Electrocardiogram (ECG) Design Project

1. Abstract

Electrocardiography (ECG) is the interpretation of the electrical activity of the heart over a period of time. The ECG signals can produce important information on the heart's functionality. In this report we will discuss the process of making a simple heart ECG monitor with the use of a simple analog circuit design. This project was mainly done in two stages: breadboard implementation and final implementation. The signal from the ECG electrodes is given as the input and it is amplified using an instrumentation amplifier. Then, a high pass filter, low pass filter and a notch filter are used to filter the noises in the signals while further amplifying the filtered signal as well. The final output of the circuit is the ECG signal, and it is displayed using the oscilloscope.

2. Introduction

A gadget called a cardiac ECG monitor can show a real-time electrical reading of the human heart. The objective of this challenge was to create a tool that can acquire 3-lead ECG readings using electrodes. It was necessary to display the signal using the proper method. Because of the relatively tiny amplitude of the electrical signals generated by the human body, we were required to apply our analog electronics expertise to enhance signal quality while amplifying the necessary signals. The device overall takes the ECG signal from the ECG probes as the input and displays the ECG waveform as the output.

3. Functionality description

There are 2 main functions of the ECG monitor:

- Amplification of the small heart signal
- Filtration of internal and external noises

Therefore, the circuit consists of an amplifier and 3 filters to remove the noises.

3.1 Amplifier

The amplification of the heart signal is done in 3 stages. However, the main amplifier used in this circuit is the instrumental amplifier. Additional amplification is done by some of the filters as well. Since the magnitude of the usual ECG signal is in the range 0.1mV - 5 mV, it was decided that a total amplification factor around 1000 would be enough. An ideal bio-potential amplifier possesses the following characteristics.

1. Have high input impedance.
2. Built with safety in mind.
3. Safety measures are taken to avoid macro and micro shock since the signal is generated by a living organism.
4. Isolation and protection are used to set limits to the current flowing through the electrodes.
5. The amplifier's output impedance needs to be extremely low in order to drive any external load with the least amount of distortion.
6. Since the signal is very small, the amplification is high.
7. A high common mode rejection ratio to eliminate offset signals.
8. Most bio-potential amplifiers are differential, in order to make sure that the noise is not amplified.

The instrumentation amplifier, that contains the above characteristics is used in the circuit. It can eliminate the common mode noise, (high CMRR) and provides high input impedance.

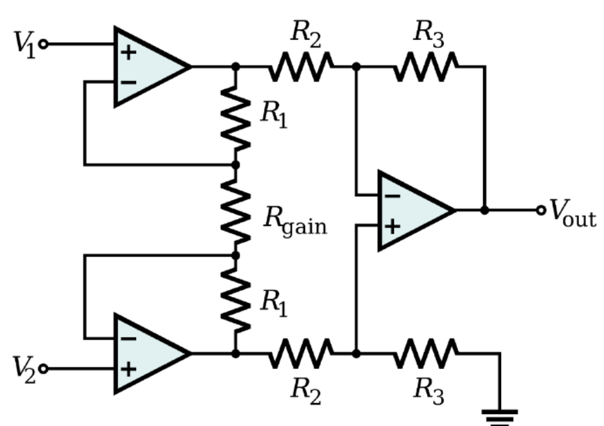


Figure 1: Instrumentation Amplifier

The overall gain is given by,

$$\text{Gain} = \left(1 + \frac{2R_1}{R_{gain}}\right)\left(\frac{R_3}{R_2}\right)$$

3.2 Filters

The many noises in the signal must be filtered using various filters. Since the usual ECG signal is said to have a bandwidth of 0.05 Hz - 150 Hz, a high pass filter is used to remove the low frequency noise resulted from muscle movement, respiration, patient movement, and the low pass filter is used to filter the high frequency noise due to electrode contact issues, electronic devices in the and electrostatic potentials. In addition, a notch filter (band stop filter) is used to filter the 50Hz noise that is resulted by the power supply.

