

A Design of ECG Amplifier

ECE 525 Project #1

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September 28, 2003

Part I : Problem Description

Use OpAmps to design an ECG amplifier. This amplifier should allow differential input, have enough gain to amplify a small ECG signal (<4mv) and reject DC, 60-Hz and high frequency noises.

Requirements:

- ✓ Differential input
- ✓ Adjustable gain: 200 – 2,000
- ✓ Bandpass filter:
- ✓ Minimize 60 Hz noise

Part II : Background of Design

The Electrocardiograph (ECG) signal is an electrical signal generated by the heart's beating, which can be used as a diagnostic tool for examining some of the functions of the heart. It has a principal measurement range of 0.5 to 4 mV and signal frequency range of 0.01 to 250 Hz. ¹ A typical ECG signal shows the classic PQRST and T complex, as shown in Figure 1. ²

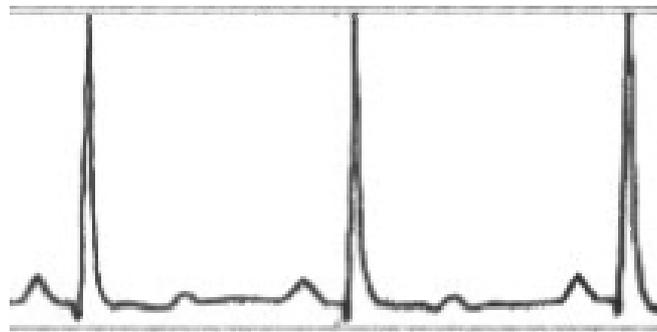


Figure 1 Typical ECG Signal

There are many factors that should be taken into consideration in the design of an ECG amplifier, such as the frequency distortion, saturation distortion, interference from electric devices and other sources. The most important kind of noise in an ECG amplifier is the 60 Hz noises, since using a band-pass filter can easily reject both the DC and high frequency noise. A major source of noise when one is recording or monitoring the ECG is the electric power system, as shown in Figure 2(a). Electromagnetic interference from nearby high power radio or television can also be picked up by a close loop of lead wires. Figure 2(b) illustrates the electromyographic noise, whose source is located in the body itself.

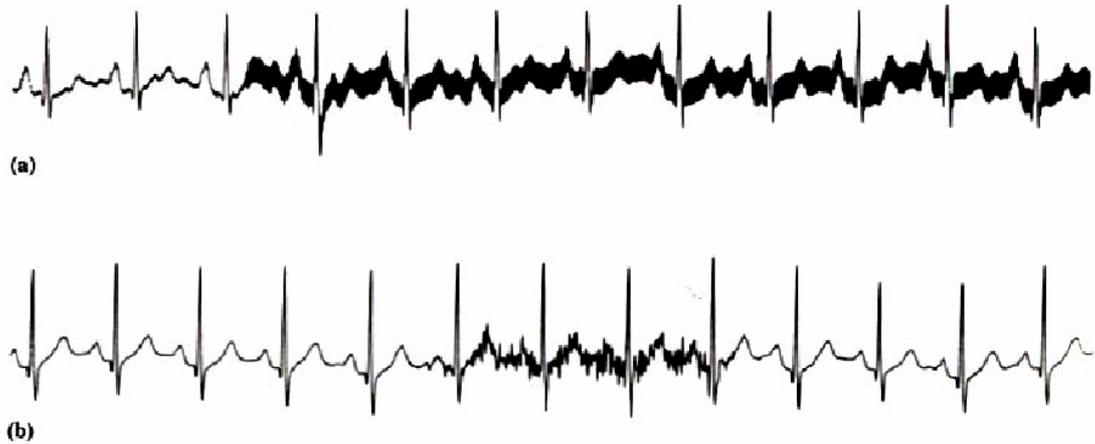


Figure. 2 (a) 60-Hz power-line interference. (b) Electromyographic interference on the ECG.

