Study on conditioning and feature extraction algorithm of photoplethysmography signal for physiological parameters detection

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***Abstract*--Photoplethysmography(PPG) signal can reflect many physiological parameters, such as heart function, blood vessel elasticity, blood viscosity and so on. It was a novel noninvasive method with the advantage of convenience and accuracy. It was important to find efficient pre-processing and feature extraction algorithms to deal with original PPG signal, which was interfered by many other factors. Many practical methods including median filtering and FIR filtering was used. A new algorithm based on wavelet transformation was proposed for eliminating the baseline drift. Feature points extraction was another key issue. An improved differential algorithm was used to solve this problem. All of these practical algorithms provided an effective platform for physiological parameters detection.**

Keywords—PPG; physiological parameters; wavelet transform; baseline; differential; feature detection

I. INTRODUCTION

Photoplethysmography (PPG) was a photoelectric method for measuring the volume of tissue blood, which was based on the change of blood volume in every cardiac pump. Compared to traditional method, PPG was a novel noninvasive method with the advantages of convenience and accuracy. Until now, PPG has been widely used for the detection of many basic physiological parameters [1], such as blood oxygen [2], heart rate, breath [3] and blood pressure [4]. Besides, PPG could also reflect some other important cardiovascular parameters, such as atherosclerosis etc. [5]. So there's great meaning to make a deep analysis of the PPG signal in order to extract various physiological parameters containing in it with high accuracy.

However, the recent researches were mainly focused on the relationship between the PPG signal and physiological models [6-8]. Most of these researches were based on ideal PPG single, which was very hard to get in real experiments due to the existence of motion artifact, power line interference, baseline drift and some other noises. From this aspect, it is also important to find efficient pre-processing and feature extraction methods for original PPG signal.

II. PPG SIGNAL FEATURES

PPG signal was generated by periodic ejection of the heart, so it has a close relationship with the ejection period, from which the heart rate (HR) could be extracted. In another aspect, the blood flowing in the vessels was affected by the vessel elasticity and blood viscosity. So that many cardiovascular information, such as the degree of angiosclerosis, could also be picked up from the PPG signal. All the physiological parameters could be reflected in PPG signal feature points, as shown in Fig.1.

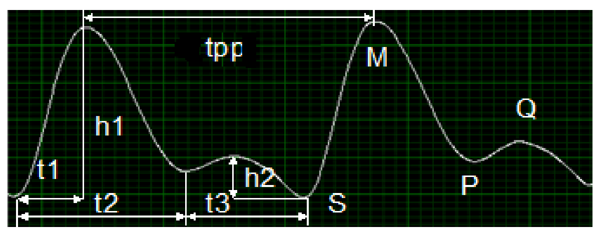


Figure 1. Standard PPG signal and its feature points

As noted, in the typical PPG signal, the section from point S to M represents the rapid ejection phase; from M to P is the late phase. Point M is the main peak of the signal. At this point, the blood pressure (BP) is highest in the whole period. Another crest Q is called dicrotic wave, which could reflect the compliance of the arteriola; point P is called dicrotic notch. HR could be obtained from the interval of two main peaks (TPP); time interval of M-Q was an index of arteriosclerosis [1]. However, due to the presence of various factors, the feature points for real PPG signals were always hard to get directly. So there's great meaning to find efficient and practical pre-processing and feature extraction methods to pinpoint the PPG signal.

III. PPG SIGNAL PROCESSING ALGORITHM DESIGN

Processing procedure of the PPG signal primarily contains two parts: signal conditioning [9] and feature extraction [10]. The main algorithms and procedure was displayed in Fig.2. The signal conditioning procedure consists three main steps: removing singular values, FIR low-pass filtering and baseline drift elimination. Signal feature extraction aims to extract all the feature points of the PPG signal, based on which the physiological parameters would be derived.

A. Signal conditioning algorithm design

Median filtering was an efficient method for removing singular values from the signal with sharp noise [11]. The maximum and minimum points could be kicked off to make the signal smoother. In experiment, a 5×5 template was used for median filtering.

