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Design of a Real-Time ECG Filter for Portable Mobile Medical Systems

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ABSTRACT Electrocardiogram (ECG) signal is a direct and effective way to find cardiovascular disease timely, which can intuitively reflect changes of the heart beat and activities of different parts. Due to the noise interference from surroundings, acquisition of real-time and high-quality ECG signal is a big challenge for portable mobile medical systems. Integer coefficients infinite impulse response (IIR) digital filter is suitable for portable mobile platform, but it will be a little bit of distortion. So, an improved integer IIR filter for portable ECG monitors is presented in this paper. The proposed IIR filter can instantaneously and effectively eliminate baseline drift of main interference frequency band and 50-Hz power frequency interference in ECG signal. The method is verified by a specific example and MIT/BIH Arrhythmia Database. The improved integer coefficients IIR filter was applied in a portable mobile medical system. It can meet the requirements of ECG filtering in real-time and filtering performance.

INDEX TERMS ECG, integer coefficients IIR filter, portable mobile medical system.

I. INTRODUCTION

The electrocardiogram (ECG) signal is applied widely in diagnosis for heart disease, which generally ranges from 0.1 mV to 2.5 mV [1]. Compared to external interference, it is weak which can be submerged easily and influences the diagnostic results seriously [2]. Moreover, the noise is generally present in the original signal. So eliminating the signal noise is essential important for signal processing.

Portable medical devices is very popular among consumers, but also will bring the new problem, such as the signal noise [3]. Hardware filtering technique for processing ECG signal was proposed decades ago and it was applied widely in medical treatment. However, it has several disadvantages. Because all parameters must be set in advance, it has no capability for adjusting the filtering frequency along with changes of the external environment (noise becomes stronger or frequency changes). When roll-off characteristics of the filter are controlled loosely, it may result in distortion of the ECG signal and seriously affect the signal feature extraction point. With the advent of the modern signal processing theory and the progress of the computer performance, the software filtering technique become feasible. In addition, compared to the hardware filtering technique, it has many inherent advantages, such as low cost, high flexibility, high efficiency and high accuracy. So the digital filter is developing trend and the future in many fields.

Usually, the frequency spectrum of normal ECG signal range from 0.01 Hz to 100 Hz and 90% spectral energy of the signal focus on 0.25 Hz to 35 Hz. The noise of ECG signal frequency is mainly distributed in the two bands. One is the baseline drift which is generated by breathing and muscle motion and mainly in 0.05∼2 Hz. The other is a 50/60 Hz frequency interference generated by the utility grid. The baseline drift belongs to the low frequency signal. It is easy and disciplinary to express in mathematical functions, so some people expresses the discrete acquisition signal point baseline

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drift by mathematical function and difference between the measured value and the estimated value to achieve the goal of filtering out low frequency interference.

Poungponsri S had put forward using intelligent algorithm to filter out the baseline drift [4], [5]. The article has good filtering effect, but the neural network algorithm used in this paper has great uncertainty and a large amount of calculation. So it is not suitable for real-time monitor system of ECG. Kang W-S et al. studied the current hot of the signal processing-wavelet transform [6], [7]. They put forward discrete wavelet and wavelet reconstruction to filter out baseline drift, but the amount of calculation is also too large. For the 50/60 Hz power line interference, there are many methods. Mukher jee who used the adaptive feedback filter effectively filter out interference [8]. Wavelet transform is adopted to update threshold to filter out the power frequency interference [9]. This method can't only filter out noise but also have no damage to ECG signal. Finite impulse response (FIR) filters and Infinite impulse response (IIR) filters are also used to eliminate noise aof ECG signals. The FIR filter has the advantages of simple structure and no time-delay but with the large amount of calculation. IIR filter is a recursive from FIR filter, which can use smaller computation than it of FIR filter to achieve the same effect.

Traditional integer coefficients IIR digital filter is suitable for portable mobile platform. But ECG signal will have little distortion after processing by the integer coefficients IIR filter. So an improved integer IIR filter for portable mobile ECG monitors is presented in this paper. The proposed IIR filter can effectively eliminate baseline drift of main interference frequency band and 50/60 Hz power frequency interference in ECG signal.

II. EXPERIMENTAL SECTION

For acquisition of ECG signal, the interference sources of environmental noise can be classified into the following groups: power frequency interference, low-frequency baseline drift, muscles movement interference and contact interference caused by electrode impedance changes [10], [11].

(1) The power frequency interference

The power frequency interference is the largest interference source of ECG signal. Due to connection with the power grid, the 50 Hz AC couple with human body to generate the common-mode interference. Although the ECG acquisition circuit has some common-mode rejection ratio, it cannot completely eliminate the common-mode interference when the common-mode interference is strong. Therefore, a software filter for filtering out this interference is needed.