To eliminate the noises mentioned above, we can use differential amplifiers, as

shown in Figure 3. The output of this circuit is $v_{out} - v_{ref} = \frac{R_4}{R_3} \left(1 + 2 \frac{R_2}{R_1}\right) (v_1 - v_2)$. If

the input is a common mode voltage ($v_1 = v_2$), then $v_{out} = 0$. If on the other hand

$v_1 \neq v_2$, then the differential voltage ($v_1 - v_2$) produces a differential gain. Since most noises are common mode voltage, the differential amplifier can eliminate them. This three-op-amp amplifier circuit is frequently called an instrumentation amplifier. It has high input impedance, a high CMRR, and a gain that can be changed by adjusting R_1 . This circuit finds wide use in measuring biopotential, because it rejects the large 60 Hz common-mode voltages that exist on the body.

In many modern electrocardiographic systems, people are using a driven-right-leg system. The patient is not grounded at all. Instead, the right leg electrode is connected (as show in Figure 4) to the output of an auxiliary op amp. The common-mode voltage on the body is sensed by the two averaging resistors R_a ,

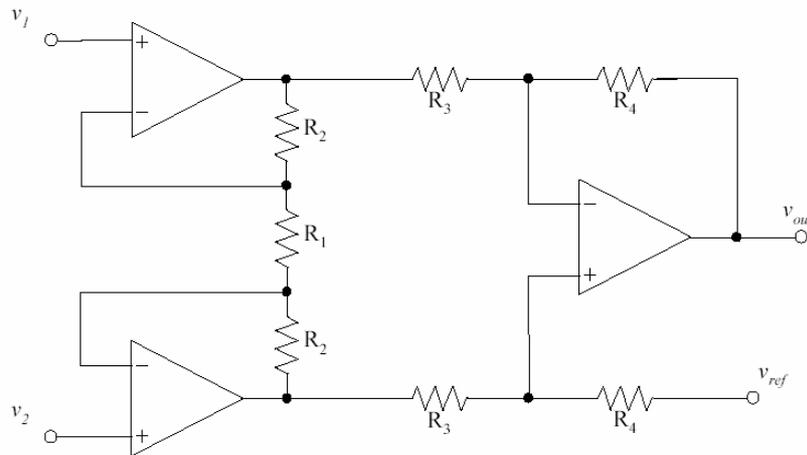


Figure 3. Three-op-amp Differential Amplifier

inverted, amplified and fed back to the right leg. Such a negative feed back drives the common-mode voltage to a low level. It can also provide some electric safety, because the auxiliary op amp will saturate when an abnormally high voltage appears between the patient and ground.

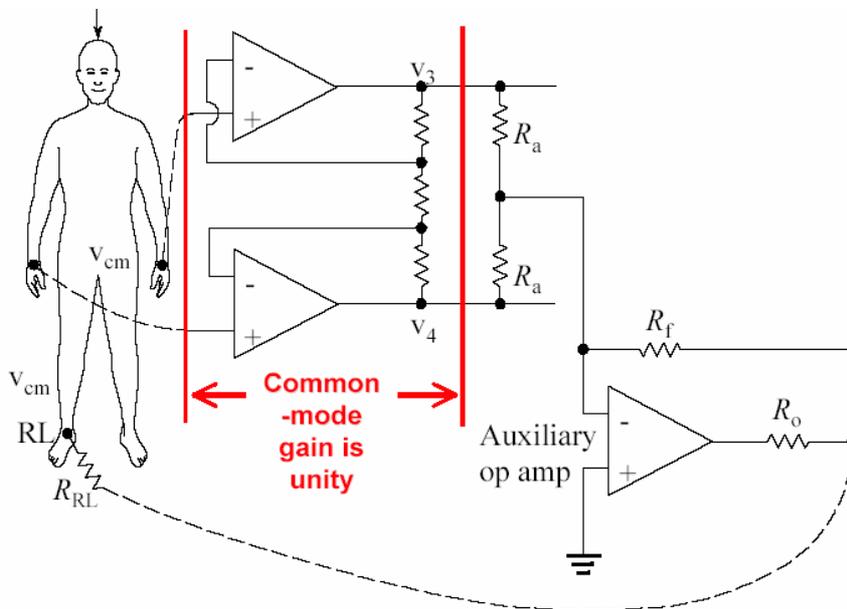


Figure 4. Driven-right-leg circuit for minimizing common-mode interference

Part III: Theoretical Design:

To meet the requirements of our ECG amplifier mentioned in Part I , we need to design an cascade circuit, which consists a differential amplifier (Instrumentation Amplifier), a Low Pass Filter, a High Pass Filter and a gain stage. The order of these stages is based on the consideration of reducing noises. For example, in the following cascade chain (Figure 5), the output noise is

$$((n_1 * A_1 + n_2) * A_2 + n_3) * A_3 = A_1 A_2 A_3 * n_1 + A_2 A_3 * n_2 + A_3 * n_3,$$

so the best placement of the three stages should be $A_1 > A_2 > A_3$.

