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Conference Paper · December 2017

DOI: 10.1109/EICT.2017.8275164

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Baseline Wandering Removal from ECG Signal by Wandering Path Finding Algorithm

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Abstract—**This work investigates to remove highly wandered path from ECG signal. In normal condition, ECG signal contains a very little amount of baseline wandering which can easily be removed by high pass filtering. On the other hand, acquired ECG signal during walking, running, push-up or pull-up the body contain different shapes of baseline wandering which cannot be possible to remove by conventional filtering concept. To meet the challenge, in this paper we have proposed a baseline wandering removal technique based on baseline wandering path finding (BWPF) algorithm. This BWPF algorithm works by piecewise polynomial fitting. In this paper, the impact of this algorithm on wandered ECG signal is discussed elaborately with graphical interpretations. In addition, it is also shown that why this algorithm works better than the conventional polynomial baseline wandering removing technique.**

Keywords— Electrocardiogram (ECG), baseline wandering, baseline wandering path finding (BWPF) algorithm, polynomial fitting.

I. INTRODUCTION (HEADING 1)

Electrocardiogram or ECG refers to the recording and graphical representation of the functionalities of human heart. ECG is the most applying biomedical signal compared to the others. It is an important tool to identify the abnormalities of heart and therefore most of the doctors prefer to observe the ECG report before prescribing a cardiac patient. A typical ECG signal with its prominent peaks is given in Figure 1. From the figure we can see that there are some peaks of different shape those are named as P wave, QRS complex, T wave and U wave sometimes as given in figure. These waves carry different information about heart's functionality and shows significant change in case of abnormalities. Since this is a noninvasive and easy way to get this signal from human body, doctors are depending on ECG for cardiac treatment from 1901[1].

Based on ECG, huge research works have been done by a lot of researchers during last 100 years. Almost all findings have already been discovered as well as signal processing related different problems are also solved with a number of methods. Nonetheless, in this paper, we would like to share an interesting problem. In our laboratory we use world's most popular module BIOPAC MP36 [2] to acquire ECG signal. BIOPAC MP36 gives proper ECG graphs through BSL (Biopac Student Laboratory) software when body is at rest or static condition. The problem arises when we would like to acquire ECG for some conditions or research purposes such as running, walking, push-up, or pull-up the body. In these cases, the ECG signals we get are drifted with a high degree from baseline. This drift from baseline is also known as baseline wandering. Baseline wander means the effect where the base axis of ECG signal appears to 'wander' or move up and down rather than being straight. The post processing of the ECG signal is necessary to get different information like heart rate, cardiac output, stroke volume, and other features. It is not possible to write an algorithm to get these features from ECG signal without removing baseline wander. In addition, BIOPAC software does not provide any solution to this problem. Therefore, baseline wandering removal becomes the first step among the other post processing steps.

There exists a lot of research works based on removal of baseline wandering. Most of the research works are based on the filtering techniques. In [3] finite impulse response (FIR) filter is used to remove baseline fluctuations. A suitable impulse response is designed with a pass-band ripple of less than 0.5 dB and high stop-band attenuation is considered in this case. The non-adaptive filtering approaches mainly include IIR filter, FIR filter and notch filter. The high pass filter with 0.5Hz cut-off frequency can be used to remove the interference of baseline wander, which can filter out signal component with frequency below 0.5Hz while frequency above 0.5Hz are preserved. Furthermore this type of filter faces a drawback of time delay to get the filtered signal. Thus, the meaningful information contained in the initial stage of getting ECG signal can't be resolved or can be lost due to the failure of correcting baseline distortion [4].

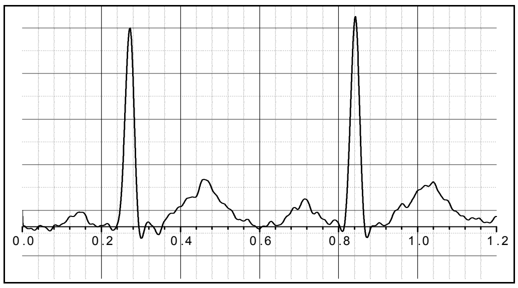

Figure 1. A typical ECG signal.