(2) The low-frequency baseline drifts

The measurement method of ECG signal is checking the bio-electric potential change of human body surface, so breathing shadow activity of changes makes ECG signal mix with low frequency interference signals. Low frequency interference sources will make ECG signal drifted, thus it's very disadvantageous to extract the ECG characteristic points.

(3) Muscles movement interference

Due to stress or other reasons, human body will make muscle shivering spontaneously. The frequency of this kind of interference sources ranges from 0 Hz to 10 KHz. Because of its short duration, the time of interference to ECG signal is short and it can be neglected.

(4) Contact interference

Due to the human body movement or other causes, impedance of electrodes may change; along with the pressure change of skin. The change will generate the contact interference, which is short time but high amplitude. This interference can be estimated by fixing the ECG electrodes or detection posture while monitoring the ECG signal.

Other interference usually mixed in ECG through mutual superposition or multiply mode. So ECG signal processing is mainly aimed at eliminating these two kinds of noises: one is power frequency interference, another is low frequency baseline drift. These two kinds of noises have caused great interference to the ECG signal.

A notch filter circuit can be designed to filter out the 50 Hz frequency. As we know, the filter characteristics of the hardware filter have been fixed when it's designed. Facing the complicated and changeable external environment, ECG signal might still have the above interference, so it should be processed again by software filter.

In contrast to the hardware filter, software filter has three congenital advantages:

Firstly, it will not reduce the Q point drift when the outside temperature changes, which can make the signal distortion. Secondly, software filter can change the filter by changing codes, so it has more flexibility than the hardware filter. Finally, it will not add hardware cost, whether in the mobile terminal or PC, the filter algorithm meeting requests of the computational complexity and real-time response can be found.

Next, this article analyzes the ECG signal through the analysis of ECG signal frequency distribution.

A. THE FREQUENCY DISTRIBUTION OF ECG SIGNAL

The discrete Fourier transform is a basic method in signal processing field. But because of the large amount of computation of discrete Fourier, the past computers cannot meet the computational requirements. In the 1960s, American scientists simplified discrete Fourier calculation process according to the symmetric matrix of the discrete Fourier transform, This is the FFT(fast Fourier transform) which is now often used in the signal processing [12].

We can set the sampling frequency, and then use the electrocardio-electrode to connect the specific of the body to obtain the ECG signal. In our system, the sampling frequency of ECG signal is 480 points per second. Figure 1a and figure 1c are the original ECG signal with power frequency interference and the original ECG signal with baseline drifts respectively in time domains. FFT is used to process the sampled data in time domain and they get the spectrogram as shown in figure 1b and figure 1d.

