Scilab case study project on ECG Signal Processing and Heart Rate Frequency Detection

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Abstract

Electrocardiogram (ECG) signals are used to monitor the electrical activity of the heart, but they are often affected by noise and interference that make analysis difficult. This project uses a GUI-based ECG signal processing system developed in Scilab for visualizing, filtering, and analyzing ECG recordings. The application allows users to upload ECG data, add controlled noise, view the raw signal, and apply digital filtering techniques. A notch filter is used to reduce 50 Hz power-line interference, while smoothing operations improve signal quality. The filtered signal is then converted into an energy signal that shows the R-peaks of the QRS complex. Based on the detected R-peaks, the heart rate is estimated in beats per minute (BPM). The project partially replicates the reference paper ECG Signal Processing and Heart Rate Frequency Detection Methods as it does not implement all the heartbeat detection algorithms presented in the paper. Instead, it focuses on ECG filtering, R-peak enhancement, and a threshold-based heart rate method.

1. Introduction

Electrocardiography (ECG) is a widely used technique for recording the electrical activity of the heart over time. It is a composite of five waves, Q, P, R, S and T. It plays an important role in healthcare, medical research, and biomedical engineering by providing valuable information about cardiac function. With the advancement of digital signal processing tools, ECG analysis can now be performed efficiently using computer-based systems. Scilab provides a powerful environment for implementing signal processing algorithms and developing graphical user interfaces (GUIs). Combining signal processing with GUI design enables users to interact with biomedical signals in a simple manner.

2. Problem Statement

ECG signals are widely used for monitoring heart activity and detecting cardiac abnormalities. However, ECG recordings are often affected by power-line interference, random noise, and other signal distortions, making it difficult to accurately identify important features such as the R-peaks of the QRS complex. Therefore, there is a need for a simple and interactive system that can process ECG signals, reduce noise, and assist in basic heart rate analysis. The project is a GUI-based ECG signal processing system developed in Scilab. It allows users to upload ECG data, visualize the raw signal, introduce controlled noise, and apply digital filtering techniques. The processed signal is further analysed to enhance R-peaks and estimate heart rate from the detected peaks. The system can be improved in the future by implementing advanced heartbeat detection algorithms, adaptive filtering techniques, and support for real-time ECG acquisition. To achieve these objectives, digital signal processing methods such as notch filtering, signal smoothing, R-peak energy enhancement, and threshold-based peak detection are used. A graphical user interface is made to provide a platform for ECG visualization and analysis.

3. Basic concepts related to the topic

3.1 Electrocardiogram (ECG)

An Electrocardiogram, called ECG is a recording of the electrical activity produced by the heart during each heartbeat. It is obtained using electrodes placed on the body and is widely used in hospitals and biomedical research for monitoring heart rhythm and cardiac function. A normal ECG waveform mainly contains the P wave, QRS complex, and T wave. Among these, the QRS complex represents ventricular activity, and the R-peak is usually the most prominent point. Detecting R-peaks is useful for measuring the time interval between heartbeats.

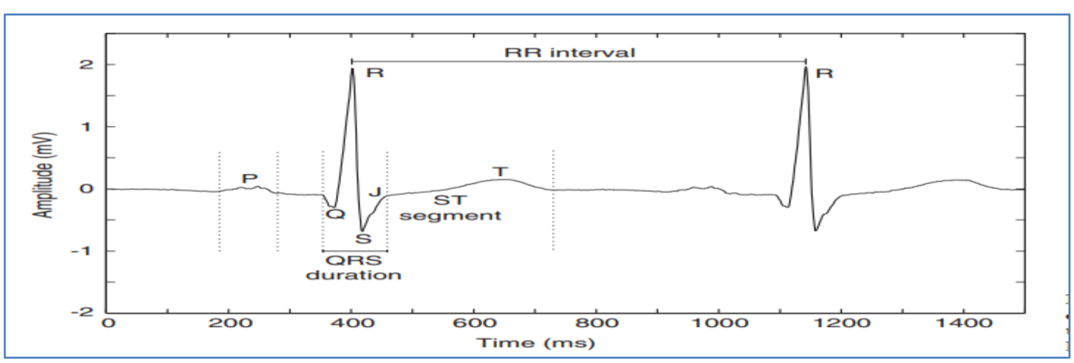


Figure 1: The onset and end of the P wave, the QRS complex, and the T wave

3.2 Power-Line Interference

Power-line interference is a common disturbance present in ECG recordings due to nearby electrical equipment, wiring, and mains supply. In India, this interference usually occurs at 50 Hz. It appears as fast unwanted oscillations over the actual ECG waveform and can make important cardiac features difficult to observe.