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A number of research works proposed different methods of adaptive filter to remove the baseline wandering such as, cascade adaptive filter in two phases in [5] & [6], adaptive filter based on error nonlinearity least mean square (LMS) algorithm in [7], constrained stability least mean square algorithm was applied to decrease mean-square error of LMS algorithm in [8]. Adaptive filtering approach usually does not interrupt the ECG frequency spectrum but it requires reference signal, which adds to the complexity of hardware and software. On the other hand, authors in [9] considered many adaptive linear neurons artificial neural network model to delete ECG baseline wander. The artificial neural network model requires a proper training stage to solve the baseline wandering problem and it is definitely a difficult way to handle the persistent non-stationary trend especially in a long-term ECG signal [4].

There are some other approaches as well to remove baseline wander. The wavelet transform is used to eliminate baseline wandering of ECG by implementing a search algorithm based on computing wavelet packet coefficients [10]. Baseline wander removal process using EMD cannot be automated because baseline wander noise may be interrupted over a number of intrinsic mode functions [11]-[12]. A similar problem arises with the wavelet approach where we cannot determine the amount of baseline wander noise present in different levels of detail coefficients [13].

Finally, in all cases one thing is common and that is, considering the cause of baseline wandering is due to movements, breathing, coughing, anxiety, stress or pain, and motion of electrodes. The aspect of our research problem is quite different on the basis of the cause of baseline wandering. We are interested to find the effect of ECG during a strong movement such as walking, running on treadmill, up and down, push up, etc. Due to these physical activities the frequency of baseline wandering cannot be within 0.05 to 0.5~0.7 assuredly, that is considered generally. Therefore, the best way is to find the accurate wandering path due to movement.

In this paper, we have proposed a baseline wandering path finding (BWPF) algorithm based on piecewise polynomial fitting. Polynomial fitting method is partially discussed in [14] where it is approached that considering a prominent knot corresponding every ECG QRS complex, wandering path can be fitted with higher order polynomial. In this case, there may arise two types of problems: 1) over fitting (due to less wandering) and 2) under fitting (due to very high drift of wandering). As a result, in our proposal to solve this problem, piecewise polynomial fitting is implemented with a satisfactory error threshold. Our proposed BWPF algorithm is also capable of maintaining the optimal polynomial order for the piecewise fitting. By the result of BWPF algorithm, the baseline wander can be easily removed by subtracting from the original noisy data.

The rest of the paper is organized as followings: i) Proposed methodology is described with mathematical clarifications in section II, ii) Results and Corresponding discussions are presented with graphical and numerical representation in section III, and iii) our total work is concluded in section IV.

II. Proposed Methodology

A. *Proposed Processing Methodology*

Since this paper investigates highly wandered ECG signal due to physical movements, a complete ECG signals of several minutes contain different types of wandering path. Therefore, total signal cannot be considered for polynomial fitting. This is because with a very high degree of polynomial will also be unable to trace the path of wandering. Considering this fact, after loading the full length ECG signal, it is divided into several segments which help to divide the wandered path into several limited ordered wandered ECG signals. In our proposed algorithm, this segmentation number will be taken as user or operator input based on the wandering path existed in ECG signal. Polynomial fitting order is self-assessed in our proposed methodology based on the threshold value of fitting. The algorithm will be started from order 1 to fit the ECG wandering path and compute its fitting error to compare the standard value given as threshold. If the error is greater than the threshold value the process will be repeated with the order=previous_order+1 and will continue the process to achieve the error value less than or equal to the threshold value.

