Electrocardiogram experiment for analog electronic laboratory

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Abstract

The measurements of biomedical signals are exciting and challenging for students of electrical and electronics engineering. This paper presents an experimental practice involving electronics instrumentation in measuring the heart beat. Students learn about electrophysiology, bioelectricity, instrumentation amplifier, and filters. The course is scalable and can provide a module about signal processing. The students are motivated with lab experiment of real-life applications (electrocardiograph) and their enthusiasm enhances their learning.

Keywords: ECG, electronic laboratory, learner satisfaction, experimental lab, CMRR.

Introduction

Learner satisfaction is an important factor for the students seeking more knowledge, even after the course is over (postlearning)[1], [2]. This postlearning and application of theories and practical information learned in the professional life of students motivates the creation of lab practical experiments. Working with practical implementation can increase the motivation and enthusiasm of students when it is based on real-life applications or visible results from lab work. The improvement in the experimental labs is important for the evaluation of learner satisfaction. Gallardo *et al*.[1] proposed a questionnaire that evaluates the principal components on learner satisfaction: content, user interface, ease of use, and motivation.

Schaefer *et al*. [3] proposed that it is essential for an engineer to be able to work at the interface of different disciplines. The following multidisciplinarity is intrinsic for biomedical engineering: electrophysiology, cardiology, electronic instrumentation, application of physics in medicine [4]. In Brazil, biomedical engineering courses are new. Traditionally, professionals in biomedical engineering have originated from different engineering, physics, and chemistry courses. Electrical and electronics engineering has been a major contributor to human resources in this area. Biomedical engineering has a few disciplines in the undergraduate courses and these areas are presented in a fragmentary, isolated (*i.e.*, unrelated to other biomedical disciplines), and noncontextualized way. These biomedical engineering disciplines are optional in the curricula, and practical classes or approaches were offered in only 14% of the total class schedule [5]. This concern providing multidisciplinarity to students from electrical engineering and electronics engineering motivates the creation of biomedical engineering courses.

In this paper, an electrocardiogram (ECG) laboratory practice experiment is presented aiming to demonstrate and teach analog electronic instrumentation for biomedical signals. A questionnaire is employed for the available motivation to the students and information to improve the course is provided.

Materials and Methods

<u>The basis of electrocardiograph signal</u>

Electrocardiogram (ECG or EKG) records the electrical activity of the heart. In medical practice, ECG is one of the most common signals used due to its noninvasive nature and the information it contains. The applications of ECG to cardiological diagnosis include: heart rate monitoring, arrhythmias (irregular rhythm of hearth beat), and infarction [6], [7].

ECG is an electrical signal recording of the small electric waves being generated during heart activity. When the electric current flows through the cardiac muscle, it causes muscle contract. The electric activity starts at the top of the heart and spreads down, and then up again. This activation sequence produces an optimal way for pumping blood. The electricity is originates from specialized cells called pacemaker cells; they are located on the top of the heart. These cells produce electricity changing their electrical charge from positive to negative and back [8]. In the biological systems, the electrical charge are ions (sodium, calcium, potassium, chlorine). The difference of ionic concentrations of intra and extracellular medium produce a difference voltage through the cell membrane, transmembrane potential. The cell membrane act as a barrier for ions. Ionic channels are membrane proteins whose function is gating the ionic flow across the cell membrane. The correct sequence of opening and closing ionic channels (fast sodium channels, slow sodium-calcium channels, and potassium channels) in the pacemaker cells membrane produce a self-excitation. This process causes automatic rhythmical discharge and a contraction of heart muscle [8].

The typical electrocardiogram trace consist of a P wave, QRS complex and T wave as shown on Fig. 1. P wave represents atrial depolarization (electrical discharge, muscle activation). The three waves of the QRS complex reflects the rapid ventricular depolarization. T wave is caused by ventricular repolarization (electrical recharge, muscle relaxation). The large QRS complex obscures atrial repolarization. The R wave to R wave interval reveals important information about the physiological state of the patient, heart rate = 60/(RR interval in seconds);

normal resting heart rate is approximately 70 beats per minutes (bpm) [4]. Analysis of variations in the instantaneous heart rate time series using RR intervals has provide an assessment of cardiovascular disease. The heart rate may be increased by slow acting sympathetic activity or decreased by fast acting parasympathetic (vagal) activity [9].

[Figure 1]

Figure 1 – The electrophysiology of the heart. The waveforms of electric pulse observed in different specialized cardiac tissue. RA, LA are right and left atrium, RV and LV are right and left ventricle.

