Enhanced Turning Point Algorithm for the Visualization and Printing of Long Term ECG Curves

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Abstract

In the modern ECG signal processing systems the typical sampling rate is between 100 to 2000 Hz. However, in many situations the amount of samples has to be reduced in a way that the significant morphological features such as peaks, valleys, actually the turning points are preserved. To solve this problem a very efficient enhanced turning point algorithm has been developed.

The original turning point algorithm has been proposed by Mueller. This method gives a compression factor of 2:1. The presented enhanced algorithm provides an arbitrary integer reduction in real-time preserving of the turning points.

We achieved an average sampling rate of 18 Hz for CTS test curves without losing any waves. Disadvantages of the method include not equally spaced sampling and widening of waves. However it does not cause any problems in case of visualization and printing of long term ECG curves at low paper speed.

A new enhanced turning point algorithm has been presented. It has demonstrated itself as a very efficient real-time method suitable to apply for visualizing and printing of long term ECG. A fraction reduction factor also can be achieved performing previous interpolation.

1. Introduction

In the modern ECG signal processing systems the typical sampling rate is between 100 to 2000 Hz. However, in many situations we have to reduce the amount of samples preserving the significant morphological features such as peaks, valleys, actually the turning points. For example visualizing and printing of the full disclosure ambulatory ECG curves. The ECG signal contains much more samples than the number of pixels required for visualization at standard paper speeds on PC monitors or on the ECG displays. The same problem can arise with printing. The average sampling frequency has to be reduced below 100 Hz, sometimes down to 10 Hz (PC monitor, 2.5 mm/s).

The first idea may be to apply a traditional DSP technique, namely the decimation. However, this approach can violate sampling theory and the peaks of the decimated signals decrease.

An intelligent non-uniform subsampling that preserves the turning points is a better solution. The original turning point (TP) algorithm has been proposed by Mueller [1]. Its main idea was to examine the trend of the sampled points and to choose only one of each pair of successive points. The algorithm reduces redundancy in the data sequence. Compression factor higher than two can be achieved by applying the original algorithm several times consecutively.

The turning point algorithm works better even at an average sampling frequency of 125 Hz (N=4) than decimation as shown in Figure 1.

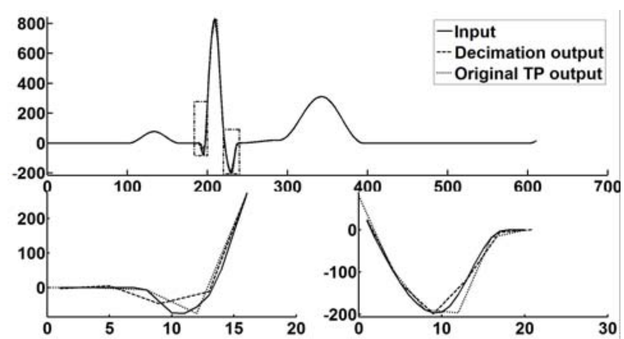

Figure 1. Reduced Q-wave amplitude at decimation. N=4.

However, the original turning point algorithm allows compression rates only power of two and loses significant morphological features at sampling frequency below 62.5 Hz, which is not tolerable (Figure 2).

The original turning point algorithm discards a turning point if it is in the pair of the other local extremum. Therefore it can lose important morphological details of the signal.

To solve these problems a very efficient enhanced turning point algorithm has been developed. This algorithm is not a compression algorithm; it is a non-uniform subsampling method. It is exclusively intended for visualization and printing of long term ECG curves at reduced sampling rate. After considerable subsampling would be impossible to restore the original signal without significant distortion.

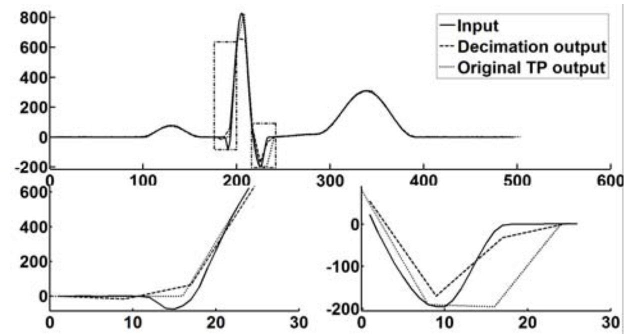

Figure 2. Reduced Q-wave amplitude at the original TP algorithm. N=8.