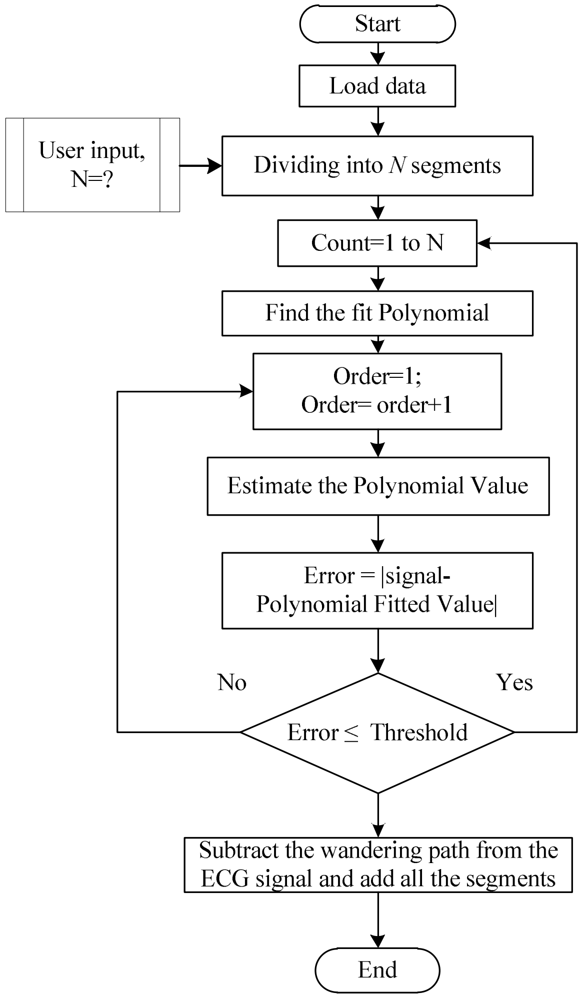

Figure 2. Block diagram of proposed baseline wandering removal algorithm

Suppose we have an ECG signal, $X(n)$ that contains N number of samples. Consider that this signal is too long and there exists wide range of baseline drift in positive and negative direction with respect to original baseline. Sometimes with a conventional polynomial fitting this type of baseline wandering cannot be estimated due to its very high degree of wander. To solve such problem, our proposed method piecewise polynomial fitting can be a solution. According to the piecewise polynomial fitting following steps have been performed:

1. Divided the signal into K equal space and form a matrix, $G(n)$ of order $K\times(N/K)$ from the original signal of order $1\times N$. Therefore, every row of the matrix represents the sub-signal of the original signal.
2. Now, fit all the rows of the matrix separately with a suitable lower order polynomial. Polynomial order can be chosen as iterative method based on a satisfactory threshold level of error. So, a matrix of fit polynomial coefficient $P[a^0, a^1, a^2, \ldots, a^k]$ will be found as ascending polynomial order.
3. Estimate the polynomial value for all the rows by applying the rule *PoG*. For each row, the wandering path will be found as a matrix, E_1 of $1\times(N/K)$ order.
4. Rearrange the estimated row wise wandering path as following,

$$S_1 = [[E_1]_{1\times(N/K)}, [0]_{1\times(N/K)}, [0]_{1\times(N/K)}, \ldots, [0]_{1\times(N/K)}]$$

$$S_2 = [[0]_{1\times(N/K)}, [E_1]_{1\times(N/K)}, [0]_{1\times(N/K)}, \ldots, [0]_{1\times(N/K)}]$$

$$S_k = [[0]_{1\times(N/K)}, [0]_{1\times(N/K)}, [0]_{1\times(N/K)}, \ldots, [E_1]_{1\times(N/K)}]$$

5. Now sum all the matrix to make a single signal as,

$$S[n] = \sum_{i=1}^{k} S_i$$

Here, $S[n]_{1\times(N/K)}$ represents the path of baseline wander.

6. Therefore, baseline wander removed signal can be easily achieved as, $\hat{X}(n) = X(n) - S(n)$.

Now, the signal can be simply filtered to prepare it for the further processing like heart rate calculation, peaks identification, ischemia detection, angina pectoris identification, etc.

B. Mathematical Explanation of Polynomial Fitting

To model a time series of data by polynomial fitting we generally consider a polynomial equation as an estimation function of the predictive model of the given data. Suppose the estimation function, E(s) is of k^{th} degree polynomial and can be presented as,

$$E(s) = a_0 + a_1 x + a_2 x^2 + \ldots + a_k x^k \quad (1)$$

Therefore the difference between actual value, y and estimated vale derived by the proposed model estimating equation, E(s) is termed as residual, R^2 which can be formulated as given (2).

$$\begin{aligned} R^2 &= \sum_{i=1}^{n} [y_i - E(s)]^2 \\ &= \sum_{i=1}^{n} [y_i - (a_0 + a_1 x + a_2 x^2 + \ldots + a_k x^k)]^2 \end{aligned} \quad (2)$$

