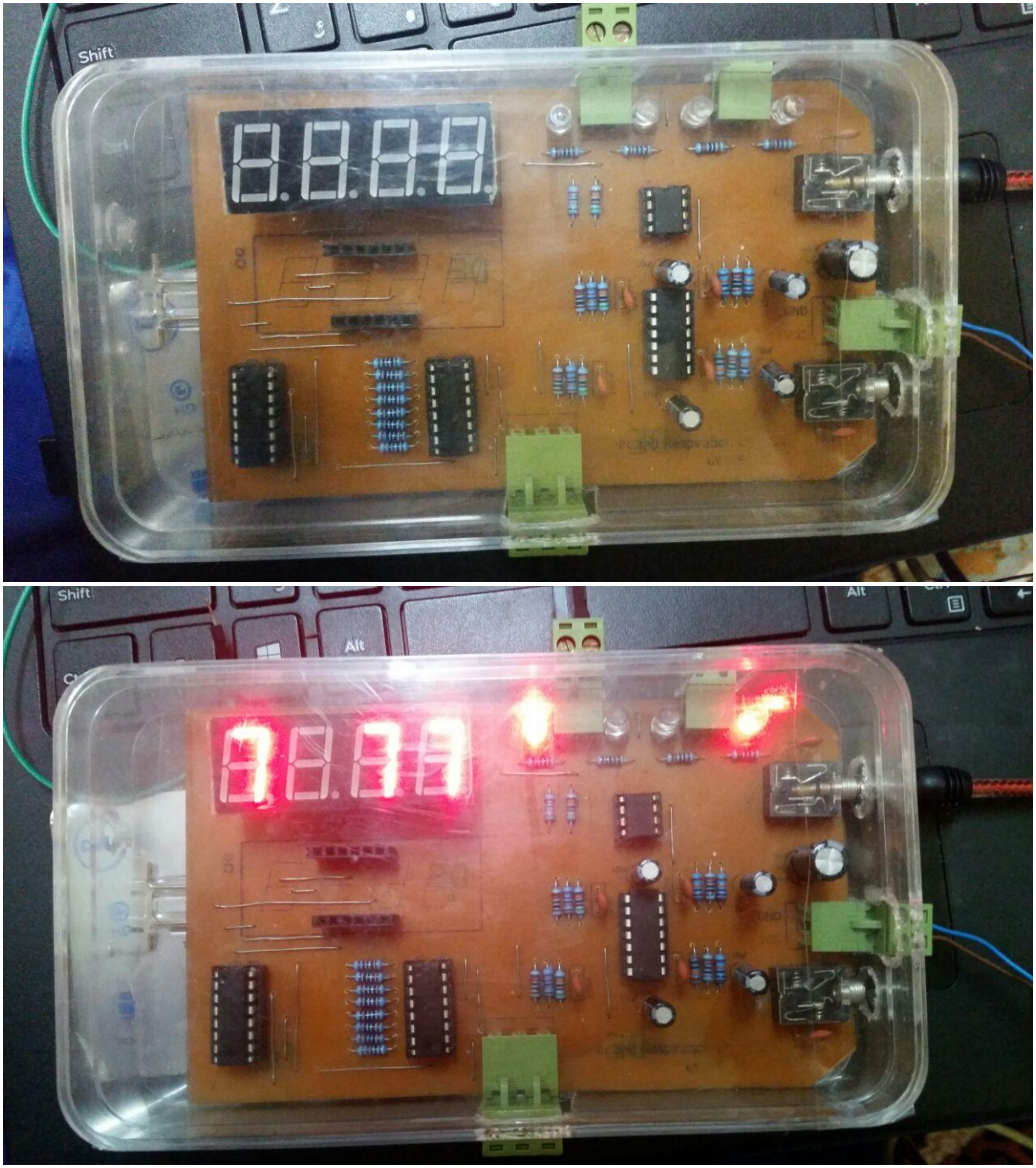


Fig 14. The final Working Circuit with its enclosure.