The biopotential electrodes convert ionic currents inside the body into input currents to electronic devices. The Ag/AgCl electrodes are formed by two interfaces: skin-electrode and electrode-metal [10]. These biopontential electrodes reduce the noise component, caused by the high skin impedance, in the recording of biomedical signal. The root-mean-square electrode noise is typically 1 to 20 μV (depending on the skin treatment [11]) [12], [13]. The frequency band ECG measurement is from 0.01 to 250 Hz and 0.5 to 4 mV [4].

Hardware circuit and experimental setup

In this section, experimental examples and theoretical materials are reported that help a student to understand and practice the signal conditioning typically required for analysis of the ECG and other biological signals. This analog electronic circuit is important because the biopotential voltage is less than 10 mV and they are subject to noise from the environment and power line [4].

The experiment consists of making an analog electronic circuit to blink the LED according to the cardiac frequency, i.e., each time the R wave exceeds a threshold. The block diagram of the experiment is shown in Fig. 2. The students assemble and test electronic parts individually: instrumentation amplifier, filters, and comparator. They combine each small circuit to make a large one. The last steps are testing all circuits and connecting on the student body electrodes.

[Figure 2]

Figure 2 – The electronic circuit consists of three modules: amplifier, filter, and comparator of the signal to blink an LED. The black dots on the body represent electrode positions. The ECG electric characteristics are 0.5 to 4 mV and 0.01 to 250 Hz.

The requirements of ECG circuits are: high input impedance (minimum loading of the measured signal), electrical protection (avoiding microshocks or macroshocks in the patient), high common-mode-rejection ratio (CMRR), high gain (order of 1,000), and adequate limit bandwidth.

<u>Instrumentation amplifier</u>

In this section, the discrete instrumentation amplifier helps students understand the non-idealities of instrumentation amplifiers. The theoretical and practical effect of tolerance resistance, offset voltage error, CMRR are presented.

The instrumentation amplifiers provide high amplification (*e.g.*, INA128, gain up to 10,000 [14] of differential signals with two or three operational amplifiers (op-amps)). The bipolar electrodes produce a common-mode voltage with respect to ground that is larger than the signal amplitude. Although the instrumentation amplifier has high CMRR and high input resistance, the asymmetry in the circuit (*e.g.*, tolerance resistors, imbalance components) will produce variation of the output common-mode level [15].

Fig. 3 presents the electric circuit of instrumentation amplifier with three op-amps. Assuming ideal op-amps with infinite open-loop gain (V5=V6), the current through R1, R2, and Rg is:

$$\frac{V2 - V1}{Rg} = \frac{V1 - V3}{R1} = \frac{V4 - V2}{R2} \tag{1}$$

[Figure 3]

Figure 3 - Instrumentation amplifier with three op-amps. There is an input signal with differential and common-mode components.

The current through R3 and R5 and noninverting input, V6, on the stage differential are:

$$\frac{V3 - V5}{R3} = \frac{V5 - Vo}{R5} \tag{2}$$

$$V6 = \frac{R4}{R4 + R6} Vref + \frac{R6}{R4 + R6} V4 \tag{3}$$

Using eqns (1), (2), and (3), the output voltage:

$$Vo = \left(1 + \frac{R5}{R3}\right)\left(\frac{R4}{R4 + R6}\right) Vref + \left(\frac{R6}{R4 + R6}\right)\left(1 + \frac{R5}{R3}\right) V2 - \frac{R5}{R3} V1 + \left[\frac{R1R5}{R3Rg} + \left(\frac{R6}{R4 + R6}\right)\left(\frac{R3 + R5}{R3}\right)\frac{R2}{Rg}\right](V2 - V1) \tag{4}$$

As $V1 = Vcm - Vd/2$ and $V2 = Vcm + Vd/2$:

$$\mathrm{Vo} = \mathrm{Aref.Vref} + \mathrm{Acm.Vcm} + \mathrm{Ad.Vd} \tag{5}$$

where

$$\mathrm{Aref} = \frac{\mathrm{R3R4} + \mathrm{R4R5}}{\mathrm{R3(R4} + \mathrm{R6)}}, \tag{6}$$

$$\mathrm{Acm} = \frac{\mathrm{R3R6} - \mathrm{R4R5}}{\mathrm{R3(R4} + \mathrm{R6)}} \tag{7}$$

$$\mathrm{Ad} = \frac{1}{2}\left[\left(\frac{\mathrm{R6}}{\mathrm{R4} + \mathrm{R6}}\right)\left(\frac{\mathrm{R3} + \mathrm{R5}}{\mathrm{R3}}\right) + \frac{\mathrm{R5}}{\mathrm{R3}}\right] + \frac{\mathrm{R1R5}}{\mathrm{R3Rg}} + \left(\frac{\mathrm{R6}}{\mathrm{R4} + \mathrm{R6}}\right)\left(\frac{\mathrm{R3} + \mathrm{R5}}{\mathrm{R3}}\right)\frac{\mathrm{R2}}{\mathrm{Rg}} \tag{8}$$

