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ECG circuit design and analysis algorithm

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Abstract. Nowadays, many people have a sub-health lifestyle: poor diet, lack of exercise, high pressure, inadequate sleep, long periods of sitting, etc. All the unhealthy behaviours will lead to chronic disease, especially heart disease. People then use wearable devices like Apple Watch to monitor their heartbeat and try to find out if anything goes wrong in advance. This paper is then going to introduce how wearable devices detect the heartbeat from two perspectives. The hardware part gives a detailed implementation of a complete design of circuits within the wearable device used to detect heartbreak. The circuit is designed to be power-efficient, resistant to noise, and capable of amplifying the input voltage by about 100 times. The circuit design would contain three main parts: the human body circuit, the three-amplifier system, and the filter system. For each part, detailed information about how to choose the value of components is provided, and how the chosen value of components meets the requirement is also illustrated. On the other hand, it will introduce three algorithms used to analyze the ECG signals output from the circuit.

Keywords: ECG circuit design, pseudo resistors, right leg driven circuit, three-amplifier system.

1. Introduction

Even though the technology associated with medical treatment has much remarkable progress, heart disease has still been the leading cause of death for men and women in the United States [1]. According to the data, one person would die due to cardiovascular disease about every 34 seconds in the United States [2]. Unlike other chronic diseases like cancer, where patients could receive proper therapy after they are diagnosed, patients with heart diseases may suffer from heart attacks and strokes, which will take the life of patients within several minutes, or even several seconds. In addition, although older people are still the main part of the dead population, the number of young people who die from heart disease is still considerable; in the current competitive society, young people would face challenges from both work and study, which makes staying up late a common behavior of the young generation. Moreover, covid has just passed less than one year. People who recover from covid may still suffer from sequela such as inflammatory cardiomyopathy.

While once the patients face the outbreak of heart disease, other people and themselves should be prepared to conduct first-aid, ensuring they can then be sent to the hospital for further treatment. Otherwise, they may pass away before they arrive at the hospital. To prepare before the onset of a heart attack, patients should first know their own conditions well. As some heart diseases like cardiac-arrhythmias cannot be diagnosed within a short time, people need to monitor their heart condition

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continuously. Meanwhile, monitoring heart conditions could also help people avoid a heart attack; when they find strange behaviors of the heart, they could go to the doctors or stop their unhealthy behaviors immediately before a heart attack occurs.

Wearable devices like a watch could be optimal types of equipment that meet the expectation. For example, you can take a quick 30-second ECG test on your Apple Watch and get a brief summary about if your heart is working well. This paper will then introduce how this technique is realized from both hardware and software aspects.

2. ECG circuit design

Since each beat is initiated by the electrical stimulus generated by the sinoatrial node (SA node), the electrical signal could be detected and measured to assess the performance of the heart. The method that monitors the heartbeat by recording the electrical signal is called Electrocardiogram (ECG or EKG). To evaluate the performance of an ECG circuit, aspects including the differential gain, the ability to deal with the noise, and the total power consumption. ECG circuit with high quality should be able to amplify the signal it received to the expected magnitude (typically, the gain should be about 40dB, which means the output voltage is about 100 times the input voltage) and cancel out the internal and exterior noise with low power [3]. This part is going to discuss the implementation of ECG. The implementation could be divided into three main parts: the human body circuit, the three-amplifier system, and the filter system.

2.1. Human body circuit

Since the human body is conductive, the potential created by the heartbeat could then be transmitted to the body's surface. To measure the electrical signals from the body surface, electrodes and leads are commonly used components. The electrode is a small conductive pad attached to the skin to receive the potential, and the lead refers to a pair of electrodes. Leads could be simply classified into two types: unipolar leads and bipolar leads. While bipolar leads measure the differential potential across a pair of electrodes, unipolar leads measure a common potential. According to Wilson's Central Terminal, the common potential will be the average of the potentials from the right arm, left arm, and left leg.