4. System model

4.1 Instrumentation Amplifier

As mentioned in the previous section, the instrumentation amplifier is used to amplify the ECG signal due to its properties such as high common mode rejection ratio, low input current and high input impedance. The LM4562 op-amp is a dual high-performance, high-fidelity audio operational amplifier. It is used in this circuit due to its specifications such as high CMRR, high slew rate, and low noise that are favorable for ECG signal amplification. According to the data sheet of LM4562,

- The common mode rejection ratio is around 120 dB, which is comparatively high value. Therefore, the amplification of common mode signal is minimized.
- The power supply rejection ratio is also high and is around 120dB.
- The Op Amp has a high slew rate of 20 μV, which is favorable for producing an output without distortion
- The power supply voltage lies in a large range from $\pm$2.5V to $\pm$17V. Hence it is more flexible to provide power.
- The gain bandwidth product is of high value around 55 MHz
- The Op Amp has a very low input offset voltage of 0.1mV.

The expected total gain of the complete circuit is 1000 and that of instrumentation amplifier is 10. The reason for not opting for a much larger gain is because the noises are not yet filtered prior to this stage. The resistor combination of R1, R2, R3 and R_{gain} approximately provides a gain of 10 and a variable resistor is used for R_{gain} to change the amplification factor when needed.

$$\text{Gain} = \left(1 + \frac{2R_1}{R_{gain}}\right)\left(\frac{R_3}{R_2}\right)$$

$$\text{Gain} = \left(1 + \frac{2*50}{10}\right)\left(\frac{10}{10}\right) = 11$$

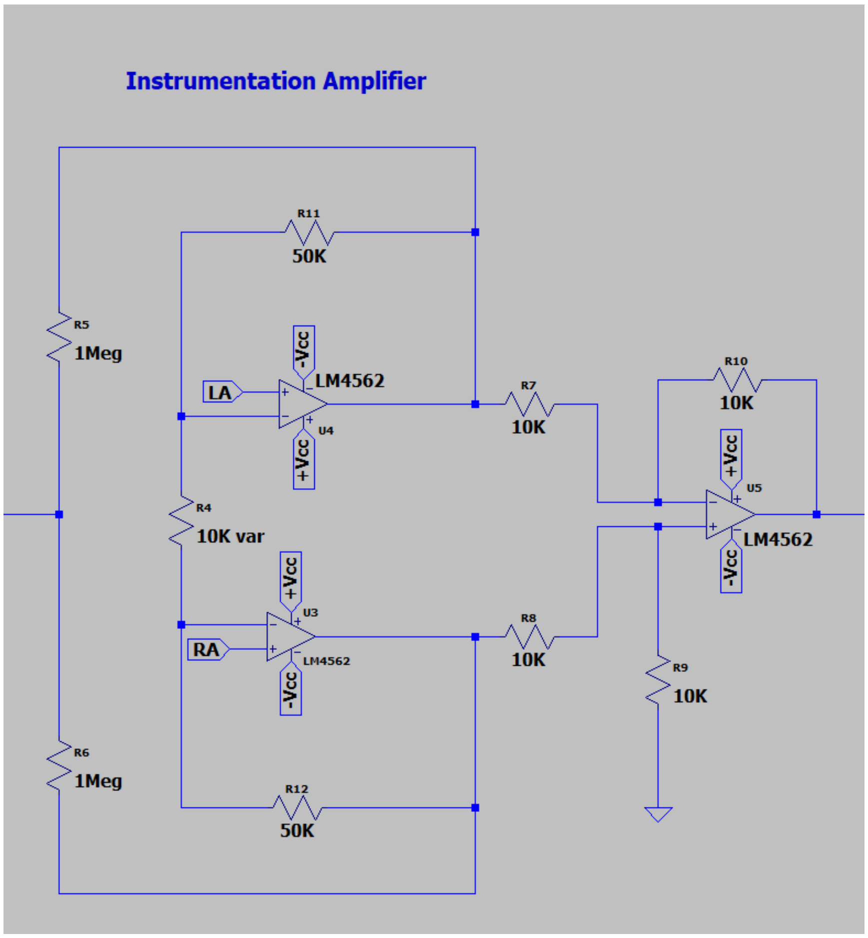


Figure 2: Instrumentation Amplifier Circuit

4.2 Leg Drive Circuit

This circuit is included in the circuit to remove the common mode signal. Here the common mode interference is passed through a unity gain inverting amplifier and its output is fed to the body through the right leg lead, thus nullifying its effect.