Suppose the imbalance of four resistors is on R5=Ro.(1+δo), δo is the sum of four resistor tolerances and R3=R4=R6=Ro. R1=Ri.(1+δi), δi is the sum of two resistor tolerances and R2=Ri. Vref is null. The common mode gain and differential gain with resistor tolerance from (7) and (8) are, respectively:

$$\mathrm{Acm}_{\delta} = \delta/2 \tag{9}$$

$$\mathrm{Ad}_{\delta} = \mathrm{G} + \frac{3}{4}\delta\mathrm{o.G} + \frac{\mathrm{Ri}}{\mathrm{Ro}}\delta\mathrm{i.}\left(1 + \frac{\delta\mathrm{o}}{2}\right) \tag{10}$$

where G=1 + (2Ri/Rg) is the ideal differential gain. Substituting eqns (9) and (10) into the CMRR $\triangleq |\mathrm{Ad}_{\delta}|/|\mathrm{Acm}_{\delta}|$:

$$\mathrm{CMRR} = \left(\frac{2}{\delta\mathrm{o}} + \frac{3}{2}\right).\mathrm{G} + \frac{2\mathrm{Ri}.\delta\mathrm{i}}{\mathrm{Rg}}\left(\frac{1}{\delta\mathrm{o}} + \frac{1}{2}\right) \tag{11}$$

From eqn (5)

$$\mathrm{Vo} = \mathrm{Ad}\left[\frac{\mathrm{Aref}}{\mathrm{Ad}}.\mathrm{Vref} + \mathrm{Vd} \pm \frac{\mathrm{Vcm}}{\mathrm{CMRR}}\right] \tag{12}$$

Eqn (9) shows that CMRR is independent of Ro. The CMRR depends on the resistor tolerance (δo and δi) and Ri/Rg. The effect of CMRR in the circuit of three op-amps is represented by an offset voltage (Vcm/CMRR) [16].

The voltage offset error introduced by CMRR is irrelevant (*e.g.*, INA128, gain of 1,000, 130 dB [14] to instrumentation operational on a chip). But, it is important to demonstrate with the experiment this error source and the problem caused.

A motivational and didactic proposal in the learning about causes of offset voltage error, CMRR, instrumentation operational, and filter was proposed using three op-amp and discrete resistors, Fig. 4.

[Figure 4]

Figure 4 – A) Discrete instrumentation operation using three op-amps, TL074. B) The voltage offset error is equalized by a trimmer potentiometer (offset, Tr1=10 kΩ). R1=R2=100 kΩ, Rg=390 Ω, R3=R4=R5=R6=10 kΩ, R7=1 MΩ, R8=1 kΩ, 5% tolerance resistor, Vcc=±9 V.

The resistors are of 5% tolerance. The CMRR without compensation, Vref=0 V, for gain of 100, is 4254 (73 dB). The experimental offset voltage is 250 mV, with G=100, and 2.62 V, when G=1,000, Fig. 7.

The DC error occurs due to: resistance tolerance, input-offset voltage, input-bias current and input-offset current [17].

The student needs to reduce voltage offset error; it is possible to alter the Vref through 10 kΩ potentiometer, as shown in eqn (12). For this test, the input signal is 5 Vpp (peak-to-peak) with 20 Hz. The input signal was reduced by a divisor voltage of about 1,000, and the output needs to be zero. After this adjustment, the student connects the -Vin input on ground, the instrumentation operational gain is about 900, and the output is about 4.5 Vpp without offset voltage.

Typical performance characteristics of discrete instrumentation amplifier

The influence of gain on experimental offset voltage was analyzed. The supply voltage was +12 V and -12 V. +Vin and –Vin was at ground, the output is open. All resistors are of 5% tolerance. The frequency dependency of gain and phase of this instrumentation amplifier circuit was measured after the voltage offset is null. The -Vin was on ground and +Vin was connected with divisor voltage of about 1,000. The input signal varied from 5 to 10,000 Hz and the gain was from 21 to 3,572.

The measurements were realized with an oscilloscope (Tektronix, model TDS2004C; Tektronix Instruments, Beaverton, OR, USA), a signal generator (model CFG253, Tektronix Instruments, Beaverton, OR, USA), and a digital multimeter (model 179, Fluke Instruments, Everett, WA, USA).

Analog active filters

The students have the opportunity to learn and work with analog filters and limit the ECG frequency band.