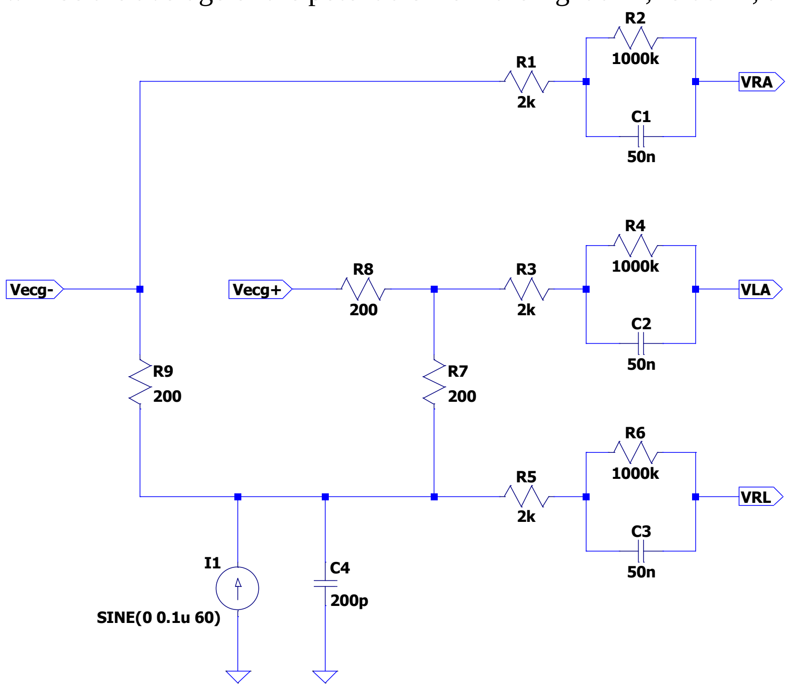

Figure 1. Human body circuit design.

The human body circuit design is shown in Figure 1. In this design, three augmented limb leads, a specific type of unipolar lead, are implemented. Even though both leads will be common for medical usage, unipolar tends to be more pervasive for its easier introduction and better position of the lead [4]. The graph above is our design for the human body circuit. The ecg+ and ecg- tags are the input potential that is read from the ECG. To mimic the noise (always 60 Hz) in real life, a current source I1 is attached to the input. VRA corresponds to the potential of the right arm, VLA corresponds to the potential of the left arm, and VRL corresponds to the potential of the right leg.

2.2. *Three-amplifier system*

The average voltage generated by one heartbeat is about 75 mini volts. The amount is so tiny that it is not suitable for further analysis. To ensure the heartbeat signal could be used for analysis, the op-amp system should amplify the signal by 40dB (the output will be about 100 times the input voltage). Since a 40dB gain is expected for the circuit, one op-amp is not an appropriate choice (typically, a power amplifier would have a 20 dB gain). Therefore, a two-step amplification is needed. In addition, this system would have two inputs: voltage from the right arm and voltage from the left arm. This system then needs to convert the differential input signals to a single-ended output. A three-op-amp system is then chosen. The common three-amplifier system is shown in Figure 2.

For a traditional three-op-amp model, the differential gain of the first stage A_{d1} and second stage A_{d2} will be:

$$A_{d1} = 1 + \frac{R1+R2}{Rgain} \tag{1}$$

$$A_{d2} = \frac{R4}{R3} \tag{2}$$

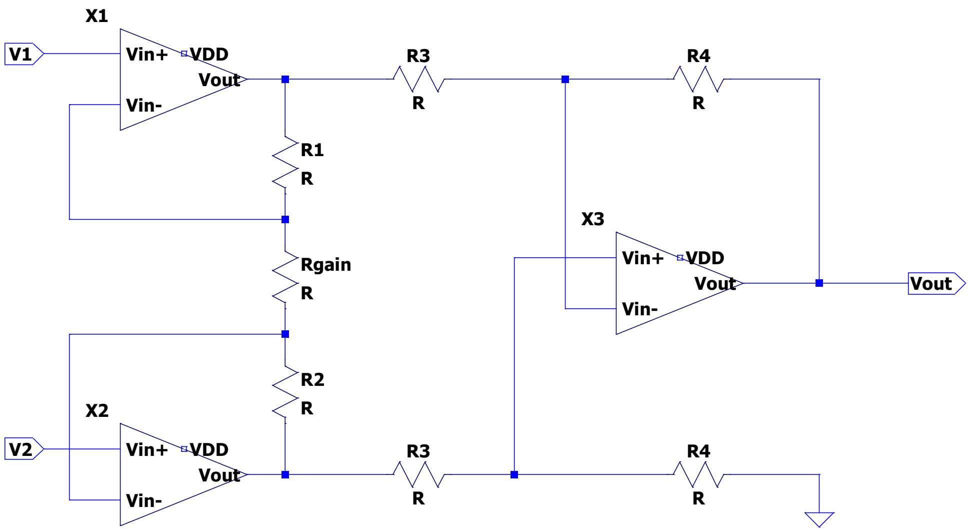

Figure 2. Common three-amplifier system.

Instead of using resistors to control the amplification amount, capacitors are used to control the amount of amplification.

Pseudo-resistors are implemented to replace resistors. With the same resistance, pseudo resistors tend to occupy less space and would create less noise than a typical resistor [5]. Since the ECG circuit would be implemented in wearable devices and wearable devices should be small for people to carry along with them daily, pseudo resistors then become a more desirable choice. The construction of pseudo resistor is shown in Figure 3.

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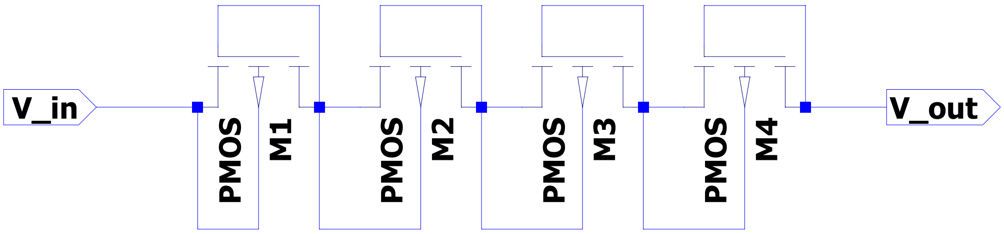

Figure 3. Construction of pseudo resistor.

Therefore, the new gain will be:

$$A_{d1} = 1 + \frac{R_{C1}+R_{C2}}{R_{Cgain}} \tag{3}$$

$$A_{d1} = 1 + \frac{\frac{1}{jwC1}+\frac{1}{jwC2}}{\frac{1}{jwCgain}} \tag{4}$$

$$A_{d1} = 1 + \frac{Cgain(C1+C2)}{C1C2} \tag{5}$$

$$A_{d2} = \frac{R_{C4}}{R_{C3}} \tag{6}$$

$$A_{d2} = \frac{\frac{1}{jwC4}}{\frac{1}{jwC3}} \tag{7}$$

$$A_{d2} = \frac{C3}{C4} \tag{8}$$

The revised three-amplifier system is shown in Figure 4. According to the data from the following graph, the first-stage differential gain will be 20, and the second-stage differential gain will be 5. Therefore, the overall gain will be 100, which equals 40 dB. The requirement for the amplifier system is met.

