ECG Signal Acquisition and Filtering

Marija Veljković, Igor Janjić, Dejan Milić, Daniela Milović

Abstract – **ECG acquisition with subsequent analogue and digital signal processing is investigated. Acquisition of ECG signal is accomplished by an analogue circuit. Noise is filtered by a hardware notch filter and series of software designed digital filters. Signal sampling is performed by using Arduino microcontroller platform. Economical and simple ECG signal detection and processing is accomplished.**

Keywords – **ECG signal acquisition, ECG signal processing, ECG signal detection, Digital filter, Sampling via microcontroller.**

I. INTRODUCTION

Electrocardiography is a measurement of the electrical activity of the heart muscle over a period of time. Cells in humans heart have different ion concentrations inside and outside of their membranes, which create small electric potentials called biopotentials. A disturbance in a biopotential gives rise to an action potential which is the depolarization and repolarization of the cell. The processes of depolarization and repolarization cause heart contractions, so the heart can perform its function of pumping blood through the circulatory system. These appear as tiny electrical signals on the skin. Essentially, electrocardiogram (ECG) signals are created by the action potentials from different nodes in the heart. The term “lead” represent the viewpoint of heart’s electrical activity. [1, 2].

There are twelve leads, which are used for measuring ECG signals. They are observed in two planes, coronal (leads I, II, III, aVR, aVL, aVF) and transverse plane (six chest leads V1–V6), from a certain angle, from which the heart is observed in the corresponding plane. In Fig. 1a are shown leads in coronal plane. Electrical flow from a different viewpoint of the heart and its direction is represented with cardiac axis. The axis is therefore conventionally referred to as the angle, measured in degrees, of the direction of electrical current. Three cardiac axes form Einthoven's triangle (Fig. 1b), used for calculating lead voltages. [1]

Accurate ECG acquisition in frontal plane can be provided by three leads (electrodes), each one connected at one of the three vertices of the Einthoven's triangle. The most prevalent and significant among these is lead II for diagnosing rhythm problems. Signals from lead I measure the variations in potential between the left arm and the right arm, with the electrode of the left or right leg acting as the ground. In Fig. 2 are shown ECG signals from different leads.

In recordings of the electrical heart activity, at each cycle of contraction and release of the heart muscle, we get a characteristic P wave, which depicts the depolarization of the atria, followed by a QRS complex formed by depolarization of the ventricles and a T wave corresponding to the repolarization of the heart muscle. A typical ECG signal is shown in Fig. 3.

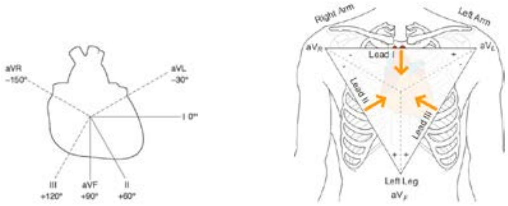

Fig. 1. a) Heart leads with corresponding angle of view, b) Einthoven's triangle

ECG machines use electrodes, which measure the ionic potential difference between their points of application on the body surface. First, due to the small range of natural ECG signal (100s of microvolts to 10s of millivolts), the measured signals need to be amplified in order to be better interpreted.

Fig. 2. Typical ECG waveforms

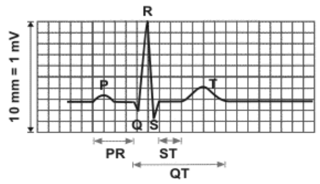

Fig. 3. Typical ECG signal

For that purpose typical biopotential amplifiers with high input impedance are used. Interference usually manifests as common mode noise across both terminals of the differential amplifier and it can be reduced with the right leg drive circuit.