Filters have many applications, they can be used to separate signals, passing those of interest, and attenuating the unwanted frequencies. An ideal filter has unity gain, or fixed gain, for the frequencies of interest (passband) and zero everywhere else (stopband). The cutoff frequency is defined as the frequency at which the ratio of the signal input and output (Vin/Vout) has a magnitude of 0.707 (or 3 dB).

The Sallen-Key configuration is one of the most widely used filter topologies. This popularity occurs because of the least dependence of filter performance on the performance of the op-amp [18]. The frequency and Q terms are somewhat independent, but they are very sensitive to the gain parameter [19].

The second-order Sallen-Key filter topology is presented in Fig. 5. The transfer function in time domain is:

$$\frac{\mathrm{Vo}}{\mathrm{Vin}} = \frac{\mathrm{Z3.Z4}}{\mathrm{Z1.Z2} + \mathrm{Z4}(\mathrm{Z1} + \mathrm{Z2}) + \mathrm{Z3.Z4}} \tag{11}$$

and the frequency domain is:

$$\mathrm{H(s)} = \frac{(2\pi f_c)^2}{s^2 + 2\pi \frac{f_c}{Q} s + (2\pi f_c)^2} \tag{12}$$

where f_c is the cut-off frequency and Q is the quality factor:

$$f_c = \frac{1}{2\pi\sqrt{\mathrm{Z1.Z2.Z3.Z4}}} \tag{13}$$

$$Q = \frac{\sqrt{\mathrm{Z1.Z2.Z3.Z4}}}{\mathrm{Z3}(\mathrm{Z1} + \mathrm{Z2})} \tag{14}$$

[Figure 5]

Figure 5 – Generic second-order Sallen-Key filter topology [18].

In this experimental activity, for high-pass filter, Z1=Z2= C and Z3=Z4=R. And for low-pass filter, Z1=Z2= R and Z3=Z4=C. f_c=1/2πRC and Q=0.5. The frequency band is 1 to 50 Hz. C=2.2 μF, R=75 kΩ (high-pass filter) and R=1.5 kΩ (low-pass filter). The low-pass filter attenuates the 60 Hz (Brazilian power-line noise). The countries with 50 Hz power line interference, the frequency band suggested is 1 to 40 Hz. C=2.2 μF, R=75 kΩ (high-pass filter) and R=1.8 kΩ (low-pass filter).

Comparator and complete circuit

The last experimental part is an easy one for students. It is essential in this part that the input signal is amplified enough to compare (about 3-8 V). The student needs to connect the three parts (instrumentation amplifier, filters, and comparator) as shown in Fig. 6. And in the last test, the input signal is 5 Vpp/20 Hz through the voltage divisor, Fig. 4B, the comparator noninverting terminal is about 10 Vpp/20 Hz, and the inverting terminal must be about 3 V, so that the LED will blink. The student removes the voltage divisor and connects the signal-shielded cable with the electrodes on the body; the electrode positions are presented in Fig. 2. The op-amp used was the same as that of filters, TL084.

[Figure 6]

Figure 6 – Complete circuit of ECG experiment. R1=100 KΩ, R2=10 KΩ, R3=390 Ω, P1=10 KΩ (potentiometer), C=2.2 μF, Rf1=75 KΩ, Rf2=1.5 KΩ, D=LED.

Learner satisfaction study

The ECG experiment was realized by 31 undergraduate students of two courses: electrical engineering and electronics engineering of Federal University of Santa Catarina. The freshman students were excluded of this study. The evaluation was conducted at the end of the course. The participants were asked to complete a questionnaire related to user satisfaction with the ECG experiment, to allow the instructors to obtain feedback on further improvements and evaluation of learner satisfaction. The questionnaire consists of 60 questions with the four dimensions of high influence on learner satisfaction: content (questions: 1-5), user interface (6-8) , ease-of-use (9-13), and enthusiasm and motivation (14-16) [1]. The participants were asked to express their opinion on a 7-point Likert scale (LS) ranging from 1 (disagree – LS (1)) to 7 (strongly agree (LS – (7)) statement. This study protocol was approved by the University ethics committee (CAEE 374.205). All participants gave written informed consent to join in this study.

The questionnaire was translated into Portuguese for use in this study. To obtain a good level of translation, a backtranslation was conducted [20]. The Portuguese and English versions of the questionnaire were reviewed by three other bilingual professors (who had to teach laboratory class) to ensure that both versions were comparable at a high degree of accuracy.

Results

Performance of discrete instrumentation amplifier

The offset voltage is dependent on gain, Fig. 7. This offset voltage may be eliminated by Vref (Fig. 4B) before the experiment. The offset voltage produced with the gain over 4,000 cannot be completely eliminated.