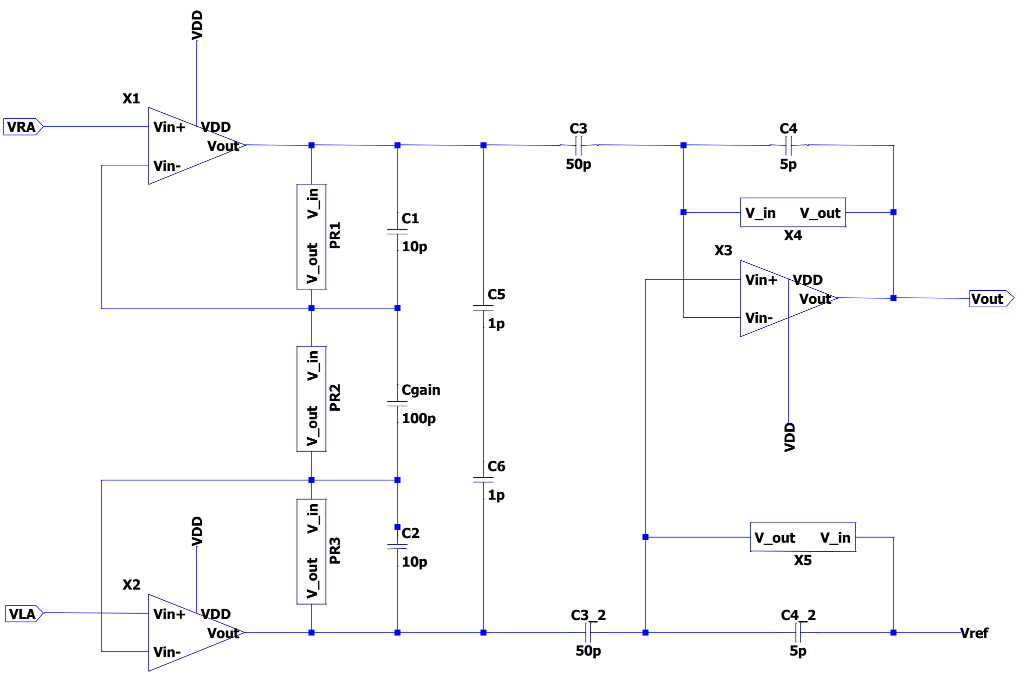

Figure 4. Revised three-amplifier system.

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2.3. Filter system

The frequency of ECG will vary depending on its usage. For example, for clinical ECG, the frequency would range from 0.05Hz to 100Hz; the monitoring mode will have a frequency from 0.05Hz to 35 Hz; and the surgical mode will have a frequency from 1HZ to 25 Hz [6]. For this design, the frequency range would be 0 to 250 Hz.

The bandpass filter consists of a high pass filter which only allows signals with a frequency larger than 0 Hz to pass, and a low pass filter which only allows signals with a frequency less than 250Hz to pass.

The frequency of the bandpass filter is calculated by:

$$f_L = \frac{1}{2\pi R_L C_L} \tag{9}$$

$$f_H = \frac{1}{2\pi R_H C_H} \tag{10}$$

The filter system design is shown in Figure 5. For the circuit below, the R_L is R_1, the C_L is C_9, the R_H is R_4, and the C_H is C_{10}. The R_2 and C_{11} are connected to the reference voltage to cancel out the noise.

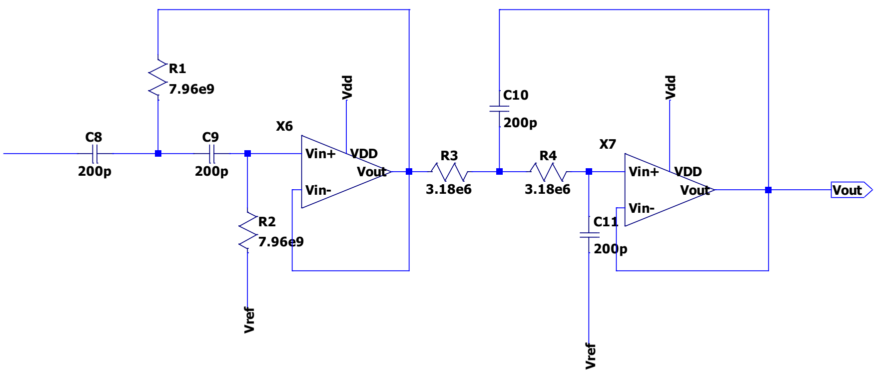

Figure 5. Filter system design.

2.4. Overall design and summary

The overall design is shown in Figure 6.