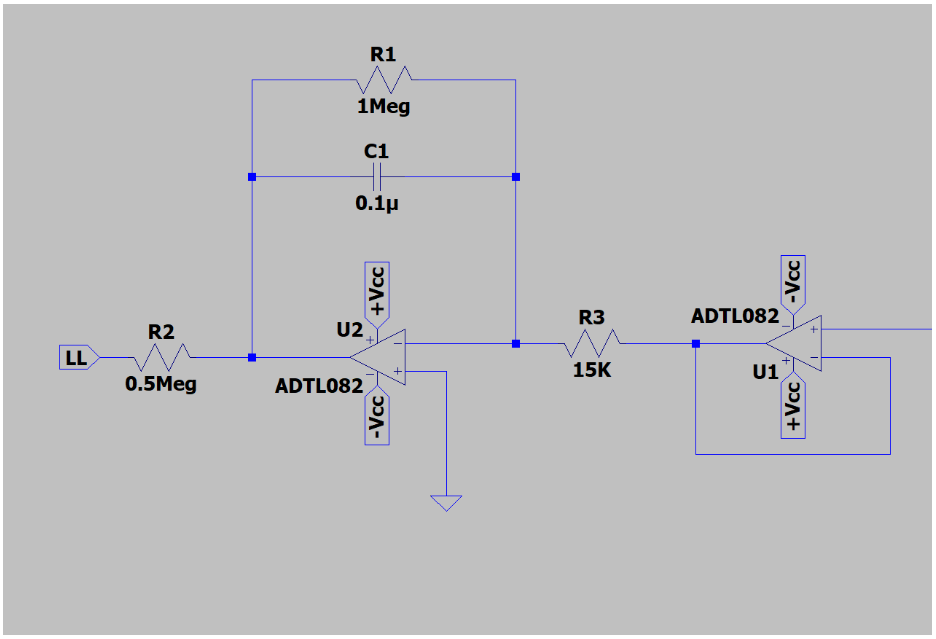


Figure 3: Leg drive Circuit

4.3 High Pass Filter

This circuit is designed to have a theoretical cutoff value around 0.05Hz. A 3rd order active filter is used to achieve this task. Resistor and capacitor values are selected to obtain the required cut off frequency and gain values.

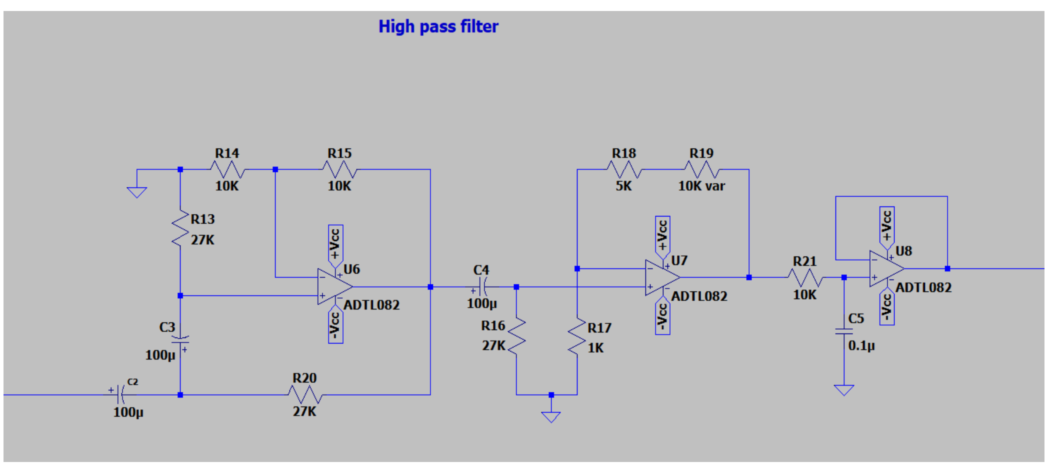


Figure 4: High Pass Filter Circuit

4.4 Low Pass Filter

A fifth order active low pass filter is used. The resistor and capacitor values are selected to obtain the required cut off frequency and gain values.