[Figure 7]

Figure 7 – The analysis of offset voltage and gain. The supply voltages are ±12 V, +Vin, and –Vin connected on ground. The circuit is formed by 3 op-amps (TL074) and 5% tolerance resistance.

Fig. 8 shows the frequency response analysis of discrete instrumentation amplifier. The error gain is less than 4% for frequencies above 300 Hz. The phase angle is less than 8 degrees for less than 100 Hz. Gain above 4,000 produces gain error up to 20%.

[Figure 8]

Figure 8 – Frequency response gain and phase of discrete instrumentation amplifier.

The gain error of an instrumentation amplifier happens due to the tolerance of resistors. The theoretical gain error was analyzed by eqn (10). For the resistances tolerances and value proposed on the Fig. 3 and gain variation of 200 to 4,000, the gain error is less than 4%. The gain error between experimental (Fig. 8) and ideal ($G=1+R_i/R_g$) gain between 201 and 3,562, on frequencies less than 500 Hz, is less than 5%.

Hands-on activities

The circuit of Fig. 6 was mounted on the breadboard as shown in Fig. 9. The suction Ag/AgCl electrodes are seen in Fig. 9. There are some cautions about the use of these electrodes instead of disposable electrode pads. Long-time measurements with a strong negative pressure may cause reddening of the skin. It is important to reduce the contact resistance between the electrode and the skin with a conductive gel. For safety considerations, *it is important to use batteries!* The shielded cable reduces the electrical ambient pollution noise.

[Figure 9]

Figure 9 –A) Module I, ECG circuit mounted on the breadboard, electrodes, and battery. B) Module II, acquisition circuit with isolation (ISO122) and Arduino Uno R3, the acquisition program is free distribution for students.

The experiment of blinking the LED with the cardiac frequency can be extended to module II, processing the ECG signal, as shown in Fig. 10A). The AD converter is done by an Arduino Uno R3 and software at PC. This new module uses the ISO122 (Texas Instruments, Dallas, USA) to isolate the equipment from high-voltage devices, Fig. 10B).

[Figure 10]

Figure 10 – Circuit of isolation (module II).

The interpretation of heart-rate variability is an important marker for heart disease diagnosis. A signal-processing analysis can produce evidences of relation between autonomic nervous system, cardiovascular mortality, and cardiac death [21]. This scope is interesting to students; they can propose some methods to make available the rate variability in time domain and spectral analysis. The basis for both analyses is the detection of peak wave R, Fig. 2, the RR intervals.

Learner satisfaction

The results of student's questionnaires are about module I, as shown in Fig. 10A). The acquisition circuit and signal processing is not valued. This measures the learner satisfaction in all stages of courses (except the freshman students), the signal processing is taught to the students after 3 years of the course. This questionnaire developed by Gallardo *et al.* [1] is a methodology for learner-satisfaction measurement in electronic instrumentation laboratory. With the four main dimensions (content, user interface, ease of use, enthusiasm and motivation), instructors assess the possible ways to improve the course, Fig. 11.

[Figure 11]

Figure 11 – Four dimensions with influence on the learner satisfaction: contentment, user interface, ease of use, enthusiasm and motivation. Likert scale (LS) ranging from 1 to 5 (disagree – vertical lines), 6 (horizontal lines) and 7 (strongly agree - solid bar) statement. Learner-satisfaction questionnaire applied to 31 students of electrical engineering and electronics engineering.

The students demonstrated a strong enthusiasm and motivation about the course. However, the dimension ease of use and user interface present 16 and 12% of negative opinions (LS from 1 to 5).

Discussion

The courses were taught to class 12 students; there was 1 instructor and 2 assistants. It was an extracurricular course of 90 min each; all students finished the experiment in this time. There were students in the undergraduate beginning; they had not experienced electronic assembling. To improve the ease of use dimension, the circuit of Fig. 6 presents reduction of components (capacitors are of the same values) and polyester capacitors (no polarity). However, the discrete instrumentation amplifier has no safety power inversion. There are IC sockets for TL074 for any eventual change, and students learn about the practical assembly.

The students with experienced electronic assembly (over second year) are suggested to improve the course with a challenger or the signal processing (module II). They finished the circuit implementation in about 50 min. The challenger may be based on the methodology of problem-based learning (PBL) [22]. The students will be challengers to process the ECG signal about analyzing the heart-rate variability.

General-purpose op-amps like the LM358, TL074 can be used instead of TL084. There are some problems about the discrete instrumentation amplifier mounted on the breadboard. The parasite capacitors on the breadboard produce alterations on the phase angle and there is no linear frequency dependency of gain. The PCB with discrete instrumentation amplifier (Fig. 4) has less than 8 degrees of phase angle and 4% error gain performance at the interest frequency (1 to 500 Hz), as shown in Fig. 8.