For achieving the best fitted estimated model equation, it is the foremost target is to minimize the value of R^2 and we know that in the minimum value of R for the different coefficient a^i, the partial derivative of R is zero which means,

$$\frac{\partial}{\partial a_i}(R^2) = 0 \quad (3)$$

From (3) we get that,

$$\frac{\partial}{\partial a_0}(R^2) = -2\sum_{i=1}^{n} [y_i - (a_0 + a_1 x + a_2 x^2 + \ldots + a_k x^k)] = 0 \quad (4)$$

$$\frac{\partial}{\partial a_1}(R^2) = -2\sum_{i=1}^{n} [y_i - (a_0 + a_1 x + a_2 x^2 + \ldots + a_k x^k)]x = 0 \quad (5)$$

$$\frac{\partial}{\partial a_k}(R^2) = -2\sum_{i=1}^{n} [y_i - (a_0 + a_1 x + a_2 x^2 + \ldots + a_k x^k)]x^k = 0 \quad (6)$$

From the relations given in (4)-(6), we get a vandermonde type matrix that can be solved for least square fitting and finally we get,

$$\begin{aligned} & y = Xa \\ or,\ & X^T y = X^T X a \\ or,\ & a = (X^T X)^{-1} X^T y \end{aligned}$$

Since we get the coefficients of the polynomial by the previous equation, the polynomial fitted valuation of the function can be easily done by multiplying these coefficients with their orders given in (1).

III. Data Collection and Processing Environment

The sole scope of this paper is to remove high degree of baseline wandering. To achieve this goal, ECG signal is acquired in Biomedical Signal Processing Laboratory of the department of Biomedical Engineering of Khulna University of Engineering & Technology (KUET). During signal acquisition, participant is requested to move their hands, legs, push up, etc. Due to these types of physical movements acquired ECG signal was corrupted with high degree of baseline wander. ECG signal was acquired by Biopac MP36 hardware and Biopac Student Laboratory (BSL) software. ECG data acquisition is performed by three leads system from two hand and one foot configuration. Data acquisition procedure from the participant is illustrated by the Fig. 3. From the figure it is observable that the acquired ECG signal contains high degree of baseline wander.

The baseline wandered signal is converted to .mat file and all processing regarding this proposed algorithm are performed by MATLAB as an offline signal processing scheme.

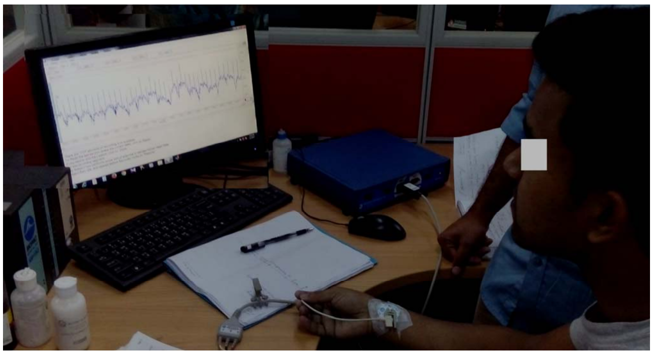

Figure 3. Data acquisition procedures in our laboratory for incorporating high degree of baseline wandering in ECG signal

IV. RESULTS AND DISCUSSIONS

Baseline wandering affects the regular shape of ECG signal and this effect can be of different kinds. In Fig.4, three types of baseline wandered signals are given. ECG signal corresponding to Fig.4 (a) contains a baseline with constant lag from baseline. This lag can be either positive or negative. In this case, the constant baseline lag is negative and this type of baseline wandering can be easily removed by band-pass filtering. On the other hand the ECG signal corresponding to Fig.4 (c) contains a baseline wandering of very slow frequency oriented drift. This type of problem is also removed by filtering technique. Nonetheless, very high degree baseline wandering is presented in Fig.4 (b). This signal is acquired in our laboratory to create this difficulty in ECG signal and this problem cannot be solved by simple filtering technique. This paper solely scopes to remove such highly drifted baseline from affected ECG signals.