3.3 Notch Filter

A notch filter is a digital filter designed to suppress one specific frequency component while allowing most other signal frequencies to pass through. In this project, a 50 Hz notch filter is used to reduce power-line interference from the ECG signal. The filter is designed using numerator and denominator coefficients based on the target frequency and sampling frequency. Its main purpose is to remove the unwanted 50 Hz component without significantly affecting the useful ECG waveform.

$$H(z) = \frac{1 - 2\cos(\omega_0)\, z^{-1} + z^{-2}}{1 - 2r\cos(\omega_0)\, z^{-1} + r^2 z^{-2}}$$

Where,

w0 = normalized angular frequency
f_0= frequency to be removed (50 Hz)
f_s= sampling frequency (360 Hz)
r= pole radius controlling the notch width

3.4 Signal Smoothing

Signal smoothing is used to reduce small fluctuations and random variations in a signal. It helps produce a cleaner waveform that is easier to analyze visually. In this project, a moving-average based smoothing operation is applied after notch filtering. The moving average calculates the average value of nearby samples and replaces each sample with this average. This reduces rapid noise components while preserving the major ECG waveform shape.

$$y[n] = \frac{1}{N}\sum_{k=0}^{N-1} x\,[n-k]$$

Where,

$x[n]$= input ECG signal
$y[n]$= smoothed output signal

N= window size
k= sample index within the averaging window

3.5 R-Peak Energy Signal

To make R-peaks easier to identify, the filtered ECG signal is further processed using baseline removal, derivative calculation and squaring. The derivative highlights sudden changes in the ECG waveform, while squaring makes all values positive and increases the prominence of large changes. The moving-average step produces an energy signal in which the QRS complexes appear as larger peaks. This energy signal is useful for applying threshold-based peak detection.