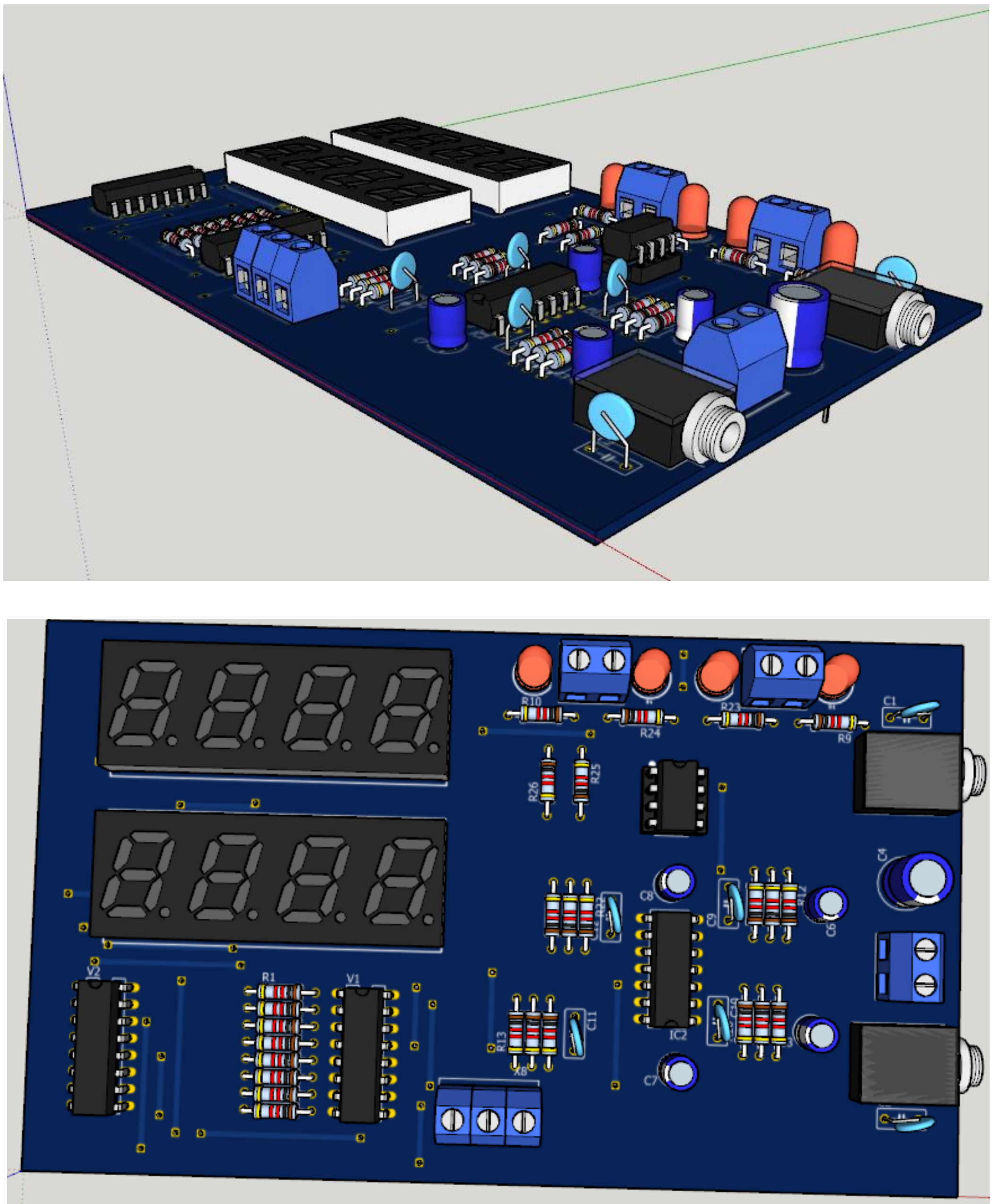


Fig 15. 3D Sketch for final PCB (SketchUP).

Code for Arduino:

```
/*
  Arduino Code to Send the 2 values of CH1 and CH2
  using Serial to LabView VISA For analysing and
  Show the final Data.

  Coded in 14/4/2018 by Mohamed Asim Abdullah
*/

const byte CH1 = A1;        // Analog Input pin For CH1
const byte CH2 = A2;        // Analog Input pin For CH1

void setup() {
  Serial.begin(115200);   // Start Serial communication with speed of 115200 bps
  while (!Serial);        // Wait for Serial communication (authentication)
}

void loop() {
  // Print the data in format of (ch1,ch2) ,So LabView can identfiy both them
  Serial.print("(");
  Serial.print(analogRead(CH1));
  Serial.print(",");
  Serial.print(analogRead(CH2));
  Serial.print(")");
  Serial.print('\n');
  delay(10);
}
```

Code for LabView (GUI):