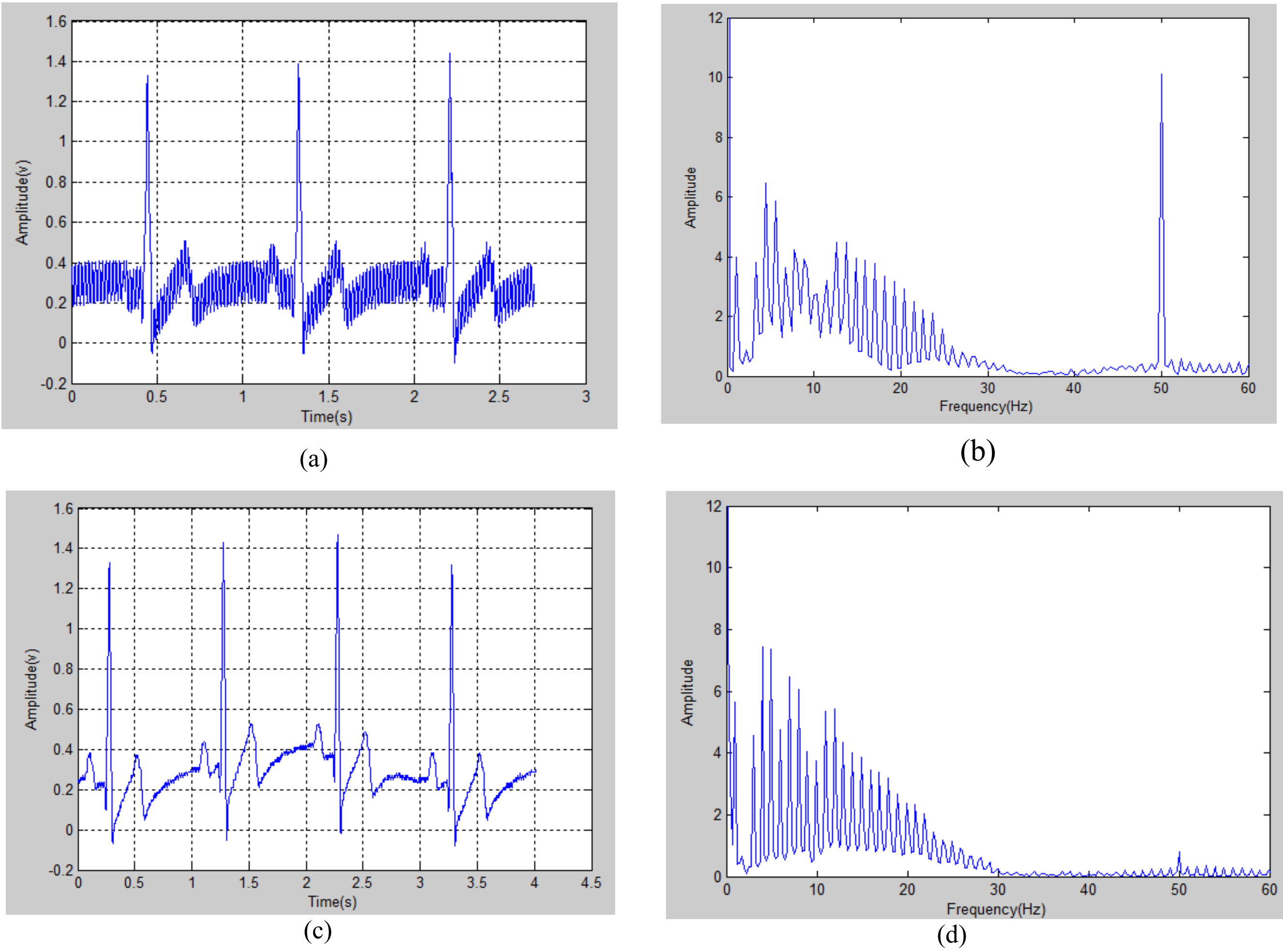

FIGURE 1. (a) ECG signal with power frequency interference in time domain; (b) ECG signal with power frequency interference spectrogram; (c) ECG signal with baseline drifts interference in time domain; (d) ECG signal with baseline drifts interference spectrogram.

If we analyze the time domain data, we can only get the relationship between signal amplitude and time t. While we can get the relationship between the signal frequency and amplitude from the data after FFT. Therefore, FFT has become the most commonly used algorithm in signal processing, then we can design the digital filter after get the signal frequency.

The ECG signal frequency distribution diagram of Fourier transform which can be seen the main information of ECG signal is below 100 Hz, and focused on the following 30 Hz already contains most of the information of ECG P wave, QRS complex, T wave. Through access to information [13], we can understand QRS are mainly distributed in 7∼27 Hz and 17 Hz is a centralized distribution frequency of QRS [14]–[16]. Other band of ECG, P wave and T wave have much lower frequency than QRS complex. From figure 1b, we can also clearly see a larger interference source at the 50 Hz ECG signal, it is by way of coupling cross-talk in 50 Hz frequency interference. And we can also see a larger interference at 0.3 Hz from figure 1d, which is the low frequency noise caused by respiratory and movement of human.

The interference frequency band has been determined, and then filters method need to be chosen. The main field of ECG filtering method with smoothing filter, wavelet transforms filter, IIR filter and FIR filter. In this paper, for the mobile terminal limited computing power into account, we take a small amount of calculation and high real-time IIR filter.

B. IIR DIGITAL FILTER

IIR filter is a recursive filter. Current output in its structure is not only related to the previous input but also related to the previous output. It is based on a simple linear filter. There are two kinds of design methods based on IIR filter: direct design method and indirect method. The direct design method is to construct IIR filters directly by constraining pole and zero distribution of the transfer function in the Z domain. The indirect method is based on the existing analog filter template to adjust each parameter of the filter according to the requirement. Then through the S domain transforming to Z domain, analog filter is mapped from the S domain to the Z domain through the Laplace transform. Thus, it becomes a digital filter which can process digital signal [17]–[19].

But the transfer function coefficients of indirect IIR filter are not integer type, it will cause a large amount of calculation. So it isn't suitable for the requirement of high real-time environment in portable ECG signal processing. In addition, its design method is simple and mature, indirect IIR filter will not be introduced in this paper.

At the end of 20th century, a filter design method has been put forward by restraining the zero and pole point placement [20], the filter can transfer function coefficients to integer variables. There is no floating-point operation in the filter so that the calculation is greatly reduced. It is the best choice for digital filter of this topic—portable mobile ECG monitor.

Next, direct IIR filter design method and its improvement will be introduced.