$$E[n] = x^2[n]$$

Where,

x[n] = R-peak enhanced ECG signal

$E[n]$= energy signal

3.6 Heart Rate Estimation

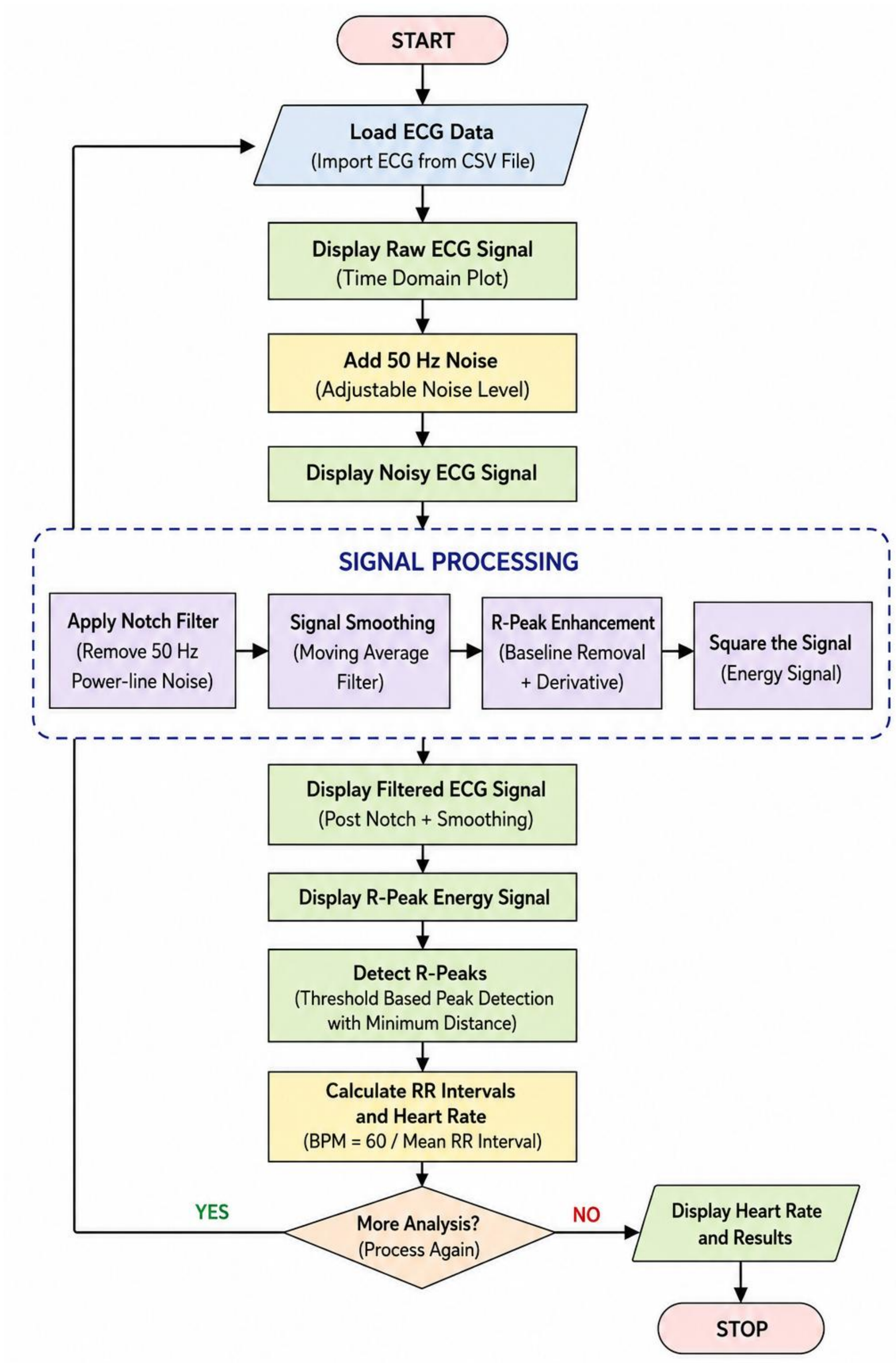
Heart rate is generally expressed in beats per minute, or BPM. It can be estimated from the interval between consecutive R-peaks. First, the difference between neighbouring peak locations is calculated in samples. These values are converted into seconds using the sampling frequency. The average RR interval is then used to estimate heart rate:

$$\text{Heart Rate (BPM)} = \frac{60}{\text{Average RR Interval}}$$

3.7 Threshold-Based Peak Detection

Threshold-based peak detection is a simple method used to identify important peaks in a signal. A threshold value is selected from the energy signal, and only peaks above this value are treated as possible R-peaks. A minimum separation condition is also used to avoid detecting multiple peaks from the same heartbeat.

4. Flowchart


START
Load ECG Data
(Import ECG from CSV File)
Display Raw ECG Signal
(Time Domain Plot)
Add 50 Hz Noise
(Adjustable Noise Level)
Display Noisy ECG Signal
SIGNAL PROCESSING
Apply Notch Filter
(Remove 50 Hz Power-line Noise)
Signal Smoothing
(Moving Average Filter)
R-Peak Enhancement
(Baseline Removal + Derivative)
Square the Signal
(Energy Signal)
Display Filtered ECG Signal
(Post Notch + Smoothing)
Display R-Peak Energy Signal
Detect R-Peaks
(Threshold Based Peak Detection with Minimum Distance)
Calculate RR Intervals and Heart Rate
(BPM = 60 / Mean RR Interval)
YES
More Analysis?
(Process Again)
NO
Display Heart Rate and Results
STOP

5. Software/Hardware used

- Operating System: Windows 11
- Toolbox: None
- Hardware: None
- Software: Scilab 2026.0.1

6. Procedure of execution

Step 1: Open ecg.sce.

Step 2: Go to Execute -> Save and run.

Step 3: The GUI window will open, click on “Upload ECG CSV”.

Step 4: Select the CSV file you want to open from the mit_databases folder.

Step 5: Observe the raw ECG signal graph.

Step 6: Now adjust the slider to add noise to the ECG signal.

Step 7: Click on “Apply Digital Filters” button.

Step 8: Observe the smoothed signal, R-peak Filtered signal and calculated heart rate.