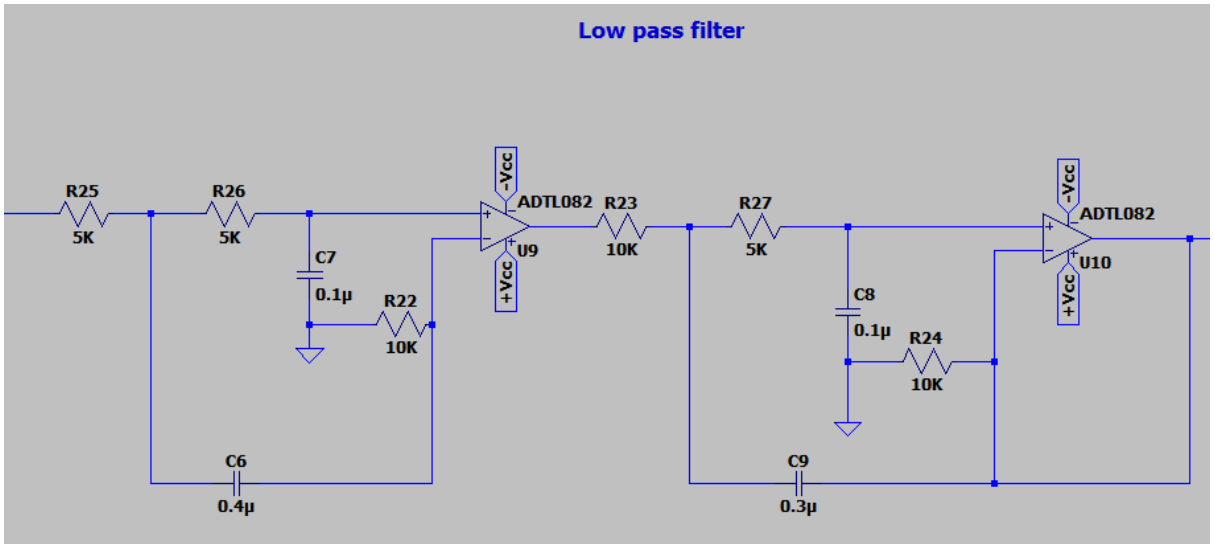


Figure 5: Low Pass Filter Circuit

4.5 Notch Filter

This circuit is included to remove the 50Hz noise caused by the power line interference. A twin T notch filter is used.

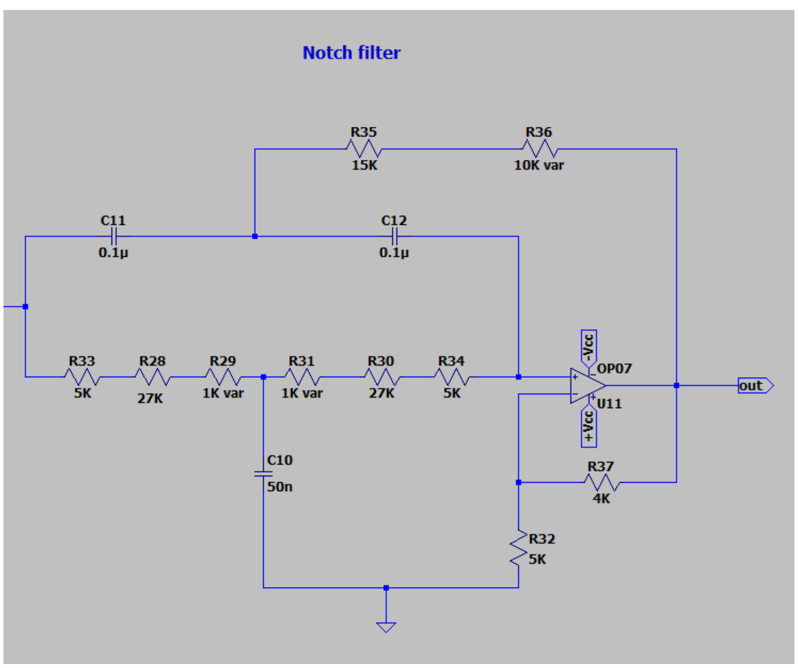


Figure 6: Notch Filter Circuit

4.6 Op-amp selection

There are a few specifications that the op-amps used in these circuits should have.

- High CMRR: Common mode rejection ratio must be high to eliminate common mode noises.
- High PSRR: Power supply rejection ratio must be high to eliminate the amplification of any changes in the power supply.
- High slew rate: It is preferred to get an output without distortion.
- Low input offset voltage
- High gain bandwidth product

Out of the op-amps available in the Sri Lankan market, the LM4562, TL072, and NE5532 seemed to comply with the above requirements, with LM4562 showing the best performance. However, they were scarce to find and comparatively of a larger price. Hence, the LM4562 was used for the instrumentation amplifier and the TL072 was used for the other circuits. Both these op-amps are dual op-amps. They were selected to minimize the space taken by the components.