C. DESIGN PROCEDURE

According to the noise frequency which needs to be eliminated, the design method of integer coefficients digital filter is calculating for each position of the frequency in the Z domain of unit circle. Zeros are placed in these locations and poles are placed in where overlap with filtering frequency in the pass-band frequency points. So poles and zeros can be canceled out each other. It compresses the each signal frequency to the edge of unit circle in Z domain and every point at the edge represents the corresponding digital angular frequency. The result of multiplication of every point with multiple zeros distance is numerator. The result of multiplication of every point with multiple poles point distance is the denominator. The ratio of the above two is the current frequency shift coefficient in the transfer function. It is the structure of recursive filter as described above.

According to the spectrum analysis based on the current data collected by ECG acquisition board in Section 2.1, we can know the major influence of noise on the ECG signal are baseline drift caused by breathe, its frequency is 0∼1 Hz; the second most influencial noise is power line interference caused by 220 V, 50/60 Hz AC power grid. In order to eliminate the noise signal of the two frequency band, we must construct two filters. The low-pass filter filters out the 50 Hz frequency interference, the high-pass filter filters out baseline drift from 0 to 1 Hz.

1) DESIGN OF INTEGER COEFFICIENTS LOW PASS FILTER

Digital angular frequency in the Z domain [21]:

$$\Omega = \frac{1}{f_{ad}} {}^{*} f_s {}^{*} 2\pi n, \quad n = 0, 1, 2, \ldots \tag{1}$$

$f_{A/D}$ is the sampling frequency, f_S is the current frequency. The frequency fc = 50/60 Hz needs to be eliminated, when f_{ad} = 480, $\Omega c \approx n\pi/5$ ($n = 0, 1, 2, 3 \ldots, 9$). In order to eliminate the noise of the maximum amplitude of 50/60 Hz, we place n zero on $\Omega c \approx n\pi/5$ ($n = 0, 1, 2, 3 \ldots, 9$) in the unit circle of the Z plane. But there is another problem, the zeros which in 0 Hz and 50/60 Hz coincide at coordinate (1,0). In order to avoid the frequency overlapping, a pole and zero should be place at coordinate (1,0). They can offset each other by this method. At the same time in order to make the transfer functions stable and its molecules integer form, poles must be placed at the origin coordinate (0,0).

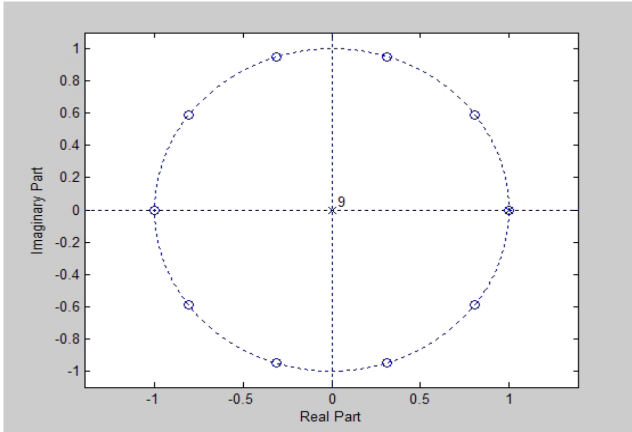

FIGURE 2. Zero and pole distribution map.

In the figure 2, the circle is zero, the fork is pole. 50 *Hz* is corresponding to the digital angular frequency n/5, so it uniformly distributes 10 zeros at $n\pi/5$, $n = 0, 1, 2, 3, \ldots, 9$ of the unit circle. The coordinate (1,0) is the location where the 0 *Hz* digital angular velocity locates and 0 *Hz* is the pass band frequency, So, in order not to remove 0 *Hz*, we placed poles and zeros to cancel each other out in coordinate (1,0). Finally, In order to guarantee the stability of the entire transfer function, we placed 9 poles inside the unit circle at the origin.

The transfer function can be written as:

$$H(j\Omega)\frac{(e^{j*0} - e^{j\Omega})(e^{\frac{1}{5}\pi j} - e^{j\Omega})(e^{\frac{2}{5}\pi j} - e^{j\Omega})\ldots(e^{\frac{9}{5}\pi j} - e^{j\Omega})}{(e^{j0} - e^{j\Omega})e^{9j\Omega}} = \frac{e^{10*j\Omega} - 1}{e^{10*j\Omega} - e^{9*j\Omega}} \tag{2}$$

Define $z = e^{j\Omega}$
Then

$$H(z) = \frac{z^{10} - 1}{z^{10} - z^{9}} = \frac{1 - z^{-10}}{1 - z^{-1}} = \frac{Y(N)}{X(N)} \tag{3}$$