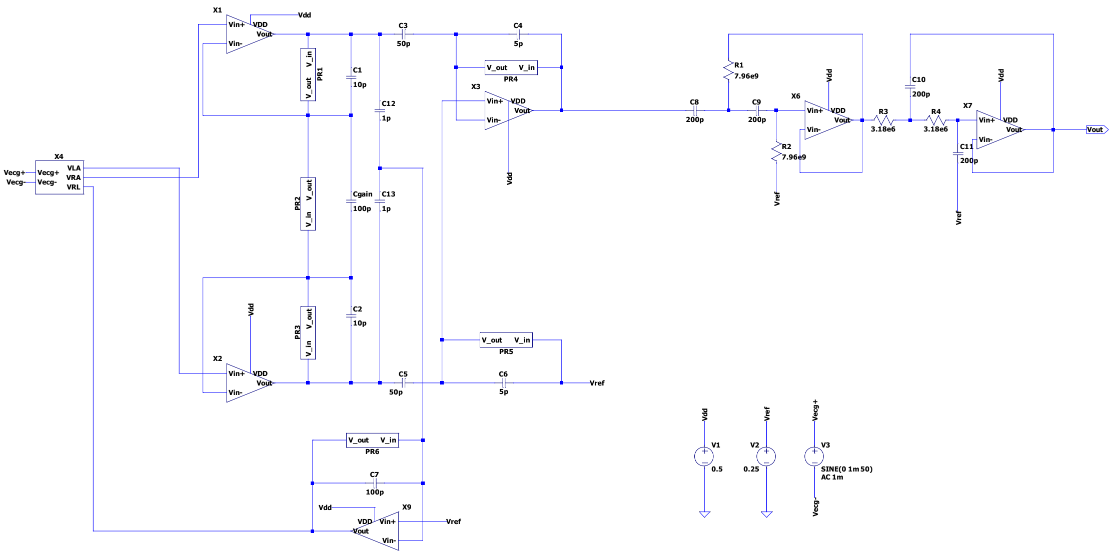

Figure 6. Overall ECG circuit design.

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Aside from the three main parts mentioned above, a right-leg-driven circuit is connected to the design. After the first amplification stage, this part would sense the common-mode voltage, invert the voltage, magnify it, and send it back to the right leg circuit. This feedback circuit would help cancel out the common mode interference created during the amplification process, and it is incredibly efficient in undermining the influence of the 60Hz noise in real life [7].

As mentioned above, the amplifying amount should be around 40 dB. According to the simulation of Figure 7, between 1-250 Hz, the amplifying amount is stable at around 43 dB, which meets the requirement.

While both the right leg feedback circuit, pseudo resistors, and the filter system contribute to noise reduction, the noise of the system is optimal, which is 170.86 microvolts.

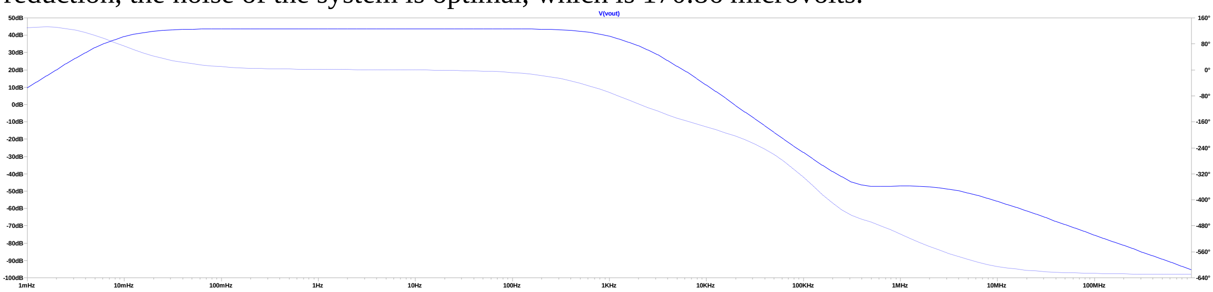

Figure 7. DB gain vs. frequency.

3. ECG analysis

Before walking into the algorithm that analyzes the ECG, the characteristic of the output signal should first be introduced.