LM4562

Slew rate: 20 V/μs

CMRR: 120 dB

PSRR: 120 dB

Gain bandwidth product: 55 MHz

Input offset voltage: 0.1 mV

TL072CP

Slew rate: 13 V/μs

CMRR: 100 dB

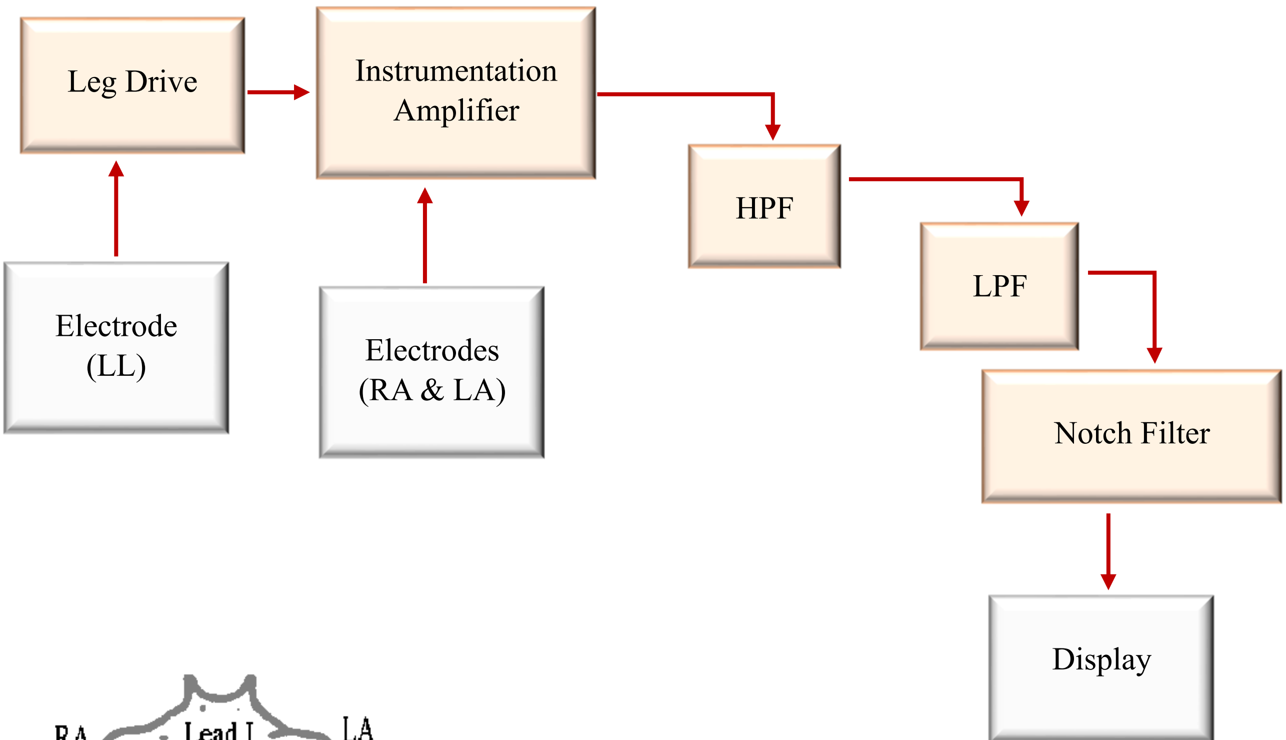
PSRR: 100 dB

Gain bandwidth product: 3 MHz

Input offset voltage: 3-10 mV

5. Schematic (Block Diagram)

The above circuits cascaded in the required order to obtain the final circuit. It was simulated using LTSpice software.