Marija Veljković, Igor Janjić, Daniela Milović and Dejan Milić are with the Faculty of Electronic Engineering, University Of Niš, A. Medvedeva, 14, 18000 Niš, Serbia,
E-mails: marija.elfak@yahoo.com,janjic90@gmail.com, daniela.milovic@elfak.ni.ac.rs, dejan.milic@elfak.ni.ac.rs

Generally, the ECG signal consists of low amplitude voltages in the presence of high offsets and noise. The most commonly used electrodes are Ag/AgCl (Silver-Silver chloride), which have maximum offset voltage of +/-300mV and the actual desired signal is +/-0.5mV superimposed on that electrode offset. In addition, power lines generate 50/60Hz noise, which forms the common mode signal. The amplitude of the power line noise could be very high and needs to be filtered [3, 4].

There are many sources of noise that can be superimposed on ECG signal. The most influential are:

1. Baseline wander (low frequency noise)
2. Power line interference
3. Muscle noise (This noise is very difficult to remove as it is in the same region as the actual signal. It is usually corrected in software.)
4. Other interference (i.e., radio frequency noise from other equipment)

Baseline wander can be removed with high-pass filter, with cut-off frequency of 0.05Hz. Power line noise is removed by implementing a notch filter at 50/60Hz [5].

ECG signal is observed in the frequency range 0.05-150 Hz.

II. HARDWARE DESIGN OF ECG SIGNAL ACQUISITION AND PROCESSING SYSTEM

The ECG signal acquisition and processing system consists of the circuits for signal detection, noise filtering, signal amplification and A/D conversion, as shown in Fig. 4. The ECG signal is detected by the electrodes, placed on patient's body, on his left arm, right arm and right leg. In Fig. 5 circuit for ECG signal detection is shown, which gives the difference between left and right arm voltage as its output. Electrodes are used for sensing bioelectric potentials, caused by muscle and nerve cells. However, the large offset is present in the system due to potential at the electrodes. The proper ECG signal detection requires its amplification and further processing in order to suppress noise that is present in measured ECG signal.

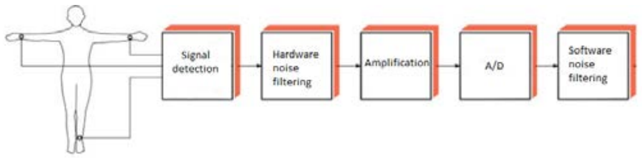

Fig. 4. Signal detection circuit

The offset superimposed by electrodes causes problems in ECG signal analysis and also limits the maximum value of gain which can be obtained from the instrumentation amplifier. With higher gains, the signal can saturate.

We used input driving circuit, Fig. 6, to remove that offset and to amplify the ECG signal for further processing in Arduino microcontroller platform. Changing the resistance of the first potentiometer, P1 provides adjusting the signal offset, while the other one is used to amplify the signal.

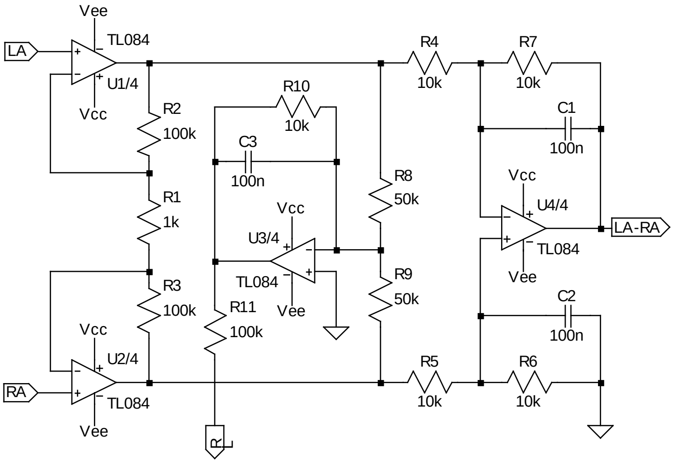

Fig. 5. Signal detection circuit [2]

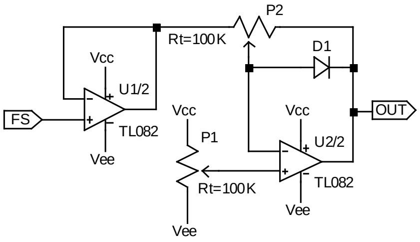

Fig. 6. Input driving circuit

The system naturally picks up the 50Hz noise from the power lines. The amplitude of the power line noise could be very high and needs to be filtered with a narrow stop-band filter called notch filter.