Therefore in this work, very high degree of baseline drifted ECG signal is considered. Generally polynomial fitting technique can be applied to remove baseline wandering but for the very long ECG signal, a high degree of polynomial fitting often fails to achieve the fitting assumption. In addition with that, high degrees of polynomial increases computational complexity. Such problems are given in Fig. 5. Where a long ECG signal is considered with different baseline wandering at different section which is unable to remove by conventional polynomial fitting algorithm.

Fig. 5(a) represents the baseline wandered ECG signal from which baseline wandering is removed by polynomial fitting algorithm with different polynomial order. Fig.5 (b), Fig.5 (c), Fig.5 (d), and Fig.5 (e) are baseline wander removed signal by polynomial order of 5, 10, 15, and 30, respectively. From the results given in Fig.5, we can observe that for polynomial order of 5 and 10 are completely failed to remove the baseline wander. On the other hand polynomial order 15 removes almost all the baseline wandering but order 30 is the best in this action. Therefore, we can understand from this result that very high polynomial order is necessary to remove higher order baseline wander. Into this bargain, it is easily perceivable that this high polynomial order may be a cause or increasing the computational complexity in algorithm and it may also face the over fitting problem because of high polynomial order. Hence, conventional polynomial fitting cannot be a solution.

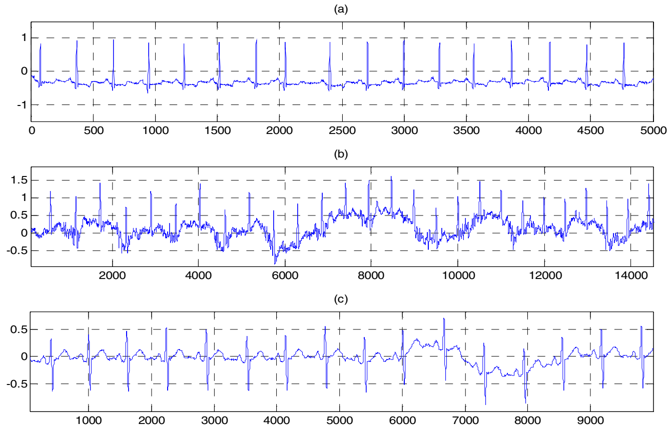

Figure 4. Examples of different types of baseline wandering. (a) & (c) ECG signals are collected from MIT Arrythmia database [15] and (b) ECG signal is acquired by the authors while participant performs physical movements.

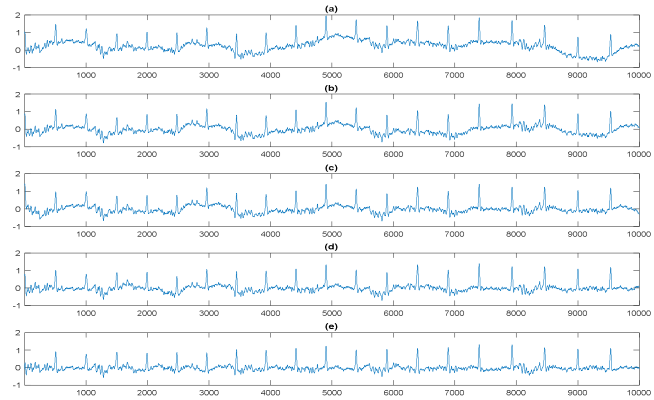

Figure 5. Baseline wandering removal by polynomial fitting based algorithm with different polynomial orders

To overcome this problem, we have proposed the BWPF algorithm which is able to apply the piecewise polynomial fitting with necessary polynomial order. Using our proposed algorithm, very highly baseline wandered signal is corrected which is given in Fig. 6. The raw ECG signal is contaminated with a very high degree of baseline wandering with different shapes in different area of ECG signal. According to our proposed algorithm BWPF, this raw ECG signal was divided into 30 equal pieces of signal and create a matrix with 30 columns. Thereafter, each column was considered as separate signal and fitted the piece of each signal with their appropriate polynomial order. The order was selected from 1 and increased to achieve the least fitting error which was previously provided to the algorithm as threshold error (0.15). Therefore the polynomial fitted results created another matrix of column 30. Then the original signal's matrix and polynomial fitting matrix were reconstructed to single dimensional signal. Therefore, mathematically, the reconstructed polynomial fitted signal is actually the baseline wandering path of the total raw ECG signal. Eventually, this algorithm finds the baseline travelling path. The baseline travelling path is finally subtracted from the raw ECG signal which gives us the baseline corrected signal. The third signal representation of Fig. 6 is the Gaussian windowing filtered of baseline wander removed signal.