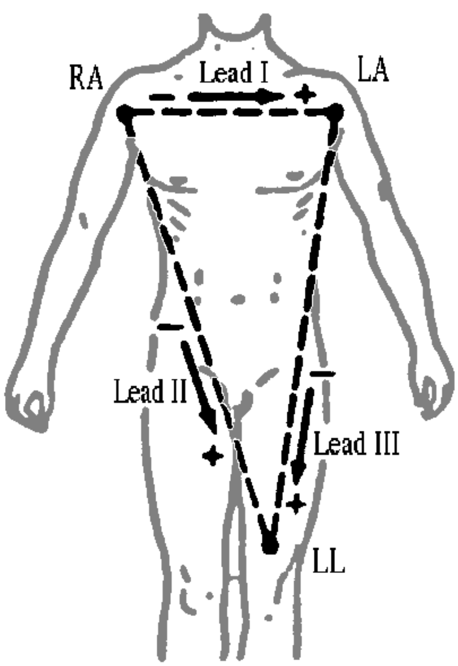


Figure 7: Electrode Placement

6. PCB Design

It was decided to design a 4-layer PCB to reduce the space taken by the PCB. Hence, the top and bottom layers were used for signal routing while the other 2 layers were used for $\pm$9V power and ground. See figures in appendix.

7. Enclosure Design

Since a display was not used, the purpose of the enclosure was to provide the required housing for the PCB and the power supply. It was designed using SolidWorks software. See figures in appendix.

8. Results

The final output results were observed through the oscilloscope due to lack of budget for purchasing a display. The output waveform had the shape of the ECG signal, but it was distorted with a high-frequency noise. The accuracy of the low pass filter must be improved in future improvements, to get a clearer signal. See appendix for the results.

9. Future improvements

• A display must be used to show the output or a use another method to display the output using mobile phone or computer.

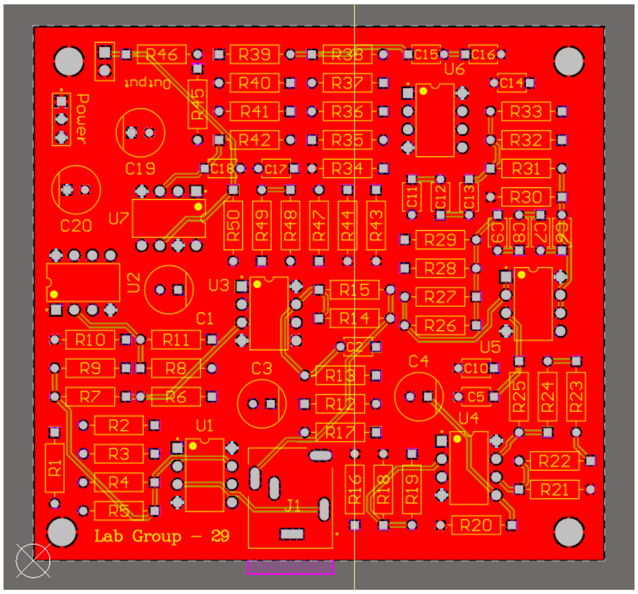
• Further filter noises and obtain a clearer signal.

10. Conclusion

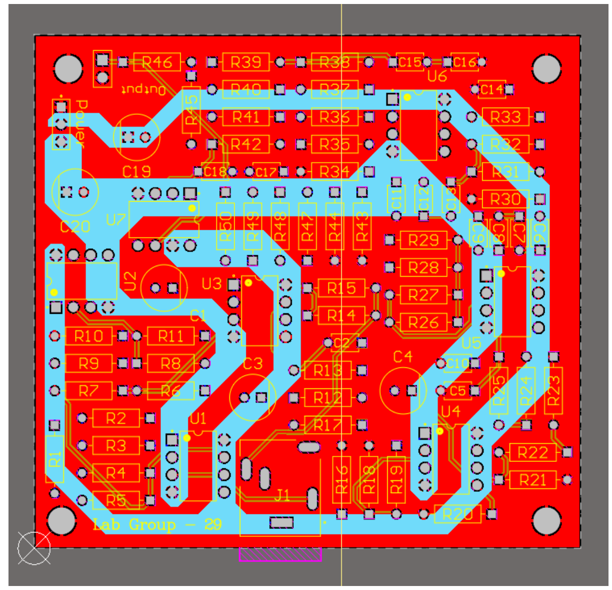
The precision of the output ECG waveform highly depends on the accuracy of the filters. Hence, it is important to test the components before soldering as well as to solder each module separately while testing. The gains should be distributed among the amplifiers and filters in the proper manner so that the amplification of noises and common mode noises are minimized.