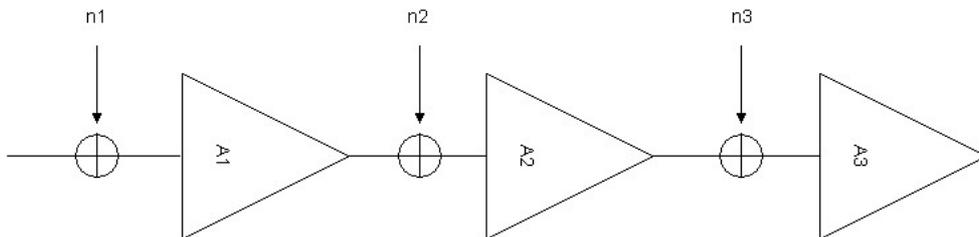


Figure 5. Example of the noise consideration in a multi-stage system

Figure 6 is the placement of our cascade design, which is on the basis of placing high gain stages early in the signal path. However, the High Pass Filter stage should be placed immediately after the differential amplifier to chop off the DC component of its output. Otherwise, this DC component will be amplified by the gain stage and may saturate the following op-amps.

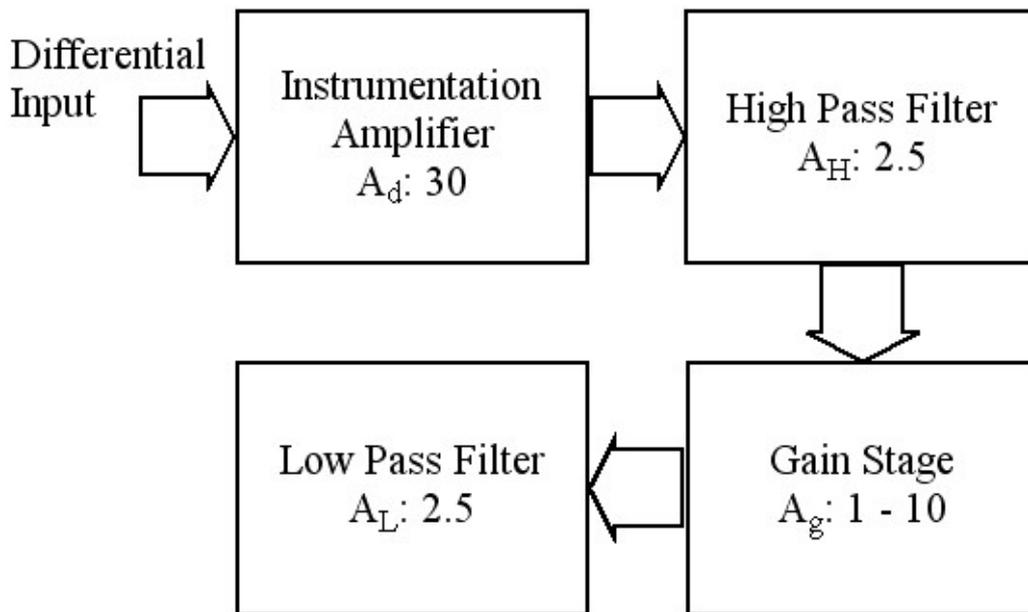


Figure 6. Placement of the cascaded stages

Differential Stage

Use Burr-Brown INA 118 as the instrumentation amplifier, whose internal circuit is shown in Figure 7. Its gain is determined by the resistor R_G .

