

Biosignal Processing

Assignment 2. Filtering of the ECG Signal for the Removal of Noise

LEARNING OUTCOMES

After this assignment the student has experience in how to

- remove high-frequency noise from a signal,
- remove low-frequency noise from a signal,
- remove power-line interference from a signal, and
- describe the effects of filters in both time and frequency domains.

BACKGROUND

ECG signals are often contaminated with a combination of high-frequency noise, low-frequency noise (baseline wandering), and power-line interference. High-frequency noise may be removed by applying a low-pass filter and low-frequency noise may be removed by applying a high-pass filter. However, improper selection of the cutoff frequencies of the filters could lead to distortions in ECG signal, such as excessive smoothing or widening of the QRS complex, and distortion of PQ and ST segments.

DATA

For this task, you need two sample ECG signals provided for you by the teacher as the files *ecg_signal_1* and *ecg_signal_2*. The sampling rate of the data is $F_s = 1000$ Hz, and you are expected to design and interpret all filters with this sampling rate.

EXERCISE

You will need to construct two figures: one for the time domain analysis, and the other for the frequency domain analysis. Thus, you will plot all the time domain signals in the Figure 1 using a 5x2 subfigure layout where entire ECG signals are plotted on the left side and single cardiac cycles are plotted on the right side for closer inspection. The power spectra will be shown similarly in the Figure 2 as with a 5x1 subfigure layout.

Note: Ensure that the axes of the plots are labeled in suitable units such as seconds, Hertz, dB, ... However, the amplitude of the signals may be shown in arbitrary units (AU). Please also put descriptive titles to all the plots.

Hint:

$$H(z) = \frac{Y(z)}{X(z)} = \frac{b(1) + b(2)z^{-1} + \dots + b(nb + 1)z^{-nb}}{1 + a(2)z^{-1} + \dots + a(na + 1)z^{-na}}$$

Implement the following steps in the selected programming language:

1. Plot the *ecg_signal_1*, over the full duration and over one cardiac cycle (time interval 1.0 - 2.0 sec) to Figure 1 (row 1).



Plot the power spectrum of the entire *ecg_signal_1* to Figure 2 (row 1). First, calculate the discrete Fourier transformation with FFT using the transform length *Nfft*. The power spectrum is obtained by multiplying the Fourier transformation by its complex conjugate:

$$S_2(\omega) = \frac{1}{Nfft} X(\omega) * X^*(\omega)$$

To scale the x-axis, use the frequency vector: $f = (0 : (Nfft/2)) * Fs / Nfft$.

2. Construct a 10-point **moving average filter** by creating the filter coefficient arrays *a* and *b* that are used in filtering with a digital filter (cf. equations 1 and 2 below). Signal: *ecg_signal_1*

The general form of moving average filter is:

$$y(n) = \sum_{k=0}^N b_k x(n - k) \quad (1)$$

Applying the z-transform, we get the transfer function *H(z)* of the filter as:

$$H(z) = \frac{Y(z)}{X(z)} = \sum_{k=0}^{N-1} b_k z^{-k}, b_k = 1/N \quad (2)$$

Based on these formulas, find the correct coefficients *a* and *b* for the filter, and then apply it to the signal *ecg_signal_1*. Plot the resulting filtered signal over the full duration and over one cardiac cycle (time interval 1.0 - 2.0 sec) to Figure 1 (row 2). Plot the power spectrum of the entire filtered signal to Figure 2 (row 2).

Obtain the magnitude and phase response of the filter and plot them in their own separate figure as subfigures.

3. Construct the **derivative based filter** to remove low-frequency artifact (cf. equation 3). To maintain the dynamic range of the filter and to avoid overflow, normalize the filter to have a maximal gain of unity: divide the *b* vector by the gain $real(max(freq_response))$.

$$H(z) = \frac{Y(z)}{X(z)} = \frac{1}{T} \left[\frac{1-z^{-1}}{1-0.995z^{-1}} \right] \quad (3)$$

Specify the filter in terms of the *a* and *b* arrays, and apply it to the signal *ecg_signal_1*. Plot the filtered signal, over the full duration and over one cardiac cycle (time interval 1.0 - 2.0 sec) to Figure 1 (row 3). Plot the power spectrum of the entire filtered signal to Figure 2 (row 3).

Obtain the magnitude and phase response of the filter and plot them in their own figure as subfigures.

4. Construct a **comb filter** to remove powerline noise at 60Hz (common in the Americas and parts of Asia) by using following arrays:

```
b_comb=[0.6310 -0.2149 0.1512 -0.1288 0.1227 -0.1288 0.1512 -0.2149 0.6310];
a_comb=1;
```



Specify the filter in terms of the a and b arrays, and apply the filter to the signal *ecg_signal_1*. Plot the filtered signal, over the full duration and over one cardiac cycle (time interval 1.0 - 2.0 sec) to Figure 1 (row 4). Plot the power spectrum of the entire filtered signal to Figure 2 (row 4).

Obtain the magnitude and phase response of the filter and plot them in their own figure as subfigures.

- Combine all three filters by convolution of the corresponding a and b arrays to get the filter coefficient arrays of the combined filter. Apply the combined filter to the signal *ecg_signal_1*, plot the filtered signal over the full duration and over one cardiac cycle (time interval 1.0 - 2.0 sec) to Figure 1 (row 5). Plot the power spectrum of the entire filtered signal to Figure 2 (row 5).

Obtain the magnitude and phase response of the filter and plot them in their own figure as subfigures.

- Repeat steps 1-5 with the signal *ecg_signal_2*. Use time interval 2.0 – 3.0 sec.
- Make a short report of your results:
 - Analyze the effect of each filter in the time domain. Make use of the plots.
 - Analyze the effect of each filter in the frequency domain. Make use of the plots.
 - How do the results differ between the studied signals?

REFERENCES

- [1] Savitzky A, Golay MJE (1964) Smoothing and Differentiation of Data by Simplified Least Squares Procedures. Anal Chem 36(8):1627–1639.