7. Result

7.1 GUI Window

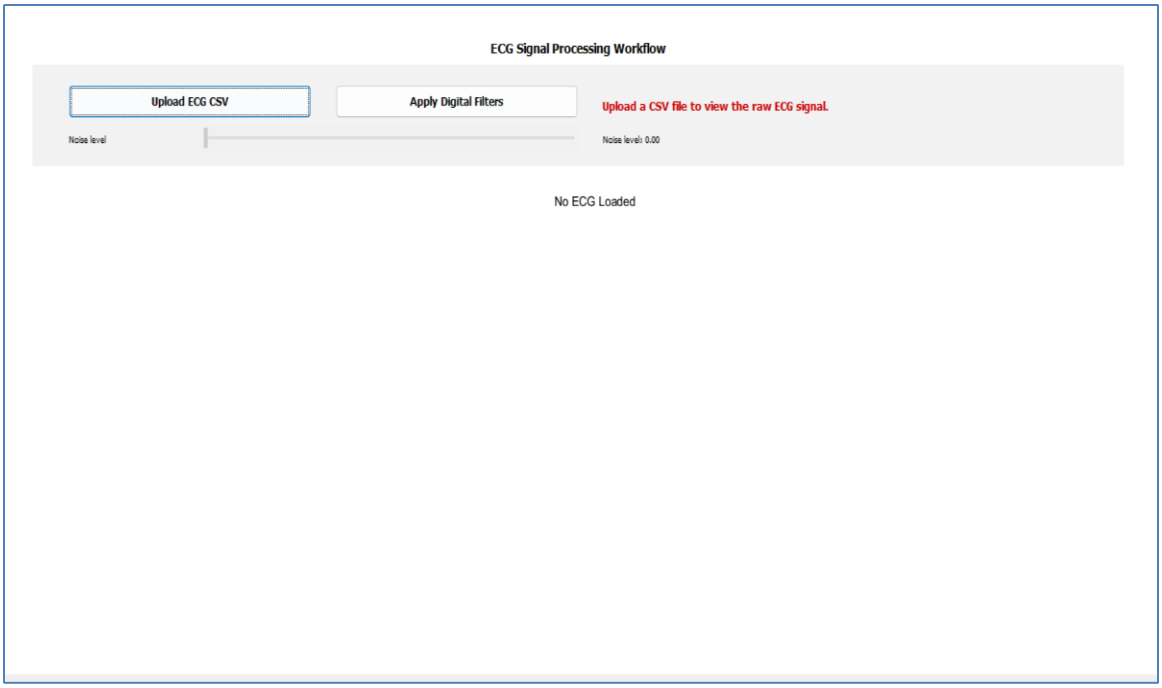


Figure 2: The GUI Window Before Uploading ECG Signal.

Inferences

- The GUI starts in an initial state where no ECG data is loaded, as indicated by the message "No ECG Loaded" in the display area.
- The interface provides separate controls for uploading ECG data and applying digital filters, ensuring that signal processing is performed only after valid data is loaded.
- A noise level slider is included, allowing users to introduce controlled noise into the ECG signal and study the effect of filtering algorithms.
- Status messages are displayed to guide the user and indicate the current state of the system.