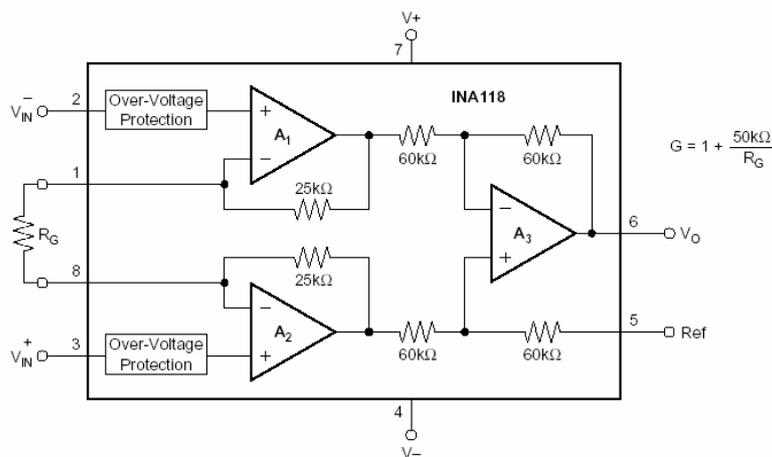


Figure 7. Internal circuit of INA 118

Sallen-Key Filter

Fourth-order Sallen-Key Butterworth Low-Pass and High-Pass Filters were adopted in our design. A fourth-order filter is made of two cascaded second-order filters. The gain of these second-order filters is determined as 1.152 and 2.235 respectively, according to Chapter 14 of Dr. Hambley's book³. The reason for designing a total gain around 2.5 is to get a low Q ($Q = \frac{1}{3-K}$), which is required in most frequently designed filters⁴. The cut-off frequency of Sallen-Key filter is

$$f_c = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}},$$

and normally people set $R_1=R_2=R$, $C_1=C_2=C$ to simplify the design (as shown in Figure 8).

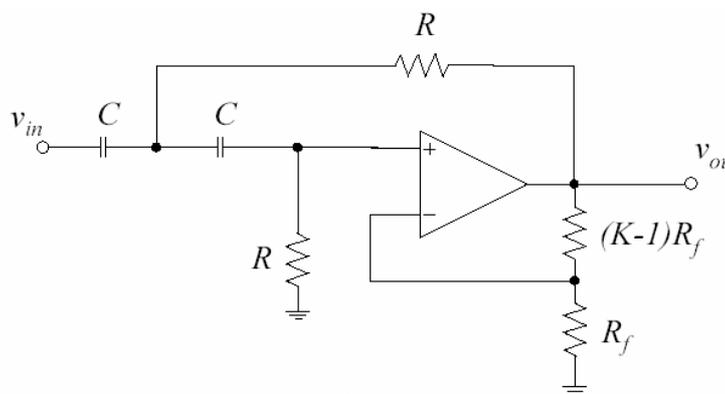


Figure 8. Simplified Sallen-Key second-order high pass filter

The capacitor and resistor values in our circuit were decided by a computer program from Texas Instruments to acquire a better frequency response and control Q more flexibly.⁵

Part IV: Prototype Circuit and Reducing 60 Hz Noise

The prototype circuit of the ECG amplifier is shown in Figure 9 and 10. To reduce the 60 Hz noise, batteries were used as the power supply and filter capacitors was also put across the power rails at each IC. These capacitors were connected as close as possible to the V+ and V- pin of each chip to maximize their filtering effects.