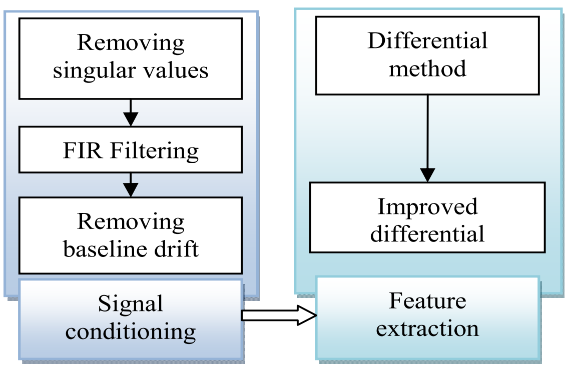


Figure 2. The main algorithms and procedure for PPG signal processing

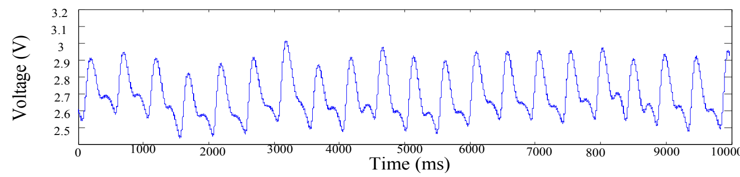
Nevertheless, median filtering could only reduce the singular values in the signal, but not effective for the high-frequency noise. So an FIR filter was added after median filtering. FIR filter with linear phase was very important for extracting time features from the PPG signal. The window function used was a modified Hamming window as shown below, whose weighting coefficient could suppress the sidelobe noise effectively [12].

$$w(n) = [0.54 - 0.46\cos(\frac{2\pi n}{N})] \tag{1}$$

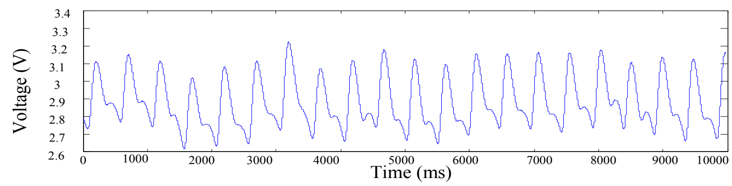
A Hamming window with 21 orders was used to eliminate the high-frequency noise containing in the original PPG signals. Sampling frequency f_s of the signal was 500Hz, cut-off frequency f_c was set to 30Hz, so the digital filter index $w_c = 2^* f_c / f_s = 0.12$. The combining filtering result was shown in Fig.3.

As shown in Fig.3, the filtered signal became smooth enough, but still with obvious baseline drift. This drift was mainly caused by breathe signal and motion artifact. Frequency band of the breathe signal was within 0.3~1Hz, which was overlapped with the PPG signal. So that traditional frequency analysis methods were ineffective to eliminate this drift.

Wavelet transform (WT) is one of the modern spectral analysis tools, which can not only analyze the frequency-domain features of short time-domain process but also can analyze the time domain features of local frequency domain[13]. An orthogonal wavelet decomposition method was proposed to eliminate the influence of the breathe signal [14]. The main procedure was to make the signal going through a series of low-pass filter and high-pass filter. The low frequency part was decomposed further. Wavelet reconstruction was a reverse procedure, as shown in Fig.4.



(a) Original signal



(b) Filtered signal

Figure 3. Median filtering and FIR filtering result compared to original signal

In Fig.4, A was approximation coefficient obtained through a low pass filter; D was detail coefficient generated by high pass filter. "↓2" represent subsample and "↑2" represent subsample interpolation. The algorithm was shown in the following equations.

$$\begin{aligned} A_{jk} &= \sum_n h0(n-2k)A_{(j-1)k} \\ D_{jk} &= \sum_n h1(n-2k)A_{(j-1)k} \end{aligned} \tag{2}$$

In experiment, "sym8" wavelet was chosen as the basic function to decompose the filtered signal. For the signal, the baseline was a slowly varying component. It could be eliminated by reconstructing the signal after the approximation components were deleted. The processing result was shown in Fig.5.

As shown in Fig.5, the blue curve was the filtered signal; the red one represent the approximate signal, that is the baseline caused by breathe and motion artifact with the bandwidth about 0.3~1Hz. The reconstructed signal with baseline eliminated was shown as the green one. Compared to the blue curve, the processed signal was much more steady and regular. This was significant and necessary for picking out the feature points from the PPG signal accurately.

