An Ultra-low Power Holter and Low Complexity Design Using Mixed Signal Processor

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Abstract. An ultra-low power, portable, and easily implemented Holter recorder is necessary for patients or researchers of electrocardiogram (ECG). Such a Holter recorder with off-the-shelf components is realized with mixed signal processor (MSP) in this paper. To decrease the complexity of analog circuits and the interference of 60 Hz noise from power line, we use the MSP to implement a finite impulse response (FIR) filter which is equiripple design. We also integrate the ring buffer for the input samples and the symmetrical characteristic of the FIR filter for efficiently computing convolution. The experimental results show that the ECG output signal with the PQRST feature is easy to be distinguished. This ECG signal is recorded for 24 hours using a SD card. Furthermore, the ECG signal is transmitted with a smartphone via Bluetooth to decrease the burden of the Holter recorder. As a result, this paper uses the Lomb method for the spectral analysis of Heart Rate Variability (HRV) better than Fast Fourier Transform (FFT).

Introduction

"Holter ECG recorder" is invented by American physical doctor Holter in 1961 [1], such a non-invasive, practical, precise and repeatable method is manipulated comprehensively in the clinic of heart diagnosis. Patients can bring Holter to record the 24h ECG at home whenever sleeping, walking, and eating. Thus, the Holter recorders require portability, low power, sufficient capacity for storing the ECG data, and capability of communication. There are some developed Holter recorders: Segura-Jucire [2] develops a micro-controller based Holter recorder which is low power, portable and only uses standard components. Kong [3] implements a real-time ECG web broadcast system which allows physicians to monitor patients at home. These papers present complete ECG systems, but both of them omit the 60Hz noise from the power line. The 60Hz noise plays an important part which has a considerable influence on the quality of the ECG signal. Therefore, Holter recorders must have a filter to reduce the level of interference for detecting the feature. Since the advance of computer technology, the digital filter can be implemented on the ASIC, DSP or microcontroller. Williams [4] designs an ASIC with digital linear phase ECG filter which uses a novel recursive multiplierless architecture. Meissimilly [5] uses a microcontroller to apply the real-time QRS detector, only uses bit-shifting and add-subtract instructions instead of floating-point multiplication. Therefore, digital filters have already been used to cancel the noise for ECG recorders during the two decade years. A digital filter is either IIR or FIR filter. An IIR filter has far fewer operations and samples than does FIR filter to produce the levels of specified attenuation, but the nonlinear characteristic with IIR filter will cause the ECG signal to be destroyed. It maybe let physicians make a wrong diagnosis. Bai [6] compares three kinds of the FIR filter design for suppressing the embedded 60Hz noise. According to their simulations, using equiripple design is the best choice. We select MSP to implement a FIR filter. A SD card [10] is very suitable to implement and apply for a Holter recorder, since its communication bases on an advance nine-pin interface and its design is operated in a low voltage. A Bluetooth [11] module is used to transmit ECG signal wirelessly to avoid adding the large components such as a LCD and a keyboard.

Methodology

A block diagram is depicted with ECG signal-flow shown in Fig. 1. The methodology describes all the components and the methods to produce a Holter recorder. The sections of the FIR filter and processor are the key to reduce the complexity of the Holter recorder. The benefits of using SD card, Bluetooth, and terminal will be described.
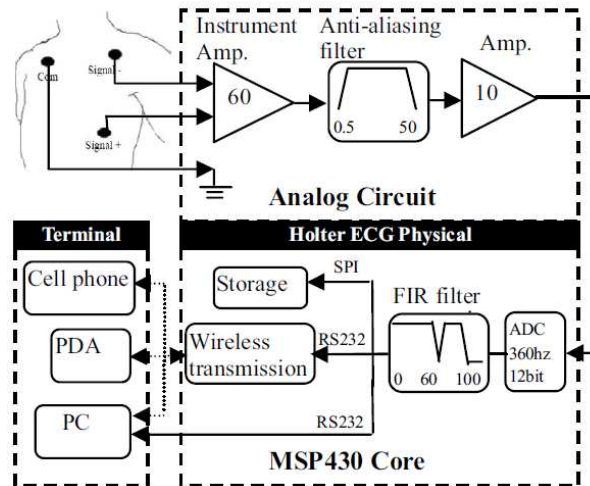

Fig. 1 Signal-flow graph representation of this Holter System.