In order to increase the roll-off characteristics of the low-pass filter, the order of filter should be increased, the formula (3) translates a two order low-pass digital filter and the transfer function is:

$$H(z) = \frac{(1 - z^{-10})^2}{(1 - z^{-1})^2} = \frac{1 - 2z^{-10} + z^{-20}}{1 - 2z^{-1} + z^{-2}} = \frac{Y[N]}{X[N]} \tag{4}$$

The amplitude-frequency response of low-pass filter as shown in the figure 3 below can be got according to the formula (4)

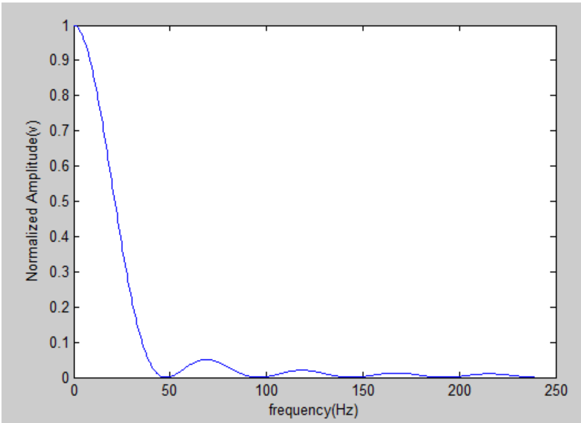

FIGURE 3. The amplitude-frequency response of low-pass filter.

2) TRANSFER FUNCTION DESIGN OF HIGH PASS FILTER

The frequency response of a multiple filter can be obtained by adding outputs of two linear phase filter with the same transmission delay. That is the algebraic sum of the filter response [22], [23]. A high-pass filter can be designed as an all-pass filter subtracting from a low-pass filter. All-pass filter is a constant coefficient of pure lag filter, it can be expressed as $Ha(z) = Az^{-m}$(A is amplification coefficient is the number of zeros).Under the ideal condition, $Ha(z)$, $H_{low}(z)$ have the same DC amplification coefficient.

We design a low-pass filter whose cut-off frequency is 2 Hz. What the frequency we need filter out is fc $= 2$ Hz. When the sampling frequency is $f_{ad} = 480$, the corresponding digital angular frequency $\Omega c \approx n\pi/120$ (n $= 0, 1, 2, 3 \ldots, 9$).

According to the design principle of the integer type filter:

$$H_{lp}(z) = \frac{Y(z)}{X(z)} = \frac{1 - z^{-240}}{1 - z^{-1}} \tag{5}$$

Subtracting low-pass filter from all-pass filter to design high-pass filter:

$$\begin{aligned} H_{hp}(z) &= \frac{P(z)}{X(z)} = z^{-120} - \frac{H_{lp}(z)}{240} \\ &= \frac{-1 + 240z^{-121} - 240z^{-120} + z^{-240}}{240 - 240z^{-1}} \end{aligned} \tag{6}$$

The amplitude-frequency response of high-pass filter as shown in the figure 4 below can be got according to the formula (6)

3) REALIZATION OF THE SHAPING FILTER

The design method of integer type filter transfer function, we design a transfer function of 50 Hz low-pass filter and 2 Hz high pass filter.

$$H_{hp}(z) = \frac{P(z)}{X(z)} = z^{-120} - \frac{H_{lp}(z)}{240} \tag{7}$$

Difference equation:

$$y(n) = 2^{*}y(n-1) - y(n-2) + x(n) - 2$$

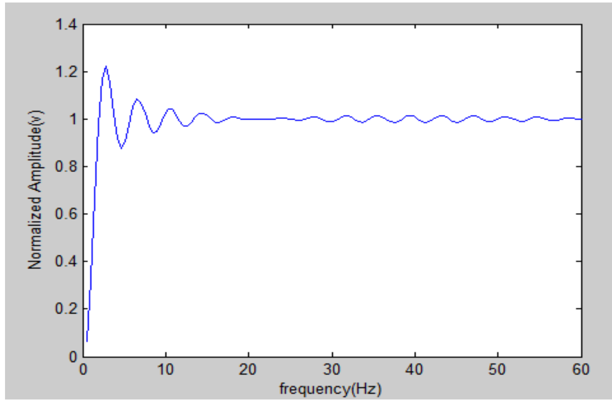

FIGURE 4. The amplitude-frequency response of high-pass filter.