7.2 Raw ECG Signal

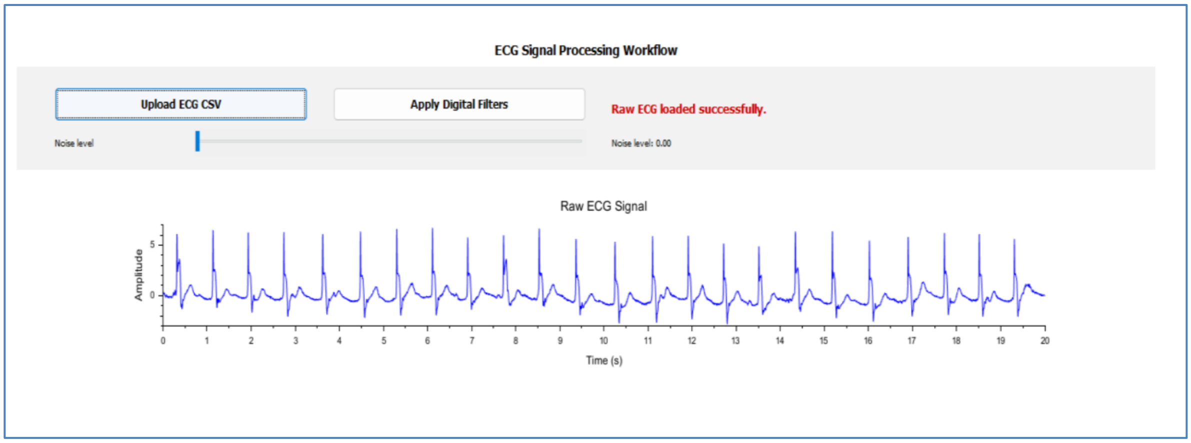


Figure 3: Raw ECG Signal

Inferences

- The ECG file has been successfully loaded into the GUI, as indicated by the status message "Raw ECG loaded successfully**.**"
- The raw ECG waveform displays P waves, QRS complexes, and T waves.
- The R-peaks appear at regular intervals throughout the recording, showing a relatively stable and consistent heart rhythm.
- The signal shows no major baseline drift or excessive noise, allowing the ECG features to be observed properly.

7.3 ECG Signal With 50Hz Noise

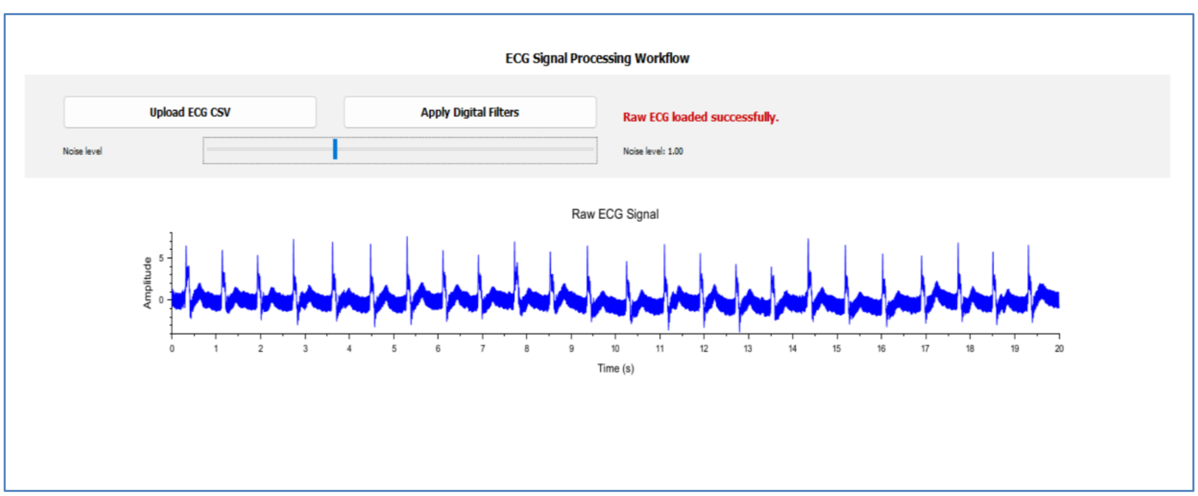


Figure 4: Raw ECG Signal with 50Hz Noise

Inferences

- The noise slider is set to 1.00, indicating that noise has been added to the ECG signal through the GUI.
- Compared to the original ECG waveform, the baseline appears thicker and more irregular due to the added noise.
- Although the signal quality has degraded, the major ECG components, especially the QRS complexes and R-peaks, remain visible.
- The added noise affects the lower-amplitude portions of the waveform more significantly than the R-peaks.

7.4 Filtered ECG Signal

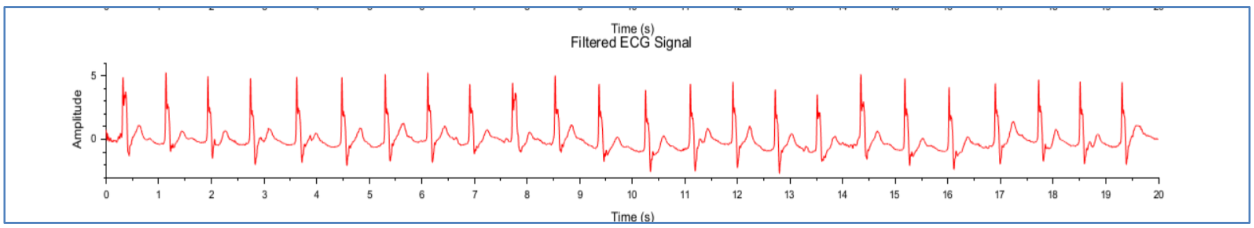


Figure 4: Filtered ECG Signal

Inferences

The filtered ECG signal was obtained by first removing the signal mean, followed by 50 Hz notch filtering to suppress power-line interference. A moving-average smoothing operation was then applied to reduce residual high-frequency noise while keeping the ECG features such as the P wave, QRS complex, and T wave. The filtered ECG signal is cleaner than the noisy ECG signal, indicating that the applied filtering techniques have successfully reduced unwanted noise components.