11. Appendix

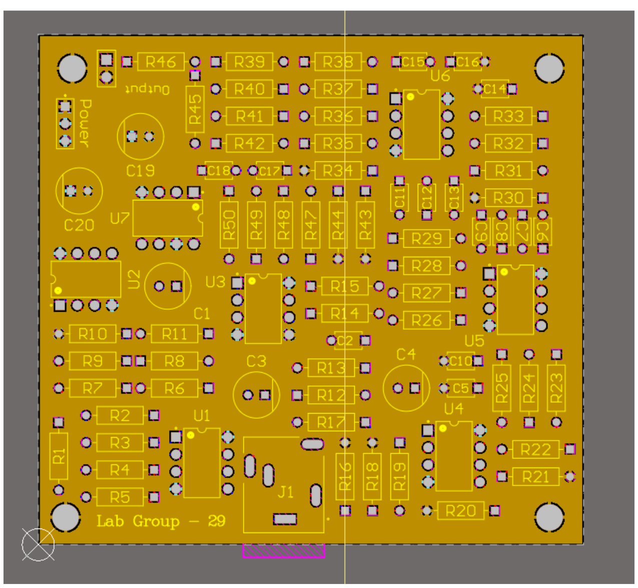
PCB Design



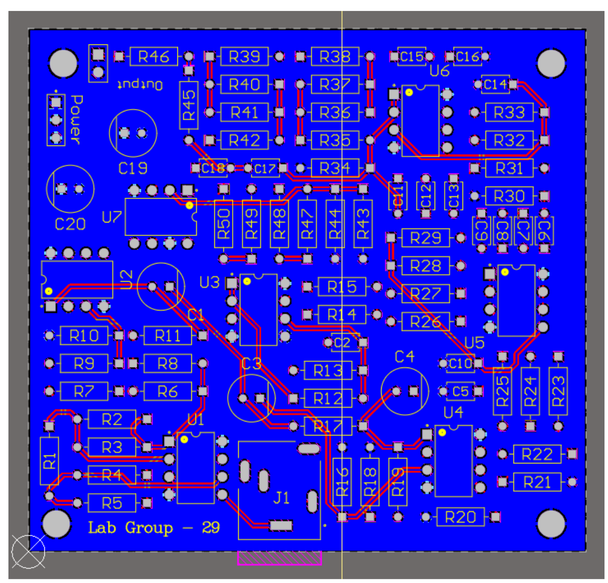
(a) Top Layer



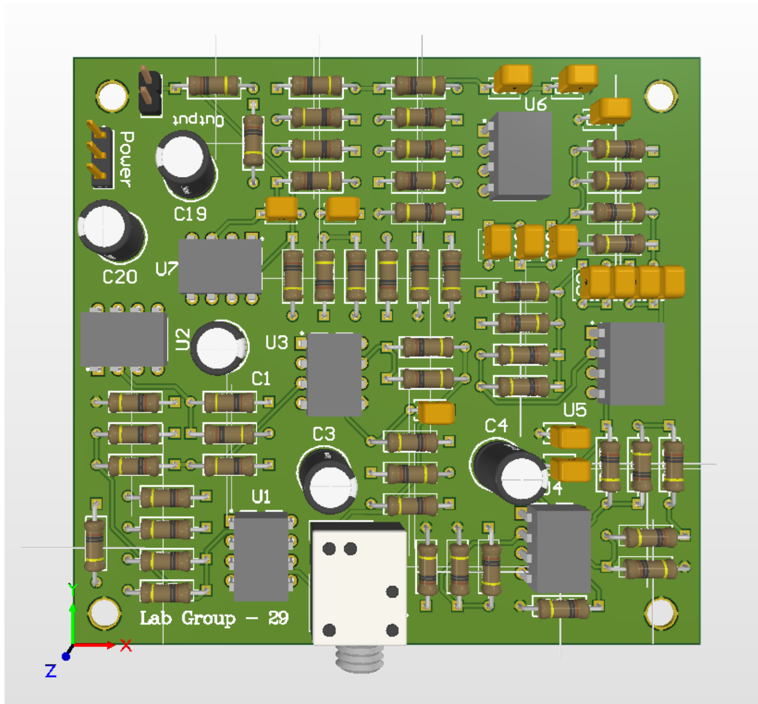
(b) Power Layer



(c) Ground

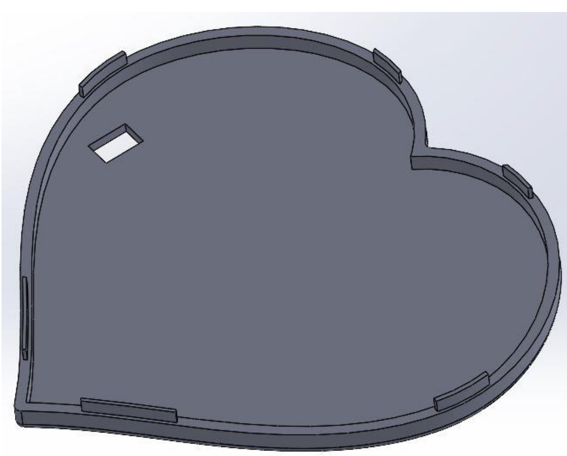