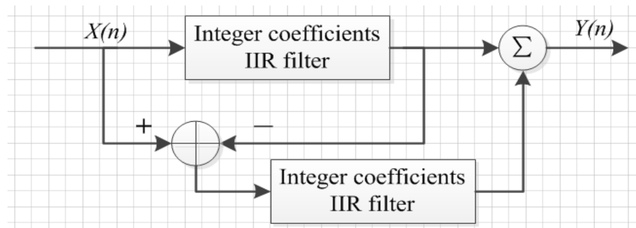

FIGURE 5. Improved integer coefficients IIR filter block diagram.

$$^{*}x(n-10) + x(n-20) \tag{8}$$

The transfer function of the high pass filter translate difference equation:

$$y(n) = y(n-120) - \frac{(y(n-1) + x(n) - y(n-240))}{240} \tag{9}$$

4) IMPROVED DESIGN

ECG signal will have little distortion after processing by the integer coefficients IIR filter, so an improved integer coefficients IIR coefficients filter is designed to get more complete ECG signal. Integer coefficients IIR filter will filter out some details. In order to keep more details, an improved integer coefficients IIR filter is proposed. Its structure designs as shown in the figure 5. In figure 5, each IIR filter module include a high-pass filter and a low-pass filter.

Firstly, ECG signal is processed by Integer coefficients IIR filter. Secondly, the original ECG signals subtract the processed signal can obtain difference signal. The difference is processed by Integer coefficients IIR filter to get compensation signal. The compensation signal eliminate the interference signal and keep the useful information. The final step is waveform reconstruction, the compensation signal adds to the signal after first filtering to get the final output signal.

III. RESULTS AND DISCUSSION

The improved integer coefficients IIR filter design method is introduced in Section 2. The following is the analysis result of the experiment.

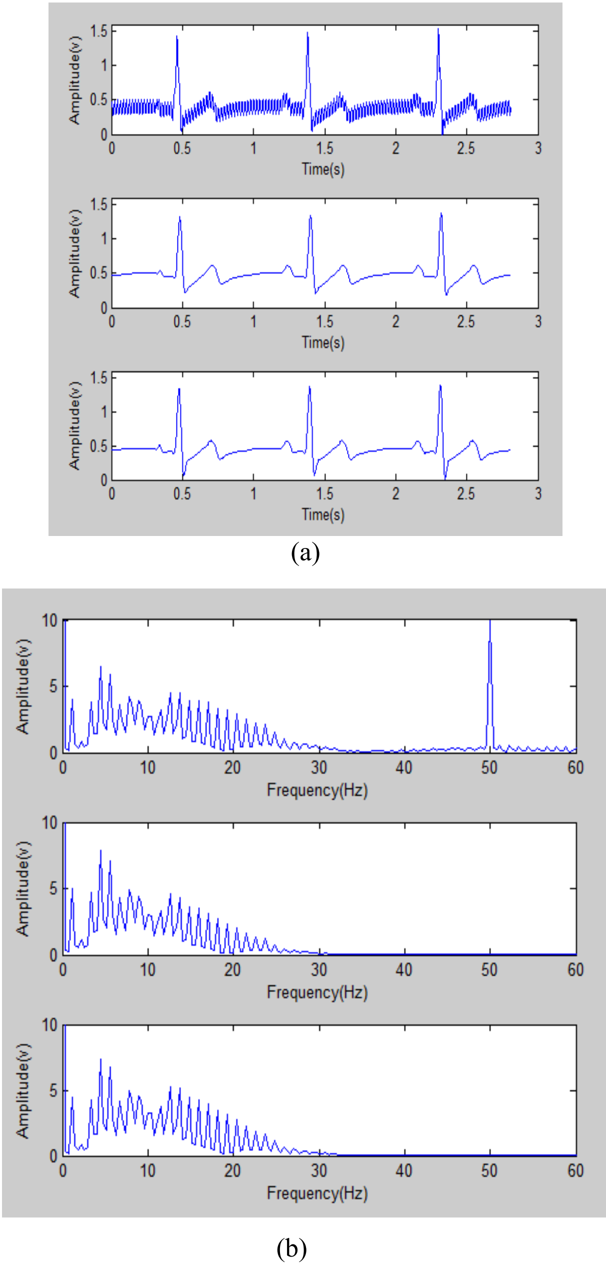

FIGURE 6. **(a) ECG signal with power frequency interference, output ECG signal of low-pass filter and improved integer coefficients IIR filter; (b) Spectrum of a section of original ECG signal, output of ECG signal after low-pass filter and improved integer coefficients IIR filter.**