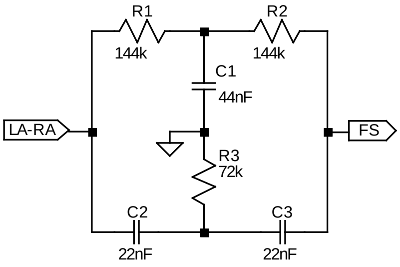

Fig. 7. Notch filter circuit

The notch filter design is shown in Fig. 7. Its transfer function is in general form [6]:

$$H_N(s) = \frac{s^3 + a_2 s^2 + a_1 s + k}{s^3 + b_2 s^2 + b_1 s + k} \tag{1}$$

with coefficients

$$a_1 = \frac{1}{R_1 R_2 C_1}\left(\frac{1}{C_2} + \frac{1}{C_3}\right), a_2 = \frac{1}{C_1}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{2}$$
$$k = \frac{1}{R_1 R_2 R_3 C_1 C_2 C_3}$$

$$\begin{aligned} b_1 &= a_1 + \frac{1}{R_2R_3C_2}\left(\frac{1}{C_1}+\frac{1}{C_3}\right)+\frac{1}{R_1R_3C_1C_2} \\ b_2 &= a_2 + \frac{1}{C_2}\left(\frac{1}{R_2}+\frac{1}{R_3}\right)+\frac{1}{R_2C_3} \end{aligned} \qquad (3)$$

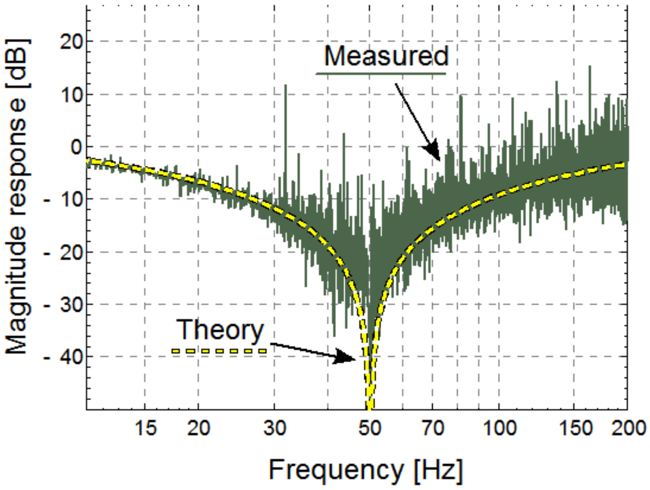

Fig. 8. Notch filter magnitude response: Theoretical (dashed line) and realized (full line)

With appropriate choice of filter elements: $R_1 = R_2 = r$, $R_3 = r/2$, $C_1 = 2c$, $C_2 = C_3 = c$, and by denoting $\omega_0 = 1/rc$, transfer function becomes:

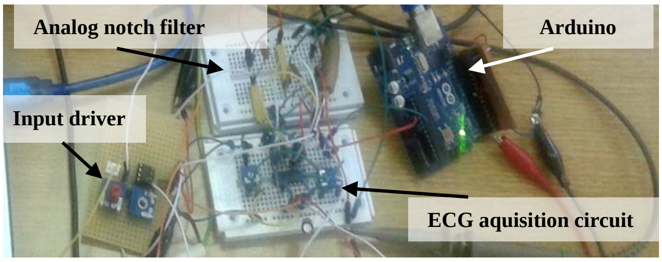

Fig. 11. Circuits prototype realizations

$$H_N(s) = \frac{s^2+\omega_0^2}{s^2+4s\omega_0+\omega_0^2} \qquad (4)$$

Obviously, the notch frequency is: $f_0 = \frac{1}{2\pi rc}$.