(d) Bottom Layer

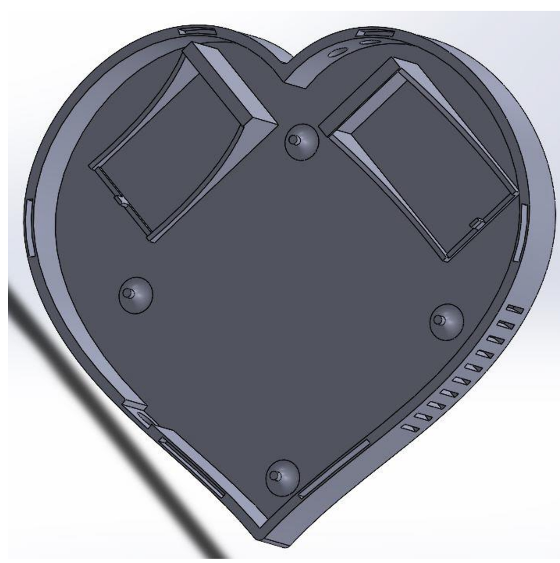


(e) Altium Design of the PCB

Enclosure Design



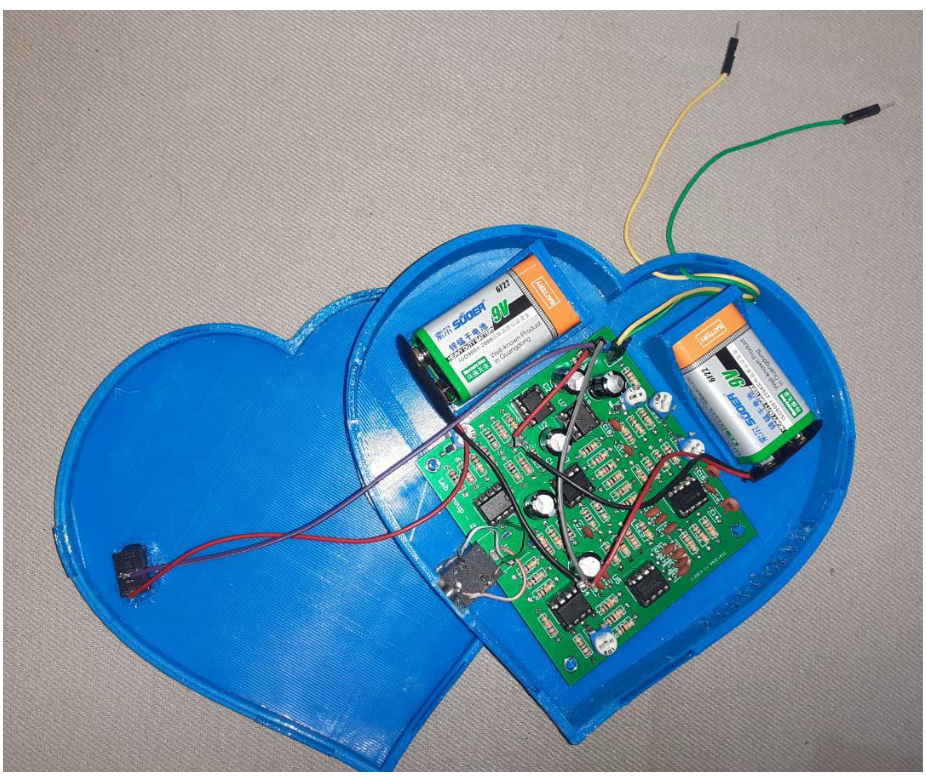
(a) Top



(b) Bottom

(c) Assembly

Final Prototype



Assembled Prototype