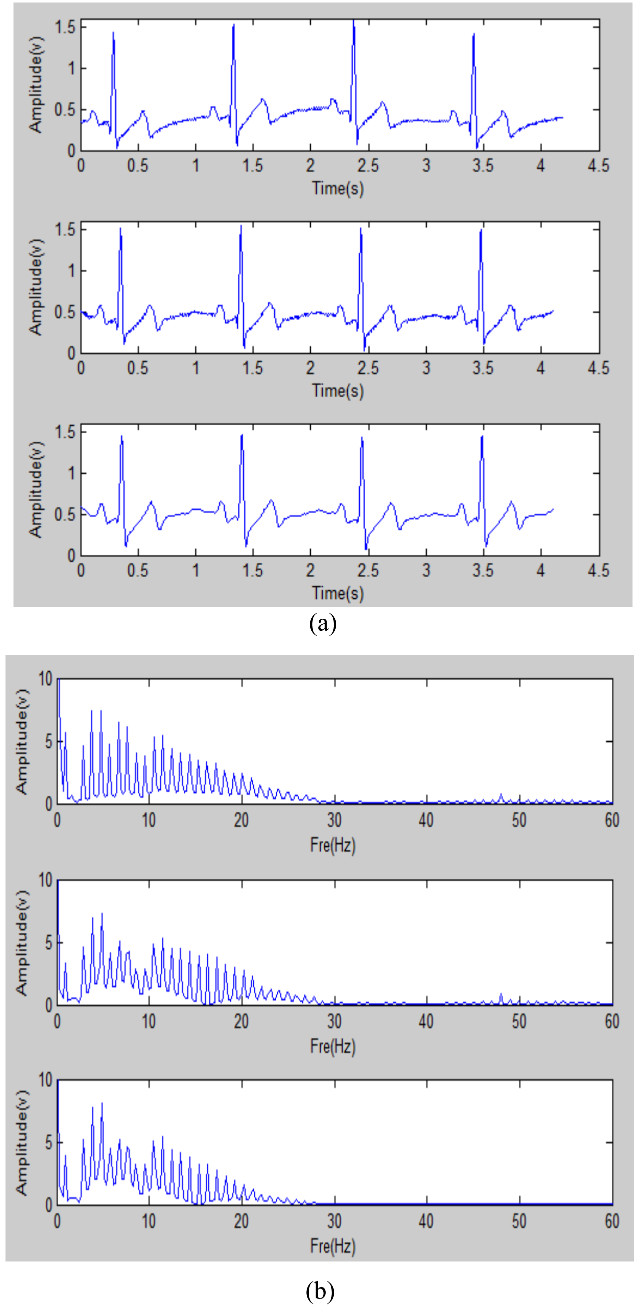

FIGURE 7. **(a) Original ECG signal with baseline drift, ECG signal after high-pass filtering and ECG signal after improved low-pass filtering; (b)Corresponding amplitude frequency response of the ECG signal filter before, after high-pass filter and after improved low-pass filter.**

A. DIRECT METHOD OF INTEGER COEFFICIENTS IIR FILTER AND IMPROVED INTEGER COEFFICIENTS IIR FILTER DESIGN RESULTS

The figure 6 is a comparison chart of IIR filter and improved IIR filter. Figure 6a is ECG signal with power frequency interference and output ECG signal of low-pass filter and figure 6b are spectrum of a section of original ECG signal and output of ECG signal after low-pass filter.

The first line of figure 6a/6b shows ECG original signal. The second line of figure 6a/6b shows the ECG signal after using IIR filter. The third line of figure 6a/6b shows the ECG signal after using improved IIR filter.

The designed low-pass filter can filter out the power frequency interference from the figure 6. But ECG signal lost little details. It can be seen by the contrast that the improved integer coefficients IIR filter keeps the details better and achieves better effect from figure 6b.

The results of processing are as below:

From figure 7, it can be found that baseline drift can be eliminated after high-pass filter and high frequency