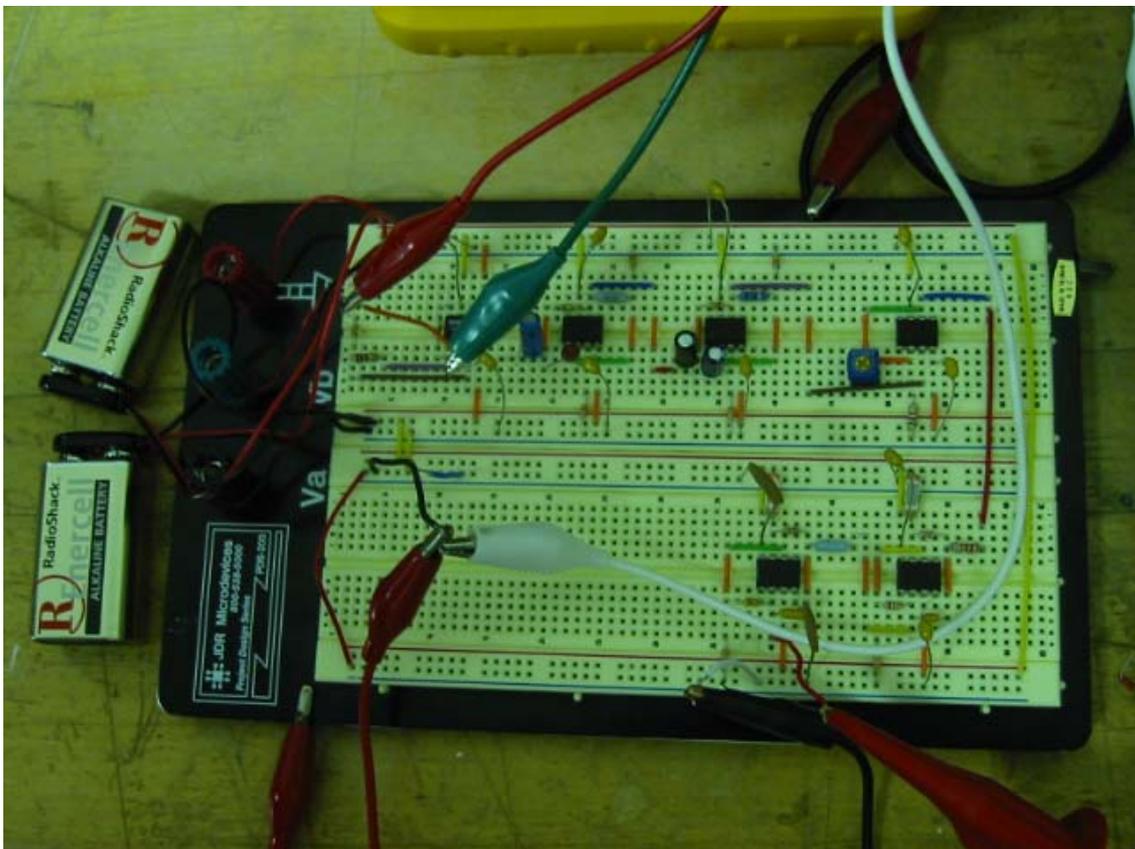


Figure 9 Photo of Prototype board

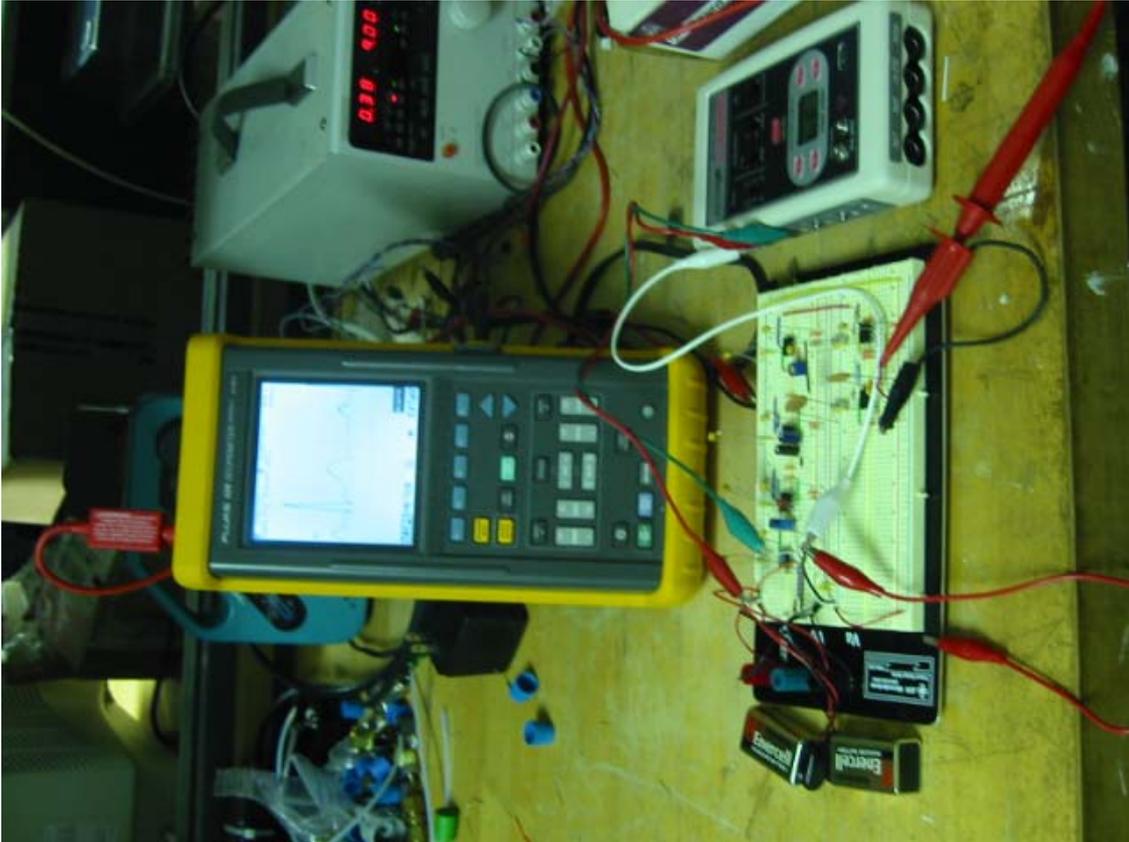


Figure 10 Photo of the ECG amplifier and testing system

Part V : Frequency Testing Results

Figure 11 is the experimental frequency response of our prototype circuit. We notice that the experimental results around the high frequency end fits the simulation well. But the frequency response at low frequency is not as sharp as the simulation results.

