Exploring the non-local similarity present in Variational Mode Functions for effective ECG denoising

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2018 IEEE International Conference on Acoustics, Speech and Signal Processing

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Introduction

- The heart is an electrical organ, and its activity can be measured non-invasively.
- ECG signal provides an electrical picture of the heart and information about different pathological conditions.
- During the acquisition process Electrocardiogram (ECG) signal gets corrupted by various noises [1].
- Noises such as powerline interference, motion artifact, white Gaussian noise, etc affects ECG.

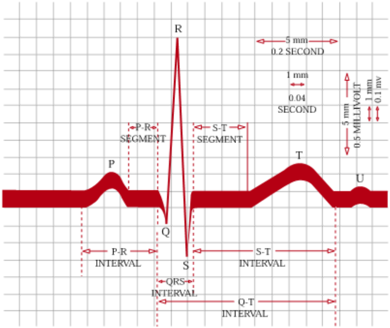


Figure 1 : ECG Signal [1]

[1] Clifford GD, Azuaje F, McSharry P (2006) Advanced methods and tools for ECG data analysis. Artech house, London.

Motivation of the Proposed Work

- The state-of-art ECG denoising techniques were mostly based on techniques such as wavelet transform, empirical mode decomposition, and non-local means.
- These methods have their individual limitations:
  - Rare-Patch effect in non-local means (NLM) estimation.
  - Algorithmic ad-hoc nature of empirical mode decomposition (EMD) lacks mathematical theory.
  - Hard band-limits of wavelet approaches.
  - The requirement of predefining filter bank boundaries in empirical wavelet transform (EWT).
- Recently proposed variational mode decomposition (VMD) technique tries to overcome such limitations.
- Efficacy of NLM in denoising lower-frequency region of ECG.

Non-local Means Estimation

- Non-local means (NLM) estimation is initially proposed for image denoising [2].
- Recently it has been applied for denoising ECG signal [3].
- NLM is a patch based technique which estimates each sample of a signal non-locally [3].
- Each patch consist of group of sample points.

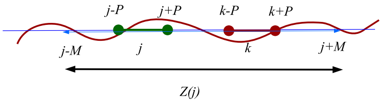


Figure 2 : Illustration of NLM Estimation

[2] Buades A, Coll B, Morel JM (2005) A non-local algorithm for image denoising. In: IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2005. IEEE, pp 60-65
[3] Tracey BH, Miller EL (2012) Nonlocal means denoising of ECG signals. IEEE Transactions on Biomedical Engineering 59:2383-2386

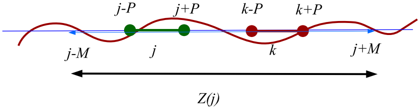
The NLM estimated signal for input signal y is represented as:

$$\hat{y}(j) = \frac{1}{Y(j)} \sum_{k \epsilon Z(j)} w(j,k) y(k) \quad (1)$$

where $Y(j) = \sum_k w(j,k)$.
The associated weight value $w(j,k)$ is as follows:

$$w(j,k) = \exp\left(-\frac{\sum_{\Delta \epsilon \delta} \left(y(j+\Delta) - y(k+\Delta) \right)^2}{2 L_\delta \kappa^2} \right) \quad (2)$$

L_δ represents the number of samples in each patch
Δ represents a local patch having N samples points.
κ is a bandwidth parameter that controls the amount of smoothing applied.



Variational Mode Decomposition (VMD)

- Empirical Mode Decomposition (EMD) is known for limitations like sensitivity to noise and sampling.
- Dragomiretskiy and Zosso[4] proposed VMD as signal decomposition technique to overcome issues of EMD.
- VMD is variational method that looks for an ensemble of modes concurrently and also computes their corresponding center frequencies.
- Unlike EMD, VMD is entirely non-recursive and theoretically well founded.
- VMD is a generalization of classic Weiner filter into multiple adaptive band.
- The variational model is efficiently optimized using an alternating direction method of multipliers approach.

[4] Dragomiretskiy K, Zosso D (2014) Variational mode decomposition. IEEE transactions on signal processing 62(3):531-544

- The variational mode decomposition model has following key building blocks:
  - Weiner Filtering
  - Hilbert Transform and Analytic Signal
  - Frequency Mixing and Heterodyne Demodulation
- The objective of VMD is to decompose the input signal z into several narrow band variational mode functions (VMFs) (m_k).
- Central frequency (c_k) corresponding to each VMFs is also computed as a sparsity prior.
- The constrained variational problem to access the bandwidth of a mode is as follows:

$$\min_{\{m_k\},\{c_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * m_k(t) \right] e^{-jc_k t} \right\|_2^2 \right\} \quad (3)$$

such that $\sum_k m_k = z$.