7.5 R-Peak Filtering

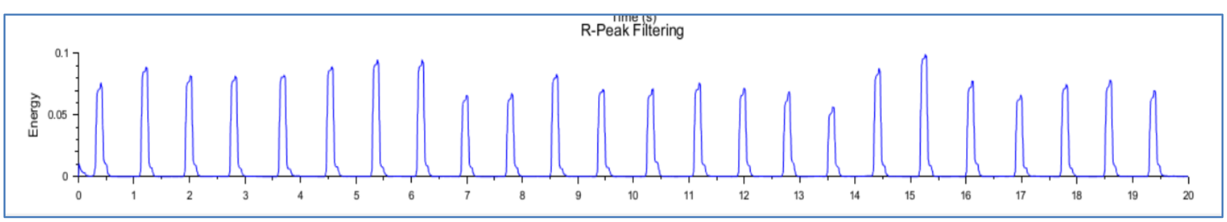


Figure 5: R-Peak Filtering

Inferences

The R-peak filtering stage enhances the QRS complexes and converts them into distinct energy peaks. This transformation reduces the influence of smaller ECG components and noise, making the signal more suitable for accurate R-peak detection and heart-rate calculation. The generated R-peak energy signal follows the same principle as the reference paper by emphasizing QRS complexes through derivative and squaring operations. However, the implementation does not include moving-window integration and adaptive thresholding stages used in the reference work. As a result, the detected energy peaks are narrower than those presented in the reference paper.