2. Method

The original algorithm has two disadvantages. Firstly, the subsampling rate can only be power of two; secondly, it can lose clinically important information. This occurs when both consecutive points of new iteration are turning points. In this situation only one of them is preserved and the other is permanently discarded.

The enhanced algorithm resolves both problems. The rate of reduction can be an arbitrary integer factor in one step, and it preserves the not applied potential turning point for next iteration.

The algorithm was tested utilizing ECG curves of CTC, CSE and MIT databases. The input signals had a sampling frequency of 500 Hz [2-4].

In most cases the output of the turning point algorithms was interpolated in the figures.

2.1. The enhanced turning point algorithm

The enhanced algorithm is very similar to the original one. The fundamental idea is the same. We want to preserve the significant turning points, where the slope of the curve changes the sign. The algorithm analyses a successive number of neighboring samples and stores one point at every iteration by considering the trend of the ECG curve. Therefore it discards the redundant and irrelevant information of the signal.

At the same time there are two important differences, which make the new algorithm much more sophisticated and faster.

In the first place our algorithm simultaneously analyses arbitrary points instead of two for saving one of them. It stores the first point and assigns it as the reference point. Then it determines the places and values of the minimum and maximum of the next N points. Depending on the values of the extrema with respect to the reference point and their order the algorithm saves one of them. Similarly to the original algorithm, if the sign of the slope of the lines between the three points is changing then the middle point is stored, otherwise the third one is.

The second difference is, unlike the original algorithm, if the middle point is stored; the third point will be memorized and applied in the next iteration as the “very first” point. If the third point was a maximum, then at the beginning of the next iteration it is assigned to the maximum value, if it was a minimum, then it is assigned to the minimum value.

The result of the subsampling a CSE ECG curve by 16 is presented in the Figure 3.

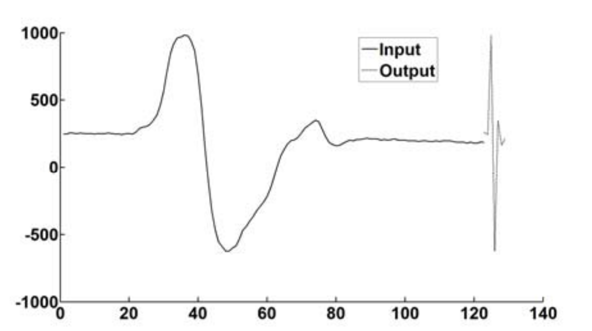

Figure 3. Subsampling factor N=16

Figure 4 depicts how the algorithm works.

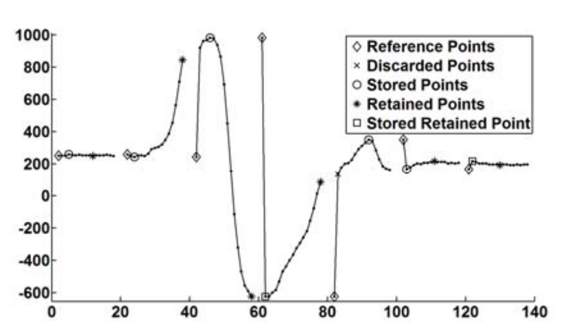

Figure 4. Iterations of new turning point algorithm

2.2. Comparison of the new turning point algorithm with the original utilizing CTS test signals

ANE20000 test signal was applied for comparing the algorithms.

The output of both algorithms was identical, without losing any peaks at the subsampling factors from 2 to 16. At the subsampling by 32 the original algorithms failed and lost five R-waves. At the same time the new algorithm lost only one Q-wave (Figure 5). Very interestingly, only 14 differences were detected between the outputs of the algorithms.