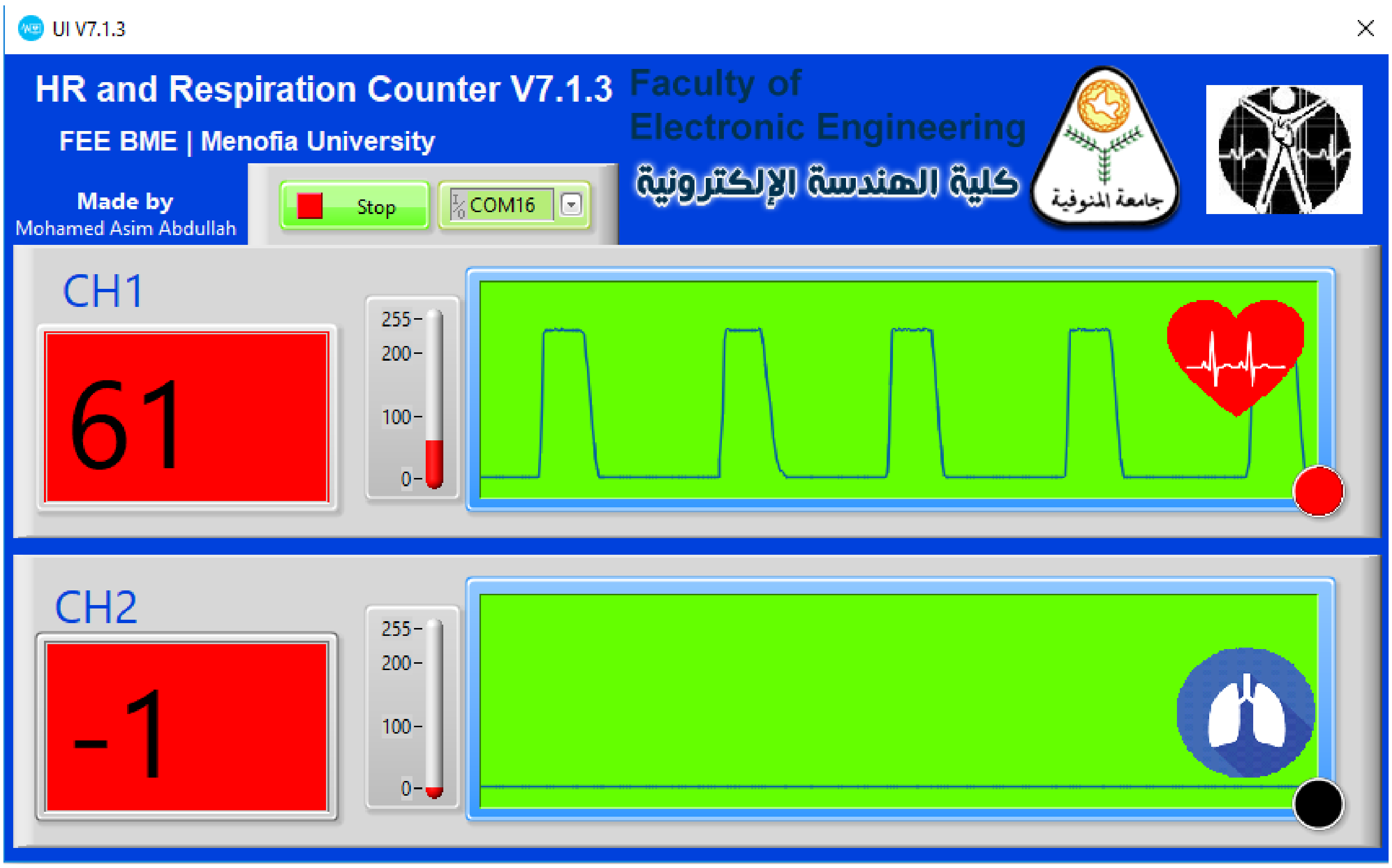
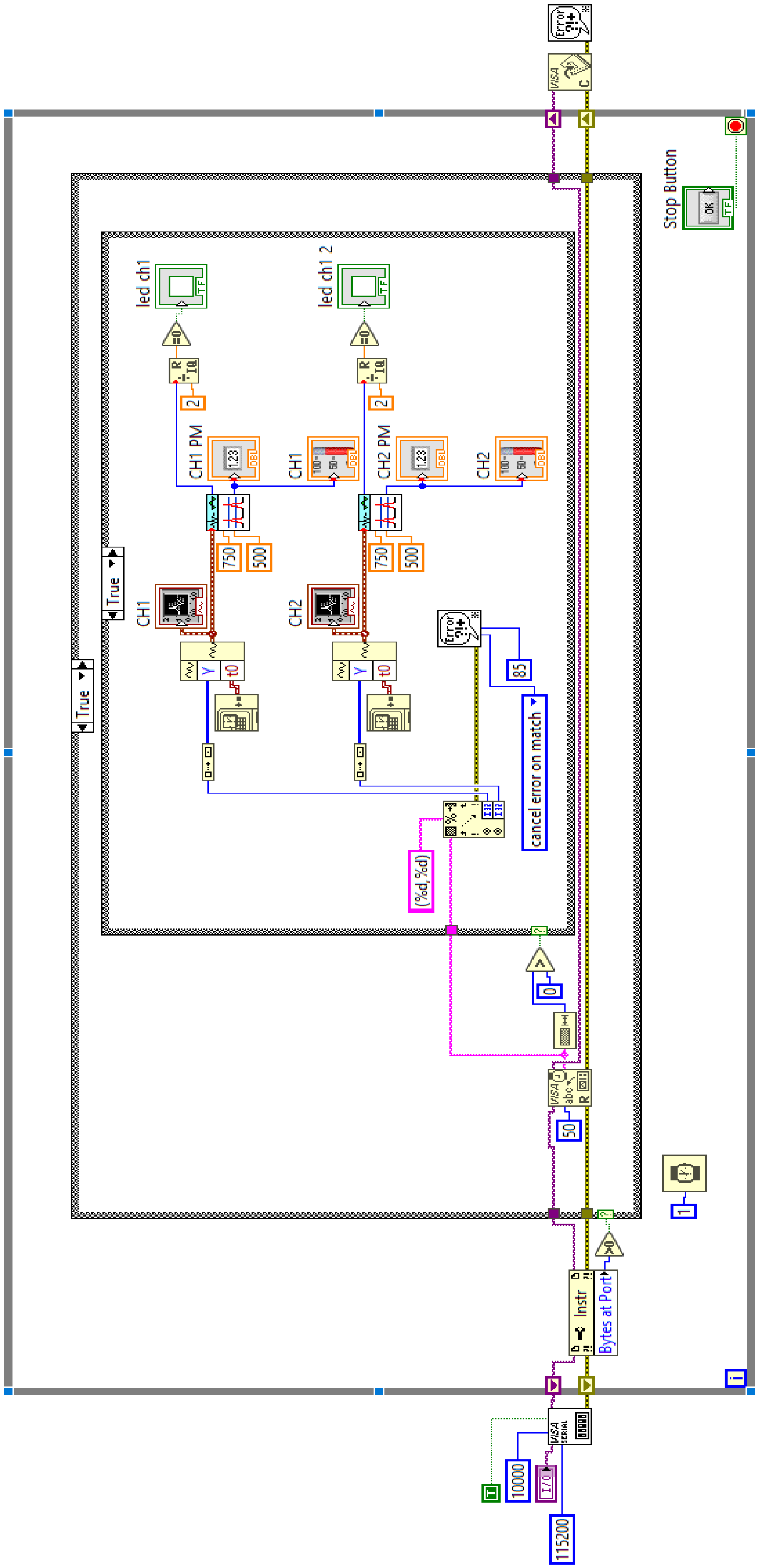