Measured magnitude response and the theoretical one are compared in Fig. 8. Accurate frequency response that agrees well with theoretical result is achieved by careful trimming of resistor values. Waveforms of ECG signals measured with, as well as without the notch filter are given in Fig. 9. It is obvious that the analog notch filter is able to eliminate the power line noise at 50 Hz. By careful examination of the waveforms, one can also notice the slight distortion of the waveform in two aspects:

-R waves are slightly attenuated, while their duration is a little longer, and

-the peaks of R waves are delayed slightly, which we

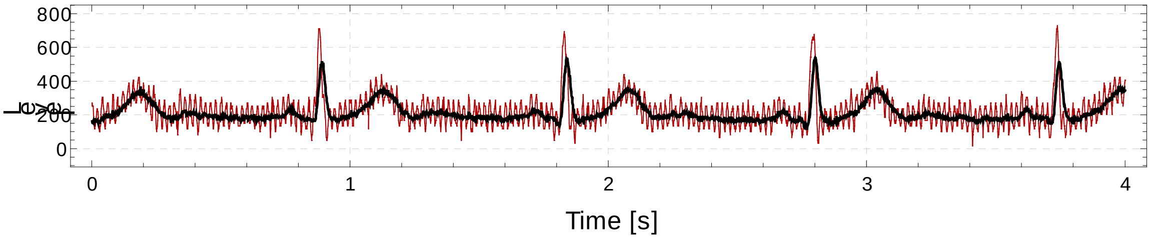

Fig. 9. ECG signals measured with and without using analog notch filter

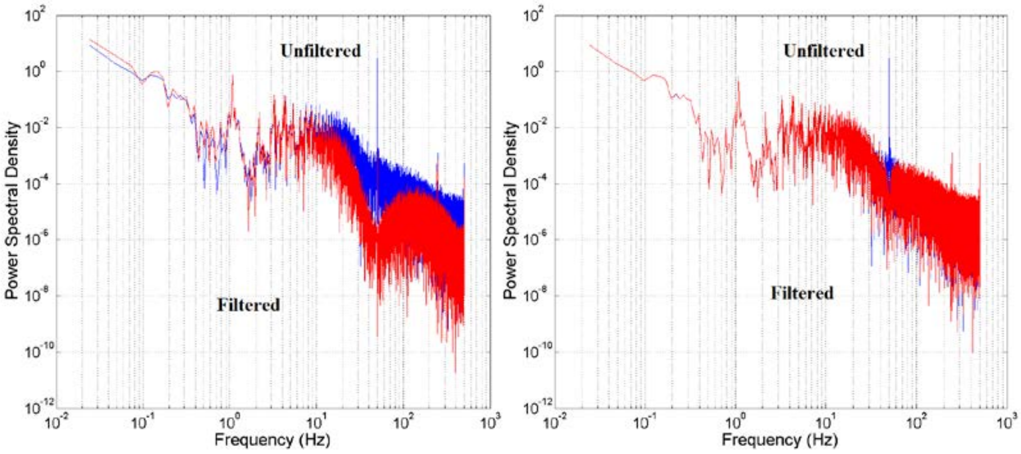

Fig. 10. Power spectral density of ECG signal filtered with analog (left) and digital (right) notch filter