B. Feature extraction algorithm design

After pre-processed, most noises and baseline drift had been eliminated. A differential threshold method was then used to extract feature points from the regular signal. This method consists chiefly of three steps: interpolation, differentiation and extreme point extraction. The interpolation algorithm was quite important for digital differential. The cubic spline interpolation method was used, which was shown in Equation (3).

$$S_i(x) = y_i + y_{i,i+1}(x - x_i) + \frac{1}{6}(x - x_i)(x - x_{i+1})$$
$$y_{i,i+1} = \frac{y_{i+1} - y_i}{x_{i+1} - x_i} \tag{3}$$

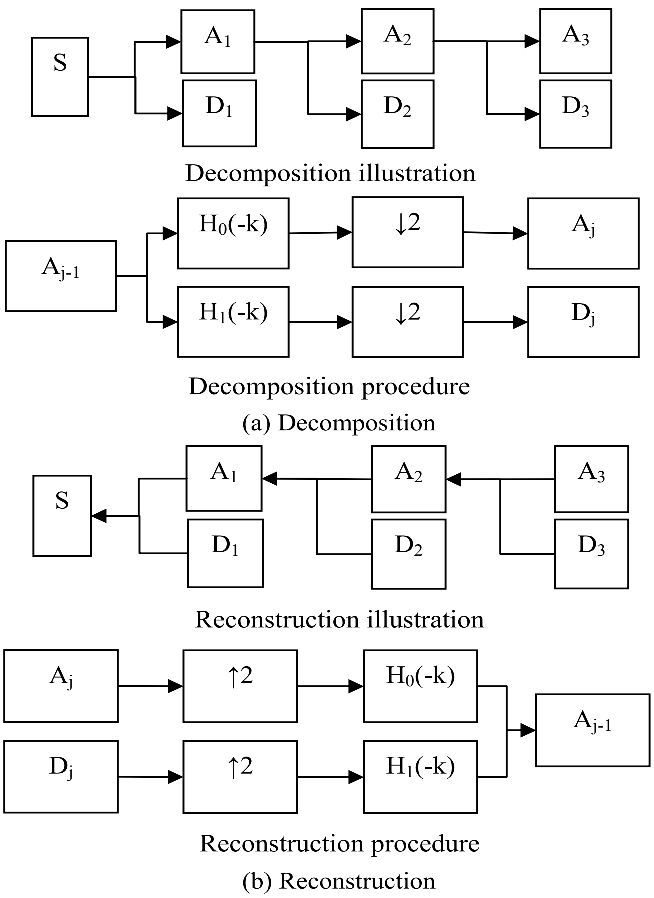


Figure 4. Decomposition and reconstruction procedure of WT used for baseline drift elimination

The cubic spline interpolation method could ensure that *S(x)* had continuous first and second derivative, which was profitable for the later differential action. Normally, the extreme points of PPG signal could be obtained from the nearest zero points in the first derivative curve. These extreme points included the start point of rapid ejection phase S, main peaks M, dicrotic notch P and dicrotic wave peak Q. The extreme points of second derivative were related to the compliance and elasticity of the blood vessel. It could be a supplementary means for the feature points extraction. The curve of fist and second derivative was showed in Fig.6.