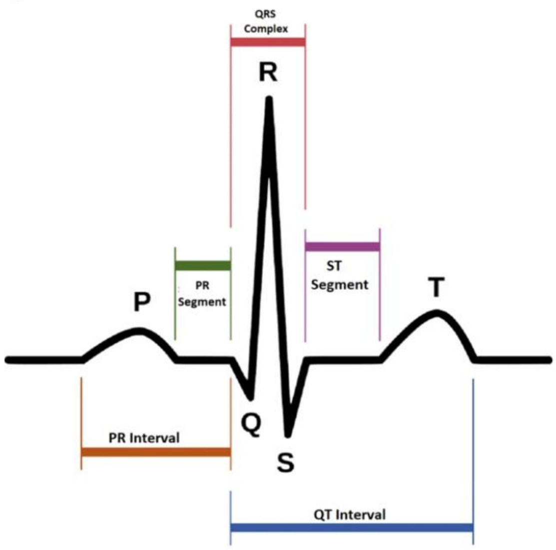

Figure 8. ECG wave [8].

The ECG wave can be classified into three waves – P, QRS, and T wave. Figure 8 is the ECG wave. The P wave is the result of atrial activation, and the PR interval is the distance between the start of the P wave and the start of the QRS complex. The PR Segment measures the distance between the end of the P wave and the start of the QRS complex. This line can also be considered as the baseline, where any amplitude will be the difference between the point and this line. The QRS complex is the result of ventricular depolarization. It will be optimal to have a shorter time interval between the beginning of the QRS complex and its end because this means the speed of ventricular depolarization is high. The T wave results from ventricular repolarization. The QT interval will be the distance between the start of the QRS complex and the end of the T wave, which is also the total time for ventricular depolarization and repolarization. There is an inverse connection between the length of the QT interval and the heart rate. In other words, a longer QT interval means a slower heart rate, and vice versa.

3.1. Peak detection
Peak detection is one of the most critical analyzing algorithms for ECG signals. Like its name, this algorithm will track the R wave in the QRS complex, because the R wave always reaches the highest amplitude of one heartbeat. Every time the heartbeat signals fill the window, the maximum value will be recorded (the R wave with the largest amplitude will be recorded). If the peak is found in the central part of the window and the new amplitude is higher than the past threshold, the threshold will be updated to the new amplitude [9].

3.2. SQRS algorithm
Unlike peak detection, which uses the ECG signal as direct input, before the ECG signals go into the SQRS algorithm, they will first pass a Finite Impulse Response filter which will create an approximated slope for the signal. If the filtered signal is larger than the original threshold, it will have two possible outcomes. First, if there are two to four signals detected within 160ms, it turns out that a normal heartbeat is recorded. Second, if more than four detections happen within 200ms, it indicates a problem. The algorithm will then reset if it faces either outcome [10].

3.3. WQRS algorithm
This algorithm will highly depend on the length transform of ECG. The algorithm will detect whether there is a rising slope of the length transform. If a length transform is detected, it means that the QRS complex begins. It could also find the end of the QRS complex through length transform. This algorithm is also able to offer extra information about the end of the QRS complex. Compared to the peak detection algorithm and the SQRS algorithm, the measurement of the WQRS algorithm would be more accurate (highest sensitivity and high positive predictivity). However, this accuracy is in exchange for processing time [10].

4. Conclusion
In conclusion, the hardware part is an ECG circuit that could be implemented into the wearable device. It could amplify the electrical signal to about 43dB, and the noise is only about 170 microvolts. Additionally, to save more space, the total capacitor is minimized, and resistors with large impedance are changed into pseudo resistors. While our circuit design could fit the basic requirements – high amplifying amount and low noise – for the ECG circuit, the real-life condition is much more complicated. Each component would be cautiously evaluated and then can be chosen as the built-up parts. For example, producers should consider which amplifier model would occupy a smaller space, become more energy-efficient, and cost less. While all the results are based on theories and online simulation, more data about hands-on experiments should be recorded to provide further information. Although many different algorithms solve the problem, there is no best algorithm for the software. People should evaluate their needs and find the algorithms that best fit their requirements.

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