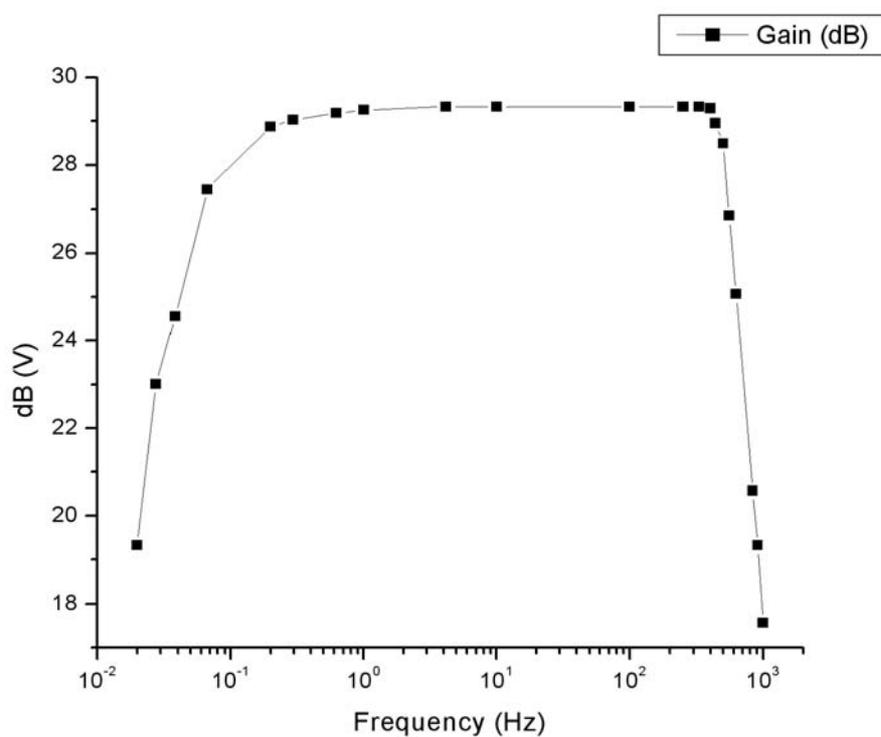


Figure 11. Frequency response of the ECG amplifier (experimental results)

Part VI: ECG Emulator Testing

Further steps to minimize 60 Hz noise include twisting the two input wire of ECG emulator to reduce the magnetic pick-up interference and connecting the ground in our ECG circuit to a large good conductor (such as the metal part of the protoboard) to increase the its area. The final ECG emulator testing shows that 60 Hz is very small (Figure 12).