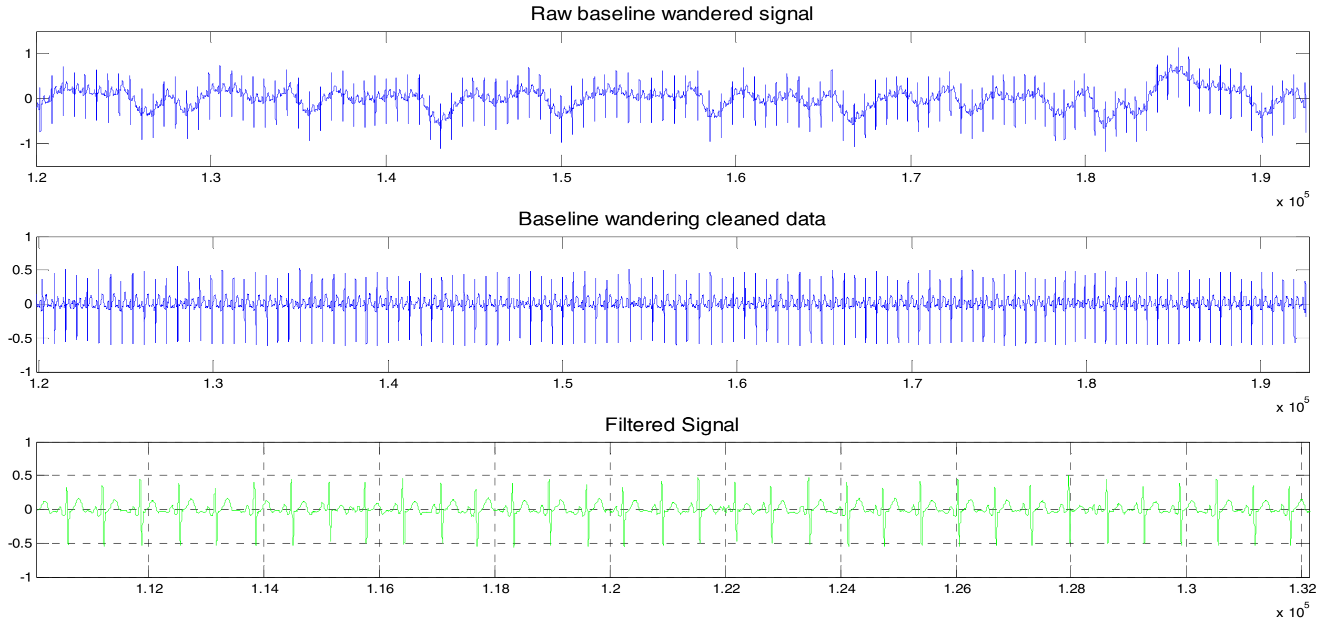

Figure 6. Results of proposed BWPF algorithm in case of very long and highly drifted baseline wander contaminated ECG signal. The first signal is raw ECG signal. Second one is baseline wander corrected signal. The third one is filtered signal of the second one and it is shown as slightly zoomed for clear appearance.

V. Conclusion

The proposed baseline wandering path finding (BWPF) algorithm provides the benefit to the user to choose the number of division of the raw signal. In addition, proposed algorithm selects the polynomial order, itself based on the threshold error rate which is able to reduce the computational complexity. From the results, it is clear that the BWPF algorithm is better than the conventional polynomial fitting algorithm in case of removing baseline wander from ECG signal. This algorithm is also applicable to the other signals having baseline wandering. BWPF algorithm will be helpful before all kinds of ECG signal processing.

Acknowledgment

This work was supported by Higher Education Quality Enhancement Project (HEQEP), UGC, Bangladesh under Subproject "Postgraduate Research in BME", CP#3472, KUET, Bangladesh.

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