- The signal reconstruction constraint is addressed by using Lagrangian multipliers, $\lambda(t)$ and the quadratic penalty term.
- The augmented Lagrangian $\mathcal{L}$ is represented as follows:

$$\mathcal{L}(\{m_k\},\{c_k\},\lambda) := \alpha \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * m_k(t) \right] e^{-jc_k t} \right\|_2^2 + \left\| z(t) - \sum_k m_k(t) \right\|_2^2 + \left\langle \lambda(t), z(t) - \sum_k m_k(t) \right\rangle \quad (4)$$

- In order to solve the above optimization problem, a iterative technique called alternate direction method of multipliers (ADMM) [5] is used.
- The convergence criteria for ADMM optimization technique is as follows:

$$\sum_k \left\| m_k^{n+1} - m_k^n \right\|_2^2 \Big/ \left\| m_k^n \right\|_2^2 < \epsilon \quad (5)$$

[5] Bertsekas D.P (1982) Constrained optimization and Lagrange multiplier methods. Academic press

Proposed ECG Denoising Technique

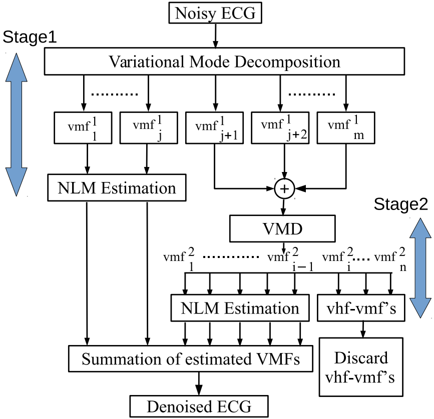


Figure 3 : Proposed method for ECG denoising. Stage 1 and Stage 2 processes are marked by vertical arrow.

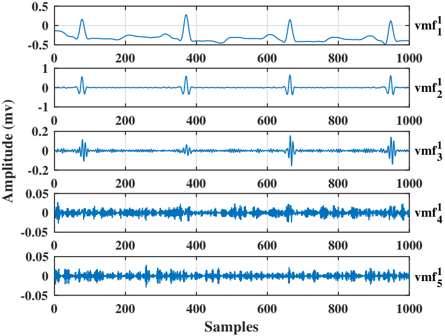


Figure 4 : Stage 1 variational mode functions (VMFs). The modes are arranged from low- to high-frequency band.

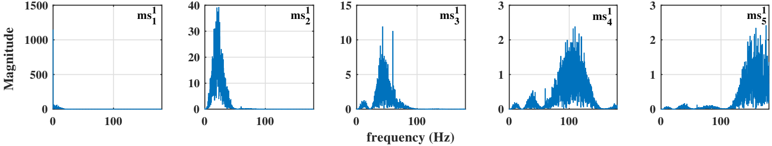


Figure 5 : Magnitude Spectrum of stage 1 VMFs. They are arranged from low- to high-frequency band region (left to right)

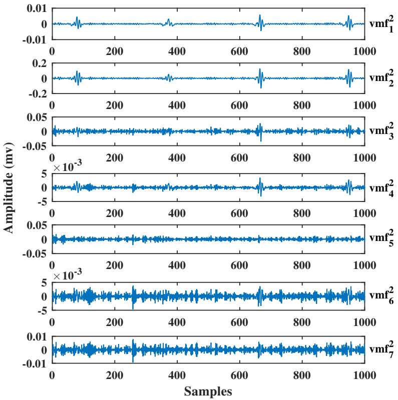


Figure 6 : Stage 2 variational mode functions (VMFs). The modes are arranged from low- to high-frequency band (top to bottom).