The questionnaire result of Fig. 11 demonstrated that electronic laboratory with practical applications in biomedical engineering motivate the students. This interest is evidenced with the questions during the course. The students have questions about bioelectric signals, interfaces between skin and electrodes, acquisition systems, signal-processing, amplifiers, and filters. Learner satisfaction is a central mediator of postlearning behavior, which links the actual knowledge with postusage cognitive structure, student communications, and reuse compartment [1], [2]. The satisfaction produces a gain in the learning, once the students research about the subject and apply the knowledge in other projects.

Fig. 11 shows the possible improvements on the course. The dimensions ease of use and user interface are associated with didactic material, learning management systems (*e.g.*, moodle), multimedia technologies (*e.g.*, forum, chats), and content.

Conclusion

In this paper, an analog electronics-based ECG laboratory experiment has been presented. This simple experiment helps the student to apply the knowledge about analog signal conditioning and understand some limitations of the amplifiers (CMRR, gain, angle phase). The main contributions of this experiment are:

- The signal conditioning was performed by a motivational experiment with ECG experiment. The students measure their own ECG signal.
- The experiment helps students to understand the basic principles of instrumentation amplifier, CMRR, filters, healthcare devices, and signal conditioning.
- The low price of the components permits the students to apply these circuits in their own projects. This course introduces the students to the biomedical signals and allows the student to exploit their creativity in developing more advanced circuits.

The questionnaire was a tool to improve the lab course and demonstrated that the applicable experiment motivates the students. Future works will improve this course with signal processing, another bioelectric signal (electromyogram, electrooculogram), and a comparison between traditional methodology and the PBL with a practical laboratory.