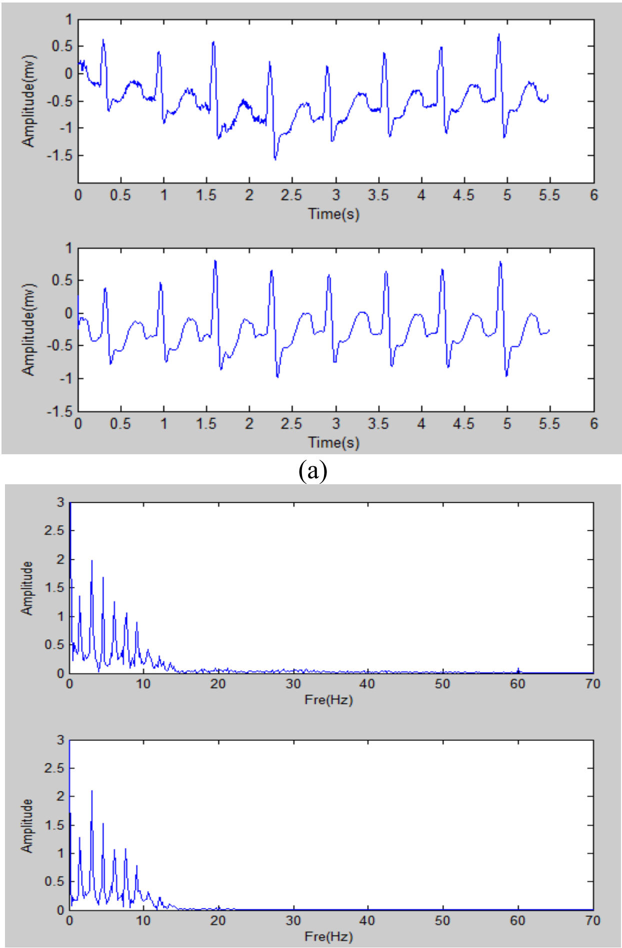

FIGURE 8. **(a) A part of data from MIT/BIH arrhythmia database and the data after filtering; (b) Spectrum of MIT/BIH ECG signal and the signal after filtering by improved integer coefficients IIR filter.**

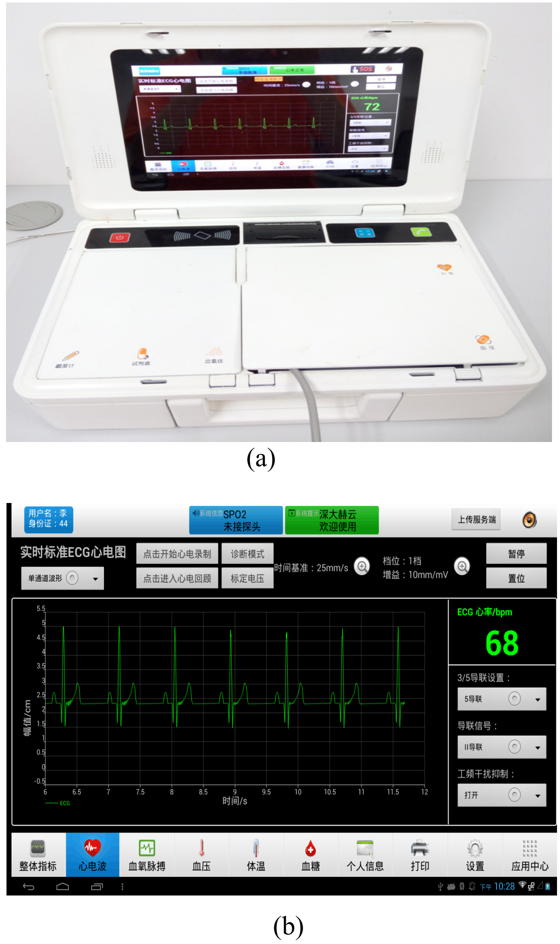

FIGURE 9. **(a)A portable mobile medical system using the proposed filter; (b) ECG display interface.**

interference signal can be eliminated after an improved low-pass filter. The first line of figure 7 shows original ECG signal. The second line of figure 7 shows the ECG signal after using the high-pass filter. The last line of figure 7 shows the ECG signal after using the improved low-pass filter. The final result has estimated the specific low frequency noise and specific high frequency noise by two different filter.

In figure 8, the test ECG data get from MIT/BIH, a standard arrhythmia database. It is used to verify the denoising performance of the proposed filter. The filter result is shown in figure 8. It can verify that the proposed filter can effectively eliminate baseline drift of main interference frequency band and 50/60 Hz power frequency interference in ECG signal.

B. HARDWARE IMPLEMENTATION

A portable multifunctional medical system using the proposed filter was designed as shown in Figure 9a. The portable medical system is multifunctional, which can process various physiological signal simultaneously, and also can update these data to could system for further diagnose [24]–[26]. Figure 9b is the real-time ECG. The illustrated electrocardiography is very clear and the filtering effect is satisfactory for the portable application.

IV. CONCLUSION

With the progress of the development of computer and electronic technology, the research on detection and diagnosis of ECG signal is more mature and effective. Based on the development of the predecessors experience to perfect the ECG monitoring system, the collection from the ECG signal to the processing analysis in the diagnosis of a series of hardware and software development is realized. Innovations mainly focus on the adaptive feedback filtering algorithm and the QRS feature point extraction dynamic threshold value method.

ECG signal pre-processing: the low-pass filter and the high-pass filter designed by improved integer IIR filter can not only eliminate the power frequency interference but also the baseline drift. The integer coefficients IIR filter can get very good filtering characteristics and it can be used in the portable mobile medical system designed to eliminate interference signal.

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