Adding small HF noise to the signal the algorithms behaved totally differently because of the point-memorizing feature of the enhanced algorithm. We added 0.5 μV RMS HF noise. This time the original algorithm missed five Q-waves at N = 8 (Figure 6). Our enhanced algorithm preserved all waves even at compression rate of N = 28.

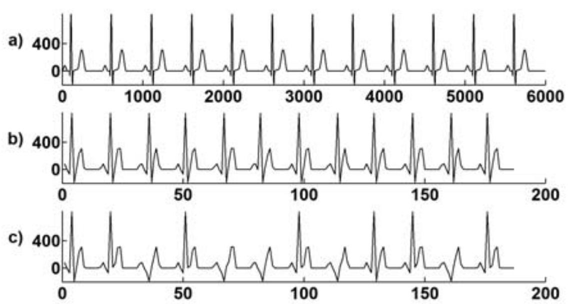

Figure 5. ANE20000 without noise. N=32. a – input, b – new algorithm output, c – original algorithm output.

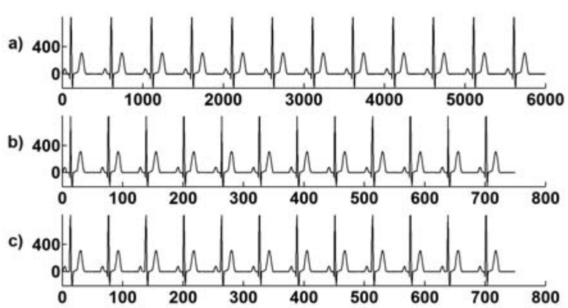

Figure 6. ANE20000 with small HF noise. N=8. a – input, b – new algorithm output, c – original algorithm output

According to the tests the original algorithm worked almost accurately at an average sampling frequency of 62.5 Hz and the enhanced algorithm worked perfectly at an average sampling frequency of 18 Hz.

2.3. Comparison of the new turning point algorithm with the original utilizing MIT and CSE signals

The performance of both algorithms was checked utilizing real ECG curves of MIT and CSE databases.

As shown in Figure 7 and 8 the enhanced algorithm accomplished the subsampling process better than the original algorithm.

At the subsampling factor N = 16 the original algorithm lost several Q-waves and QRS notching. At the same time the new enhanced turning point algorithm preserved all significant morphological details.

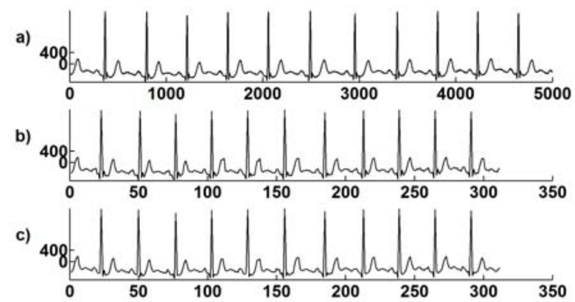

Figure 7. MIT 103, N=16. a – input, b – new algorithm output, c – original algorithm output

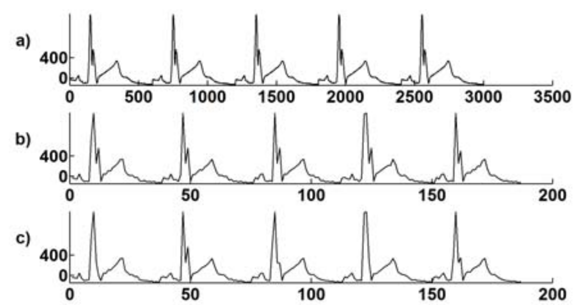

Figure 8. CSE mo_014, N=16. a – input, b – new algorithm output, c – original algorithm output

2.4. Evaluation of the performance of the enhanced algorithm

As it has been demonstrated, the new turning point algorithm performs subsampling of ECG signals much better than the original algorithm.

What is the minimum average sampling rate, at which it can be applied without noticeable distortion of ECG curves?