Acknowledgements

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Figure 1

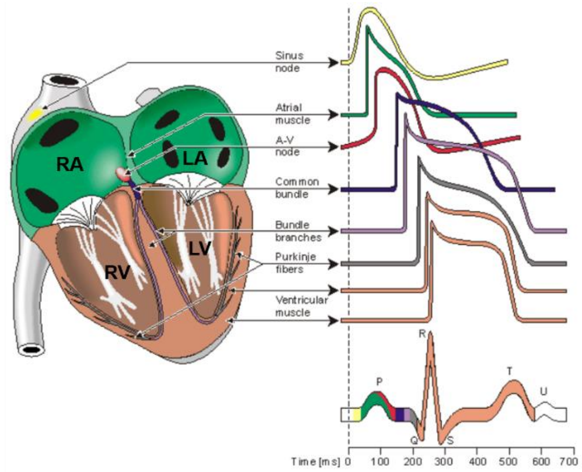

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Figure 2

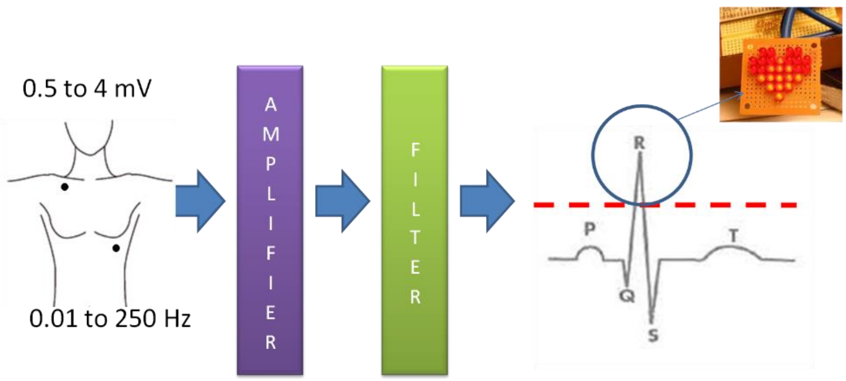


Figure 3

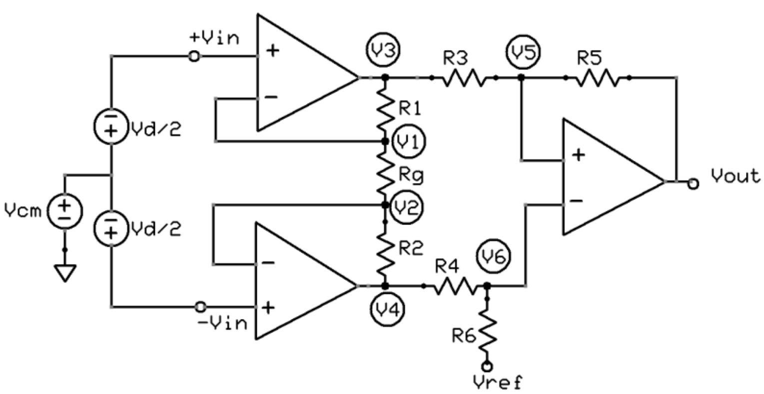
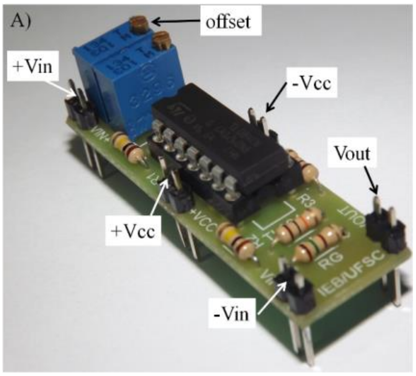


Figure 4



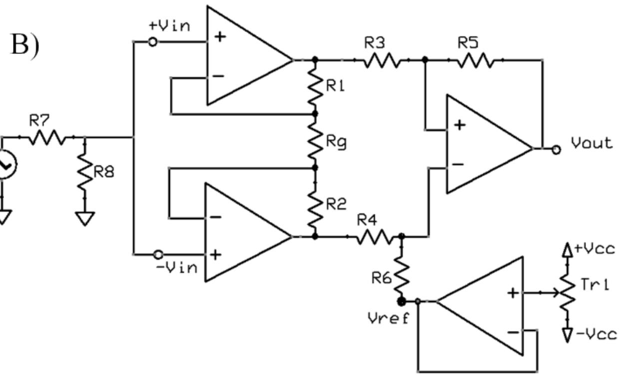


Figure 5

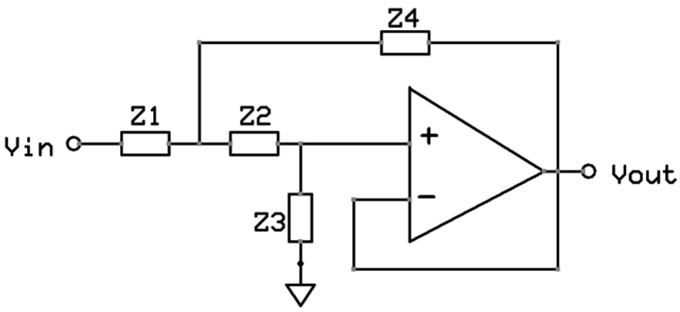
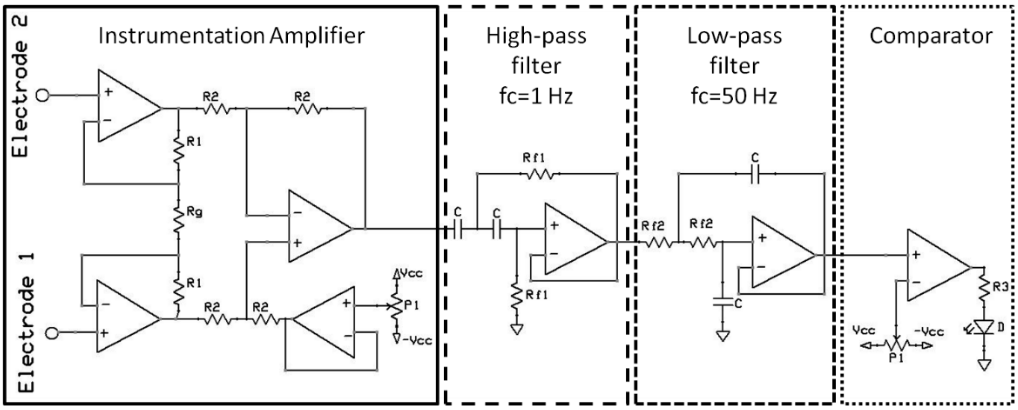


Figure 6



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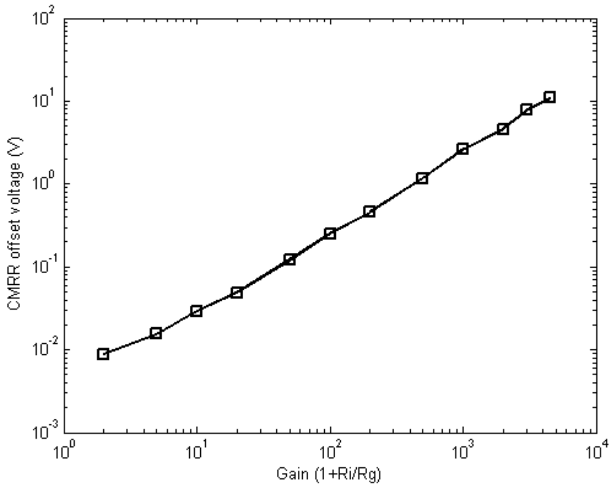