7.6 Heart Rate Estimation

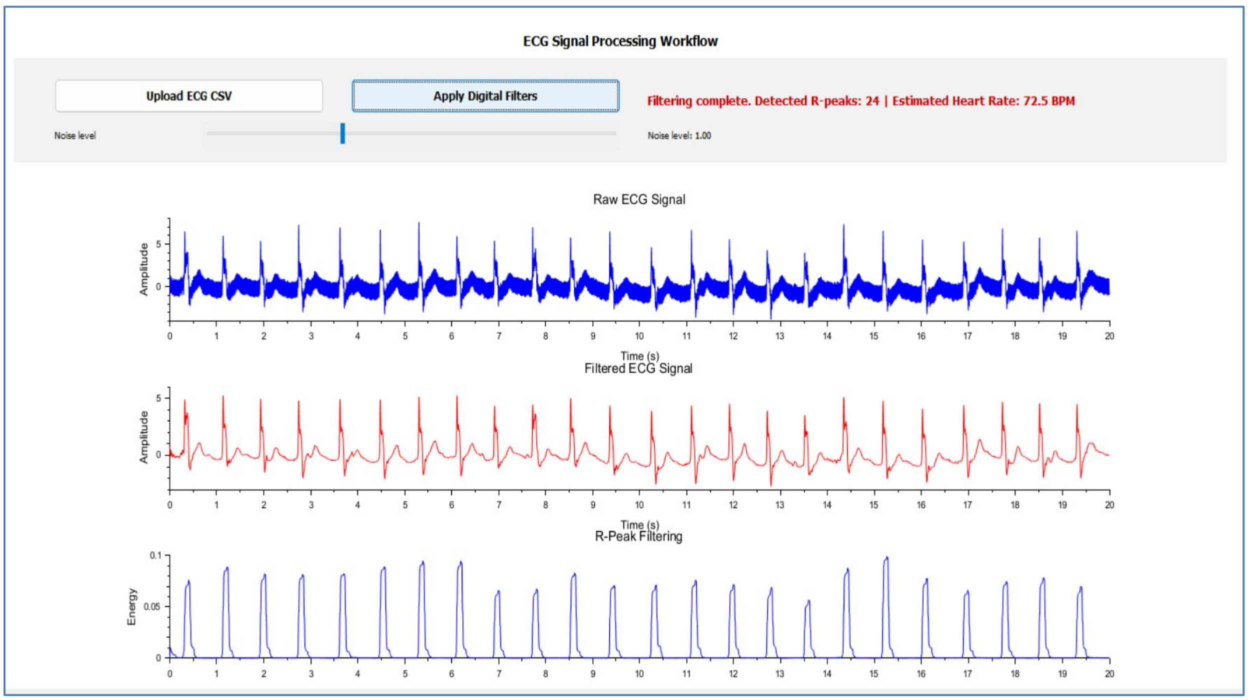


Figure 6: Detected R-peaks and Estimated Heart Rate

Inferences

The results indicate that the ECG processing and R-peak detection stages have been successfully completed. A total of 24 R-peaks were identified in the analyzed ECG segment, and the estimated heart rate was calculated as 72.5 BPM. The detected heart rate falls within the normal resting range for a healthy adult, demonstrating that the implemented filtering and peak detection methods are able to extract meaningful cardiac information from the ECG signal.

8. Scope of the Project

8.1 Elements Implemented from the Reference Paper

- **Mean removal and signal normalization:** The ECG signal is centred by removing its mean value before further processing.

- **50 Hz power-line noise removal**: A band-stop filter is used to reduce 50 Hz electrical interference.

- **Basic ECG filtering**: The project applies moving-average smoothing operation before heart-rate analysis so that unwanted disturbances are reduced and important ECG features are clearer.

- **R-peak enhancement stage**: The ECG signal is processed further using derivative and squaring operations to highlight the QRS complex and R-peaks before heartbeat detection.

- **Energy signal generation**: The processed ECG signal is squared to obtain the energy signal: E(t)=u2(t)

- **Threshold-based R-peak detection**: R-peaks are detected from the energy signal using a threshold and minimum separation between peaks.

8.2 Elements not Implemented from the Research Paper

- **Live ECG acquisition using measurement hardware:** The paper records ECG signals using electrodes, an ECG amplifier circuit, and a measurement card with a sampling frequency of 500 Hz.

- **Unit-amplitude normalization:** The paper removes the mean value and normalizes the ECG signal to unit maximum amplitude before filtering.

- **0.5 Hz Butterworth filtering:** The paper uses a second-order Butterworth filter to reduce baseline wander and breathing-related artefacts. The project uses smoothing instead.

- **15 Hz and 20 Hz fourth-order Butterworth filters:** The paper uses separate high-pass and low-pass Butterworth filters for R-peak enhancement because the Butterworth filter design functions like butter() and iir() were not available.

- **Autocorrelation-based heart-rate detection:** The paper calculates heart rate by applying autocorrelation to the energy signal.

- **Energy-envelope peak detection:** The paper smooths the energy signal using an integrator filter, creates an envelope, and detects R-peaks from this envelope.

- **Comparison of three heart-rate algorithms:** The paper compares autocorrelation, thresholding of the energy signal, and peak detection in the energy envelope. The project implements only a simplified threshold-based R-peak detection method.

- **Stress-test evaluation:** The paper evaluates the algorithms using ECG signals recorded during cycling and dumbbell exercises. Such stress-test analysis is not included in the project.

8.3 Difference Table

Feature	Reference Paper	Scilab Project
ECG Acquisition	ECG acquired using electrodes, ECG amplifier, and measurement card (500 Hz sampling)	ECG loaded from a CSV file through the GUI
Signal Normalization	Normalized to unit maximum amplitude	Not Implemented
Baseline Wander Removal	Biquad Band-Stop Filter	Digital Notch Filter
R-Peak Enhancement	4th-order high-pass (15 Hz) and low-pass (20 Hz) Butterworth filters	R-peak enhancement using filtering and energy calculation
Heart Rate Estimation	Implemented using three algorithms	Implemented using threshold-based R-peak detection

Stress Evaluation	Tested on cycling and dumbbell exercise ECG signals	Not Implemented

9. References

1) Parák, Jakub, and Jan Havlík. "ECG signal processing and heart rate frequency detection methods." Proceedings of Technical Computing Prague 8 (2011): 2011.

https://www2.humusoft.cz/www/papers/tcp11/091_parak.pdf

2) Rnmo, Leif So, and Pablo Laguna. "Electrocardiogram (ECG) signal processing." Wiley Encyclopedia Biomed. Eng.. 2006. 1-16.

3) Gacek, Adam, and Witold Pedrycz, eds. ECG signal processing, classification and interpretation: a comprehensive framework of computational intelligence. Springer Science & Business Media, 2011.