Three kinds of errors can occur during the subsampling process - substantial decrease of wave amplitude, loss of QRS notching and the small waves entirely. Hence the small details cannot be seen on the compressed signal, the most important challenge is to preserve the amplitude of the large waves.

Tests utilizing the ANE20000 signal had demonstrated that the new algorithm lost small Q-waves only below an average sampling rate of 18 Hz. R- and S-waves were entirely preserved even at a much smaller average sampling rate. The QRS notching can be discarded if it is insufficiently broad and deep.

QRS notching and small r'-waves of real ECG curves were lost below an average sampling rate of 50 Hz, but it did not cause noticeable distortion.

The new algorithm cannot preserve all turning points if three of them are in the same iteration window. However this depends on the starting point of the iterations. The algorithm is not time invariant.

The real length of the subsampled signals compared with the length of original signals is shown in Figure 9 and 10.

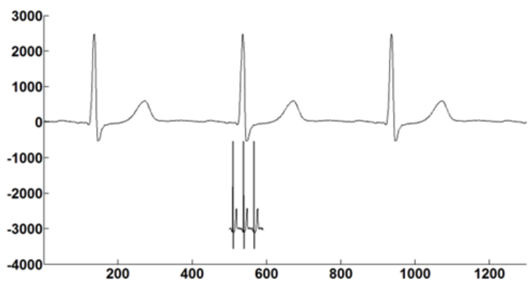

Figure 9. CSE ma_073, N=14, average f_s = 35.7 Hz.

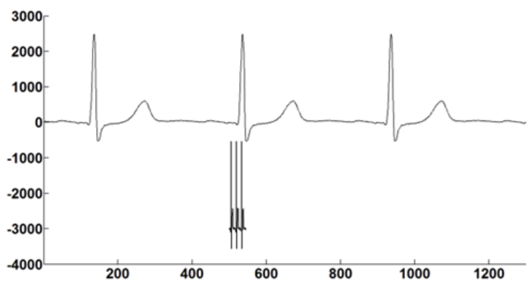

Figure 10. CSE ma_073, N=28, average f_s = 17.86 Hz.

2.5. Distortions produced by the new algorithm

The enhanced turning point algorithm is very sophisticated. It can retain almost all important turning points even at a very low average sampling rate. However the consequence of this feature of the algorithm is a noticeable widening of QRS complexes.

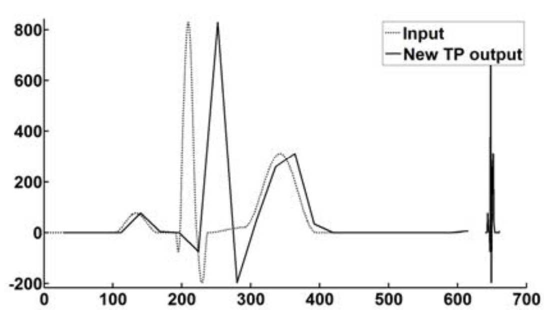

Figure 11. QRS complex widening. N=28.

In case of an average sampling rate of 18 Hz the time interval between the samples is about 55 ms. If all three waves of a simple QRS complex of 94 ms duration are preserved, then the duration of QRS complex becomes 214 ms as shown in Figure 11.

3. Results

The original method allows compression rates greater than 2:1 in more steps, but the factor can only be power of two. Our method permits a reduction with arbitrary integer factor in one step. We achieved an average sampling rate of 18 Hz for CTS test curves without losing any waves. The obtainable average sampling rate is about four times smaller than with the original algorithm. The new algorithm accomplishes the subsampling by an arbitrary integer in one step; therefore it can be significantly faster than the original algorithm at high compression rate. The disadvantages of this method are not equally spaced sampling and widening of QRS complexes. However it does not cause any problems in case of visualization and printing of long term ECG curves.

4. Discussion and conclusions

A new enhanced turning point algorithm has been presented. It has demonstrated itself as a very efficient and fast real-time method suitable to apply for visualizing and printing of long term ECG. A fraction reduction factor can also be achieved by performing a previous interpolation.

References

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