Fig 16. The Final GUI for the Arduino using LabView 2017.


Stop Button
led ch1
led ch1 2
CH1 PM
CH1
CH2 PM
CH2
True
True
cancel error on match
(%d,%d)
Instr
Bytes at Port
115200
10000
750
500
85
50

REFERENCES

[1] K. Shelley and S. Shelley, Pulse Oximeter Waveform: Photoelectric Plethysmography, in Clinical Monitoring, Carol Lake, R. Hines, and C. Blitt, Eds.: W.B. Saunders Company, 2001, pp. 420-428.

[2] E. Aguilar Pelaez et al., "LED power reduction trade-offs for ambulatory pulse oximetry," 2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Lyon, 2007, pp. 2296-2299. doi: 10.1109/IEMBS.2007.4352784, URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4352784&isnumber=4352185

[3] Reisner A, Shaltis PA, McCombie D, Asada HH (May 2008). "Utility of the photoplethysmogram in circulatory monitoring". Anesthesiology. 108: 950–8. doi:10.1097/ALN.0b013e31816c89e1. PMID 18431132.

[4] Diffenderfes, Robert (2005). Electronic Devices: System and Applications. New Delhi: Delimar. p. 480. ISBN 978-1401835149.

[5] https://datasheet.octopart.com/A000066-Arduino-datasheet-38879526.pdf

[6] Maxim Application Note 1108: Understanding Single-Ended, Pseudo-Differential and Fully-Differential ADC Inputs – Retrieved November 10, 2007.

[7] "Apex OP PA98". Retrieved 8 November 2015. APEX PA98 Op Amp Modules, Selling Price: $207.51

[8] Don Lancaster, Active-Filter Cookbook, Howard W. Sams and Co., 1975 ISBN 0-672-21168-8 pages 8-10.

[9] Muhammad H. Rashid, Microelectronic Circuits: Analysis and Design, Cengage Learning, 2010 ISBN 0-495-66772-2, page 804.

[10] https://circuitdigest.com/tutorial/active-low-pass-filter

[11] http://www.ti.com/lit/ds/symlink/sn74hc595.pdf