Figure 8

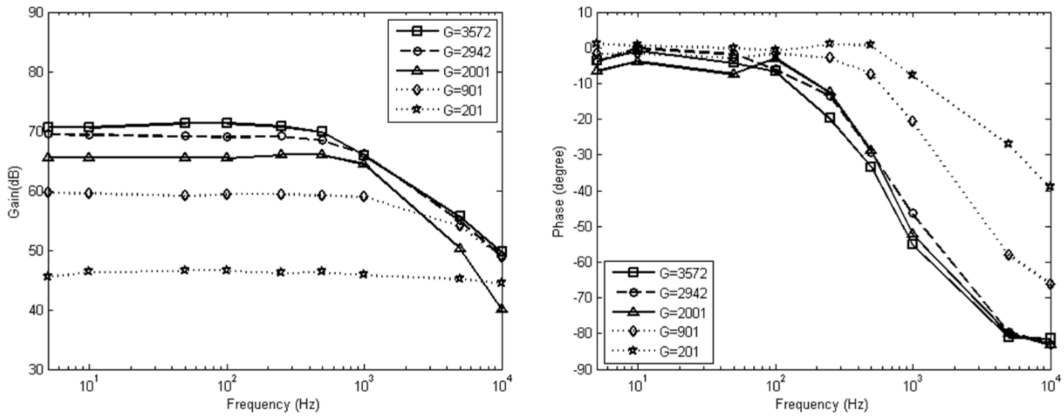

Figure 9

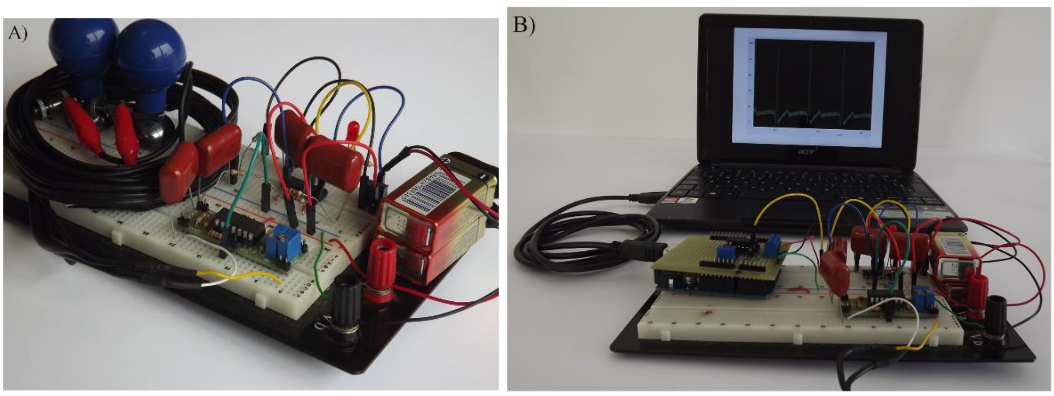

Figure 10

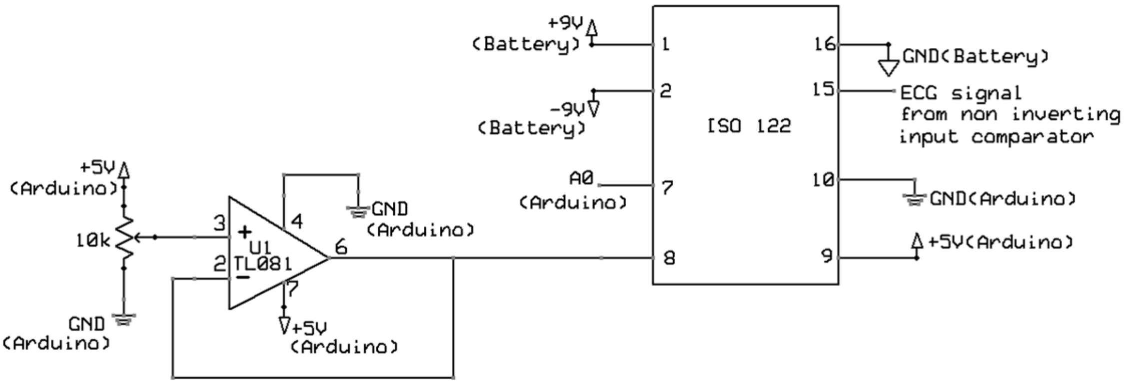

Figure 11