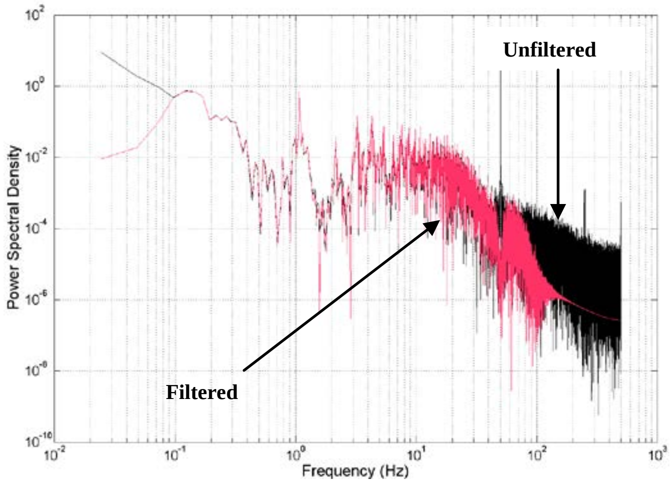

Fig.12. Power spectral density of ECG signal digitally filtered

attribute to phase shift added by the notch filter.

Power spectral density of ECG signal filtered with analog and digital notch filter is shown in Fig. 10, and the general conclusion is that the digital implementation is superior in terms of achievable Q factor.

Amplified ECG signal is converted into its digital form, using Arduino's analog to digital signal converter (A/D) [7]. The system has a sampling frequency of 1000 Hz which satisfies the Nyquist's criteria.

The circuits prototype used for acquisition and processing of ECG signals were built in our laboratory. Fig. 11 shows the realization of ECG system for measuring and processing of ECG lead I signal and Arduino microcontroller platform, connected to a PC [7, 8].

III. SOFTWARE FILTERING OF LOW FREQUENCY AND HIGH FREQUENCY NOISE

As noted earlier, ECG signals are always affected by noise. The useful spectrum of the ECG signal is in a range of 0.05–150 Hz, and software filter realizations are also applicable for removing low frequency and high frequency noises from the measured ECG signal.

Baseline wander is a low frequency noise component present in the ECG signal, which is caused by offset voltages in the electrodes, respiration, and body movement. The low frequency noise is located in the frequencies below 1Hz. It is reduced with high-pass second-order Chebyshev filter, with cut-off frequency 0.05Hz. For reducing high frequency noise, Butterworth fifth-order low-pass filter is used. The cut off frequency of the filter is 150 Hz, since the useful ECG signal is below 150 Hz. Power spectral density of ECG signal measured without notch filter, and ECG signal digitally filtered using notch, Butterworth and Chebyshev filters are shown in Fig. 12.

Software filtering is implemented in Matlab software package. Digital filters are tested on ECG signals from PhysioBank ATM database [9] during the design phase. In Fig. 13, the measured ECG signals are shown before and after digital filtering.

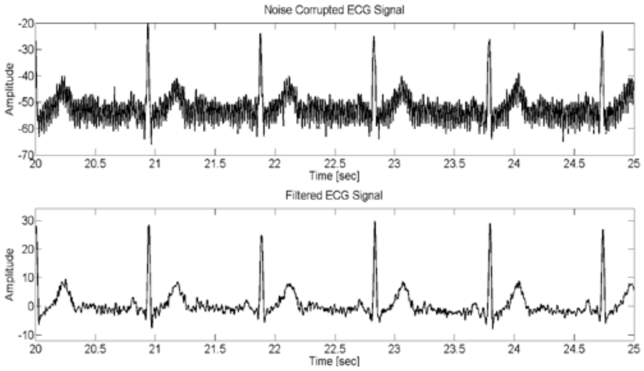

Fig. 13. ECG signals before and after digital filtering (notch, low pass and high pass)

IV. CONCLUSION

Analog filter component non-linearities greatly complicate filter design. Imperfect electronic components have tolerances of nominal values which are also temperature dependent and exhibit drift with time. In digital filters, the coefficient values are far more stable and the filters are easier to design and upgrade.

In time domain both signals – filtered with analog hardware and processed with digital filter, look very similar, but there may be significant difference for other ECG signal leads. In this paper, only the lead I is used.

Because of specific nature of ECG signal and its usual noises, it is far simpler to have software adjustable filtering system aiming to get the purest ECG signal for accurate medical analysis.

Economical angle is also very important, and the presented implementation is inexpensive and gives reliable results. This paper is a basic step for further ECG signal processing research.

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