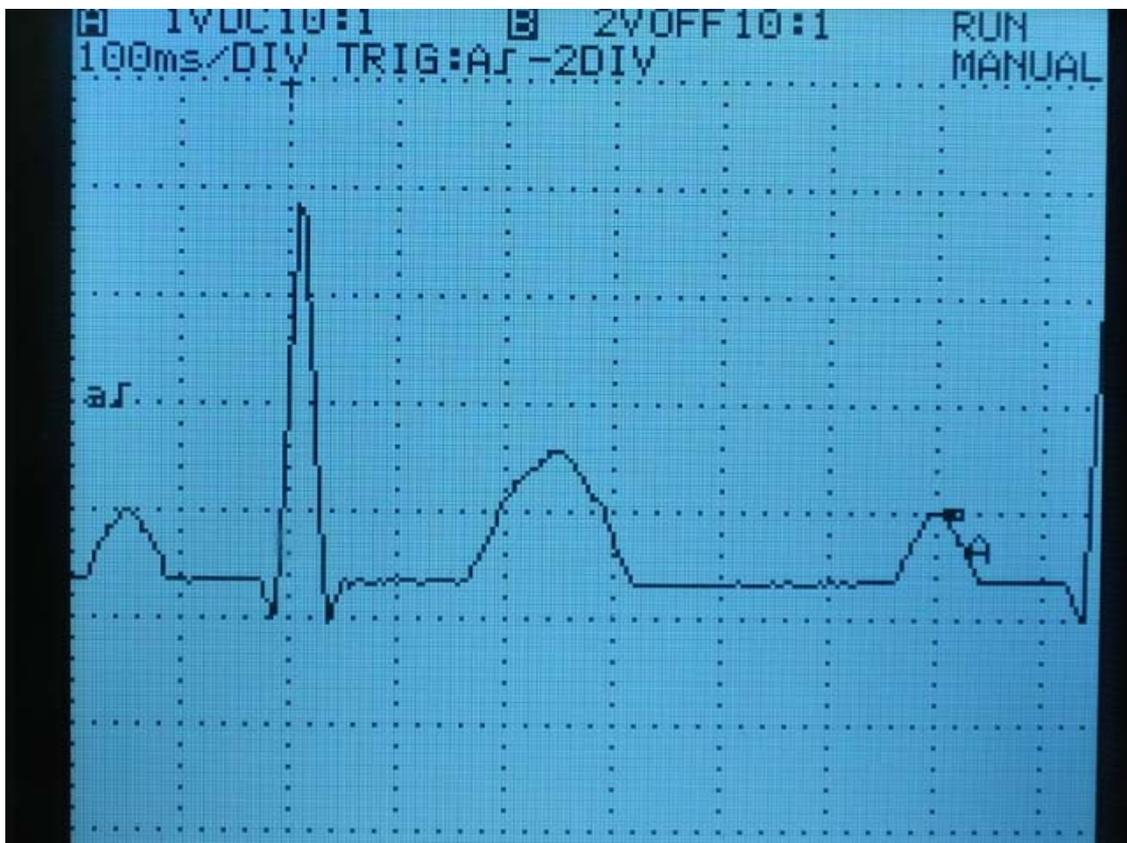


Figure 12. The ECG emulator testing result

Part VII: Conclusions and Lessons

An ECG amplifier was designed and implemented in this project. Its gain is adjustable and enough to amplify small ECG signals. The fourth-order Sallen-Key high-pass and low-pass filters rejected most of the DC and high frequency noise of the input ECG signal. 60-Hz noise was minimized by using battery power supply and filter capacitor. Twisting the inputs wire and increasing ground area is also useful. Neat wiring always helps.

The most important lesson is to check wiring very carefully before testing. Test the circuit stage by stage and solve the trickiest part first. A notch filter and driven-right-leg system will be a good choice to further reduce the 60-Hz noise.

Acknowledgements

I appreciate Mr. Tai-ho Kang and Mr. Gary Smith for their valuable discussion on the design and implementation of this ECG amplifier.

References

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