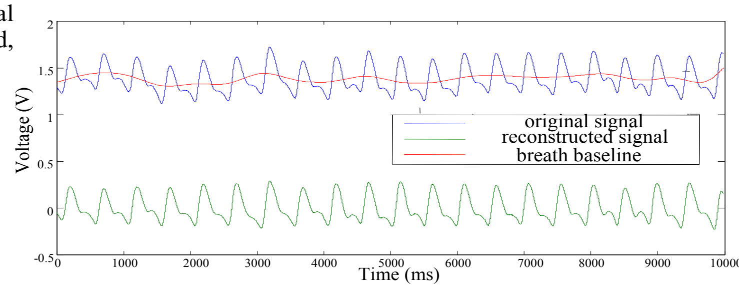


Figure 5. Baseline drift elimination result by WT method

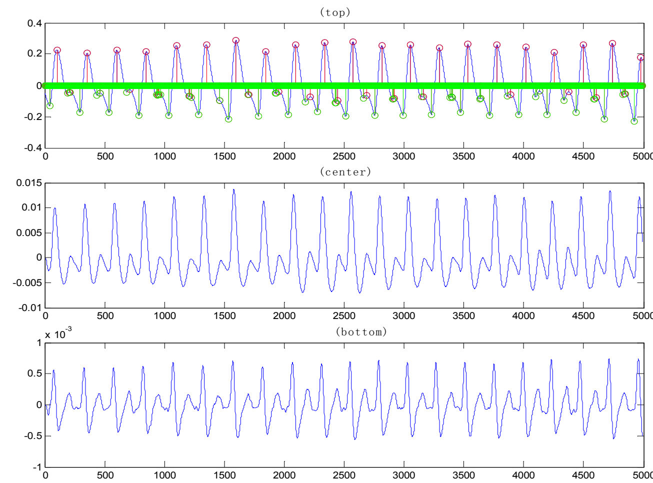


Figure 6. First(center) and second derivative (bottom) result of the filtered PPG signal(top)

Actually, every extreme points could be detected by the differential method. However, in many applications, e.g. pulse wave translation time (PTT) detection, only the start point or the main peak should be picked up. The other extreme points near the required point would be negative for its accurate locating.

To solve this problem, an improved differential algorithm was proposed. The main strategy was to cut the signal across zero points before differential. By this way, only one extreme point could be detected in every section. The main flow chart was showed in Fig.7.

As can be seen, after cut by zero-crossing point, only one extreme point could be located in every section. This method could ensure that the time interval features of PPG signal could be accurately calculated. The experiment results by the two methods were displayed in Fig.8.

With the traditional method, 3 mistake points was got in a 50s PPG signal, the error rate was about 4.1%. When the improved method was used, there was no mistake appeared. Because the proposed differential method could eliminate the false positives caused by signal jitter effectively, it was advantageous to the detection of the physiological parameters, such as HR, PTT etc.

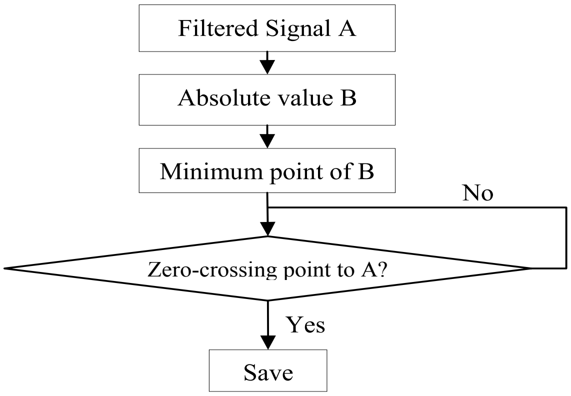


Figure 7. Flow diagrams of the improved differential algorithm

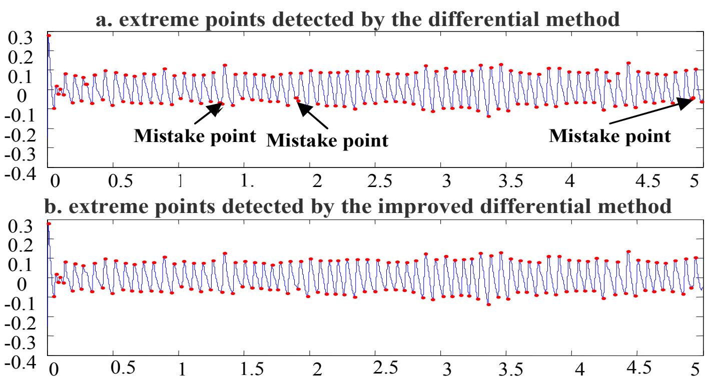


Figure 8. Comparison of feature extraction result by the differential algorithm and the improved one

IV. CONCLUSION AND DISCUSSION

As noted, PPG was a novel noninvasive method with the advantage of convenience and accuracy. It could reflect many physiological parameters and functions, such as heart function, blood vessel elasticity, blood viscosity and so on. However, the original signal was usually interfered by many other factors, such as high-frequency noise, baseline drift and so on. So it was important to find efficient pre-processing and feature extraction algorithms to deal with original PPG signal, in order to obtain the physiological parameters with high accuracy.

In the present work, many practical methods including median filtering and FIR filtering was used to remove most noises from the original signal. A new algorithm based on wavelet transformation was proposed for eliminating the baseline drift caused by breathes and motion artifact. Feature points extraction was another key issue. An improved differential algorithm was used to solve this problem. By this way, all the feature points of PPG signal could be extracted accurately. All of these practical algorithms provided an effective platform for physiological parameters detection. It should have a good application prospect.

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