

A Nonlinear Bayesian Filtering Framework for ECG Denoising

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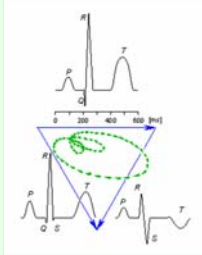
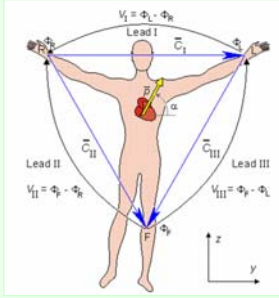
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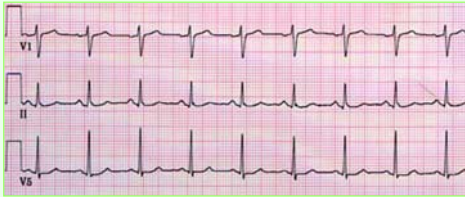
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Dipole Model of the Heart

The cardiac potentials may be modeled by a single rotating dipole located at the heart. This model is known as the **Single Dipole Model (SDM)**.



The ECGs can be considered as projections of the cardiac dipole onto the electrode axes.



Other models: Moving dipole, Multipole, Activation maps, ...

Bayesian Filters

The **Kalman Filter (KF)** is an optimal filter for linear Gaussian processes

$$\begin{cases} \underline{x}_{k+1} = A_k \underline{x}_k + B_k w_k \\ \underline{y}_k = H_k \underline{x}_k + v_k \end{cases}$$

The **Kalman Smoother (KS)** is a non-causal version of the KF which uses future measurements to give better estimates of the current state

The **Extended Kalman Filter (EKF)** is a generalization of the KF for nonlinear systems

$$\begin{cases} \underline{x}_{k+1} = f(\underline{x}_k, \underline{w}_k, k) \\ \underline{y}_k = g(\underline{x}_k, \underline{v}_k, k) \end{cases}$$

The **Extended Kalman Smoother (EKS)** is the nonlinear extension of the KS

The **Unscented Kalman Filter (UKF)** is a variant of the EKF for highly nonlinear (non-)Gaussian systems, based on the **Unscented Transform (UT)**

Particle Filters (PF) are **Monte Carlo** estimation techniques, based on **Sequential Importance Sampling** which are useful for nonlinear non-Gaussian systems

Abstract

In this work a nonlinear Bayesian filtering framework is proposed for the filtering of noisy Electrocardiogram (ECG) recordings. The ECG is modeled by a state-space nonlinear dynamic model. This model is used for constructing Bayesian filters, such as the Extended Kalman Filter (EKF), Extended Kalman Smoother (EKS), Unscented Kalman Filter (UKF), and Particle Filter (PF). The method is evaluated on several ECG recordings, and also on synthetic data produced by adding real non-stationary muscle artifacts, white and colored Gaussian noises to clean ECG recordings, and studying the SNRs and morphology of the filter outputs. The results of the study show superior results compared with conventional ECG denoising approaches such as band-pass FIR filtering, adaptive filtering (AF), and wavelet denoising (WD). The proposed technique has been recently used in a real-time ECG monitoring system.

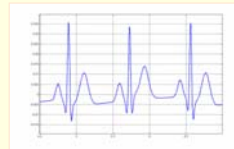
A Dynamical Model for the ECG

Based on a modified version of the synthetic ECG generator, by McSharry *et al.*

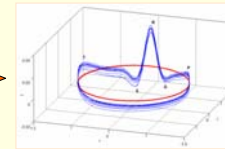
$$\begin{cases} \theta_{k+1} = (\theta_k + \omega \delta) \bmod(2\pi) \\ s_{k+1} = - \sum_{i=1}^N \delta \frac{\alpha_i \omega}{b_i^2} \Delta \theta_i \exp\left(-\frac{\Delta \theta_i^2}{2b_i^2}\right) + s_k + \eta \end{cases}$$

$$\begin{cases} \phi_k = \theta_k + u_k \\ y_k = s_k + v_k \end{cases} \quad \begin{matrix} \text{coarse ECG phase} \\ \text{noisy ECG} \end{matrix}$$

$$\omega = 2\pi \times \text{HR}, \Delta \theta_i = (\theta_k - \theta_i) \bmod(2\pi), \delta = 1/f_s \text{ and } \eta \text{ is process noise}$$

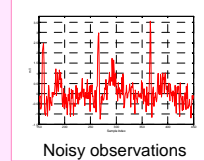


Phase space

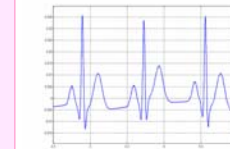


Filtering Scheme

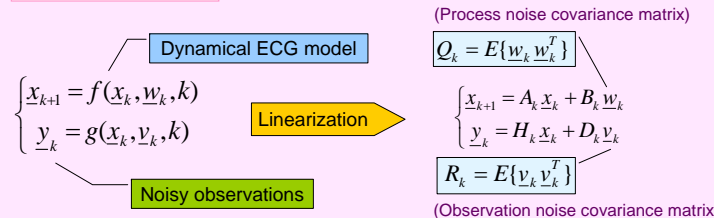
$$\begin{cases} \text{(State equation)} & \underline{x}_{k+1} = f(\underline{x}_k, \underline{w}_k, k) \\ \text{(Observation equation)} & \underline{y}_k = g(\underline{x}_k, \underline{v}_k, k) \end{cases}$$



Noisy observations



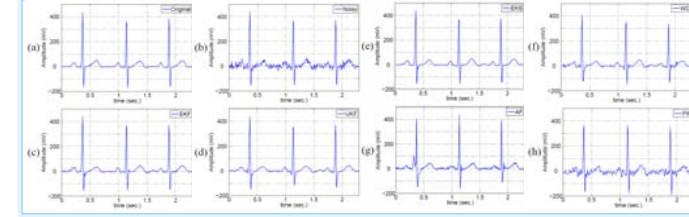
Dynamical ECG model



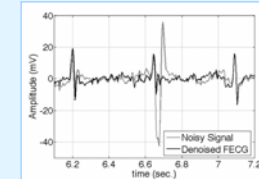
The dynamic model parameters are trained for a given set of noisy ECG recordings

Results

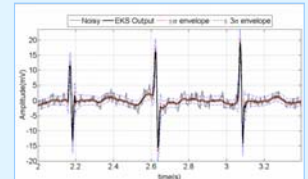
Typical results for an input SNR of 5dB:



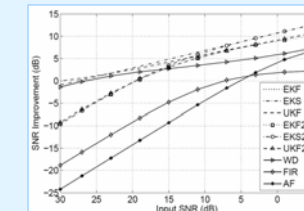
Noninvasive Fetal ECG Denoising



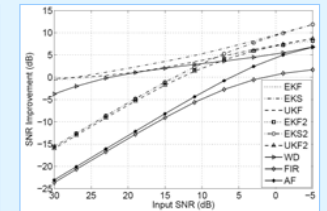
Typical ECG Denoising



Comparison with classical methods



SNR calculated over the whole ECG



SNR calculated over the ST-segment

Conclusions

The proposed method is a generalization of conventional ECG filtering approaches, with superior performance. It has found great interest for low SNR applications such as the cancellation of maternal ECG from noninvasive fetal ECG recordings, and the removal of ECG artifacts from Electroencephalogram (EEG) and Electromyogram (EMG) recordings.

References

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