Experimental Results

- The standard MIT-BIH Arrhythmia ECG database [6] is used for all the simulations presented in this work.
- All the records were sampled at 360 Hz using 11-bit A/D converter.
- Gaussian noise at various input SNR levels is added to the clean signal to generate noisy ECG.
- The performance metrics used for the comparative study are SNR improvement, mean square error (MSE) and percent root distortion (PRD).

$$SNR_{imp} = 10 \log_{10} \frac{\sum_{i=1}^{N}(y(i) - x(i))^2}{\sum_{i=1}^{N}(\hat{y}(i) - x(i))^2} \quad (6)$$

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(\hat{y}(i) - x(i))^2 \quad (7) \qquad PRD = 100\sqrt{\frac{\sum_{i=1}^{N}(\hat{y}(i) - x(i))^2}{\sum_{i=1}^{N} x^2(i)}} \quad (8)$$

where $x(i)$ is the clean ECG signal, $y(i)$ is the noisy ECG and $\hat{y}(i)$ is the denoised ECG.

[6] Goldberger AL, Amaral LAN, Glass L, Hausdorff JM, Ivanov PC et al (2000) PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Complex Physiologic Signals. Circulation 101:215-220.

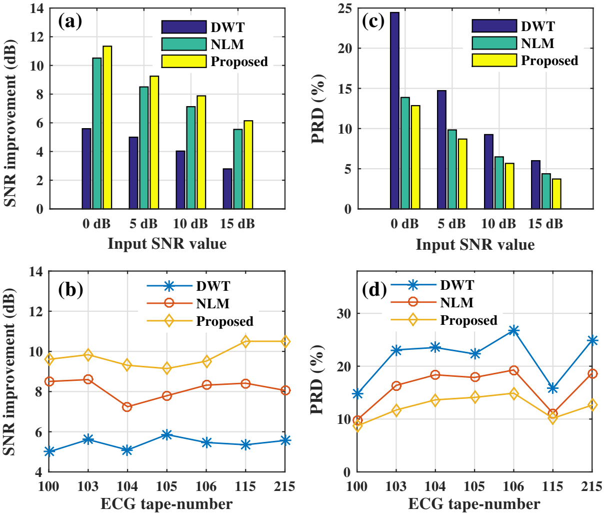


Figure 7 : Comparison of SNR improvement and PRD with varying SNR levels for different explored denoising methods.

Table 1 : The MSE values for the explored approaches with respect to all test signals at 5 *dB* input SNR value.

ECG Signal	DWT-thresholding	NLM	Proposed
100	0.0029	0.0013	0.0009
103	0.0081	0.0041	0.0020
104	0.0074	0.0045	0.0025
105	0.0073	0.0047	0.0027
106	0.0132	0.0068	0.0030
115	0.0080	0.0041	0.0024
215	0.0047	0.0027	0.0023

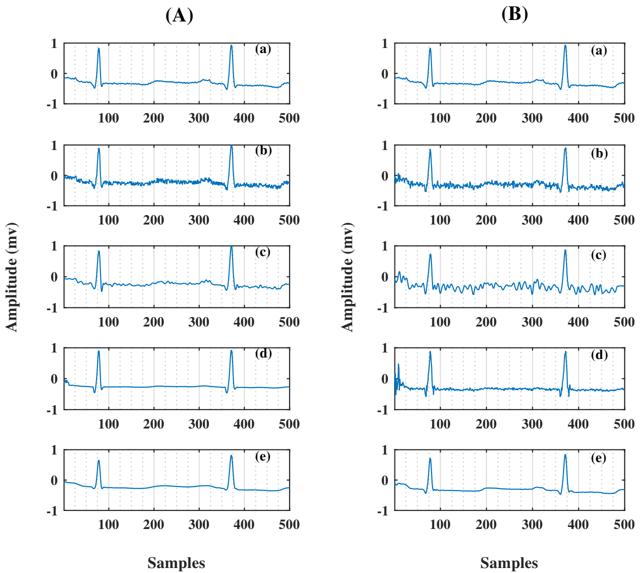


Figure 8 : Denoised EGC signal obtained for: (A) WGN noise and (B) motion artifact (MA). (a) Raw ECG, (b) Noisy ECG, (c) DWT-thresholding (d) NLM method, (e) Proposed method

Conclusion

- A two-stage VMD-NLM based ECG denoising technique has been proposed.
- The significance of using NLM estimation for denoising the variational mode functions (VMFs) is presented.
- The proposed method overcomes the rare-patch effect of NLM.
- VMD process overcomes the individual limitations of EMD and wavelet decomposition method.
- The proposed method works effectively on both white Gaussian noise (WGN) and motion artifact (MA).
- The overall denoising performance is improved compared to traditional NLM and DWT approaches.
- In Future, efforts will be made to incorporate denoising of powerline interference and baseline wander using same technique.