Analog Circuit. The analog circuits in this paper major have two parts: an instrument amplifier and a band pass filter (BPF). We use an AD620 [9] to amplify the extremely weak ECG signal from electrodes, because the AD620 is easily obtained and easily utilized. The BPF is integrated with a high pass filter (HPF) and anti-aliasing filter. The HPF is designed to avoid the DC power of ECG signals exceeding the 0 ~ 3.3 limit. The anti-aliasing filter is designed to satisfy Naquist sampling theory. A valid bandwidth for signal with 360 Hz sampling is 180 Hz. Thus, we have to cut down the signal over 180 Hz as less as possible for the accuracy of a FIR filter. In this paper, a MSP is adopted to realize the major filters such as a band pass filter and a notch filter in conventional Holter recorders to avoid the complex analog circuits.

FIR Filter. The ECG signal bandwidth specified by American Heart Association specifications is 0.5Hz-100Hz, and the additive noise during caught ECG is 60Hz.Bai [6] shows that the best design method of FIR filter for ECG signal is the equiripple design. Accordingly, we apply this FIR filter for the Holter recorder. In the digital field, the filter must to be implemented by linear convolution defined as Eq. (1).

$$y[n] = \sum_{k=0}^{N-1} h[k]x[n-k] \tag{1}$$

In this paper, the number of coefficient-N is 63 taps which are estimated by well-known Parks-McClellan algorithm, the sampling frequency and the resolution of the x[n] is 360 Hz and 12 bits respectively, the h[n] is the impulse response of the system and y[n] is the filtered ECG signal. Eq. (1) maybe implement on the DSP platform in real-time. But this paper uses the MSP which is slower than DSP. Thereby, we use a ring buffer instead of a shifted operation at memory and utilize the symmetrical characteristic of this FIR filter to reduce the number of coefficients: Symmetrical characteristic of FIR filter: We adopt the equiripple design for FIR filter whose coefficients have the symmetrical characteristic:

$$h[N-1-k] = h[k] \quad 0 \le k < N \tag{2}$$

This symmetrical characteristic can be used to reduce the MAC computation load. Ring Buffer: The time index "n" in Eq. (1) cannot be increased infinitely, because the memory for input samples is finite. We use the simply implemented and easily understood data structure for input data:

$$x[\text{mod}(n, N)] = x[n] \quad 0 \le n < \infty \tag{3}$$

The mod(n, N) means the remainder of n/N.

The placed order as a circle for input samples is called a ring buffer or a circular queue. This method does not need the mass of shifted operation for the memory when performs the convolution. When merges the ring buffer and the symmetrical characteristic to implement a convolution, the program is more complex than using Eq. (1), but a batter efficiency can be obtained. We use pseudo code to describe the algorithm as shown in Fig. 2.

```
Global variable: 1) sample, 2) n, 3) N
Procedure Convolution
        k = 0
        y = 0
        x[n] = sample (from A/D converter)
        p = q = n
        Do iterative, until k = floor (N/2)
                p = p + 1
                If p = N
                        p = 0
                End If
                y[n] = y[n] + h[k] × (x[q] + x[p])
                k = k + 1
                q = q - 1
                If q < 0
                        q = N-1
                End If
        End Do
        If N is Odd
                y[n] = y[n] + h[k] × x[n-k]
        End If
        n = n + 1
        If n = N
                n = 0
        End If
End procedure
```

Fig. 2 Convolution pseudo code

The method only uses the half number of the MAC instructions to complete convolution for every input with non-shifted operation. Consequently, the clear ECG signal which filtered in real-time is achieved. For the experimental result with the MSP430, the consuming time of computing convolution is 109 μs which is far fewer than sampling interval (2.7 ms) in this paper. Therefore, the operation of the FIR filter with 63 taps can be finished before the next acquiring sample from the ADC using the MSP430.

Processor. The advanced MSP is the MSP430 [8] which is an ultra-low-power 16-bit RISC MSP from Texas Instruments, it provides the ultimate solution for battery-powered and portable measurement applications. A MSP430 can calculate a FIR filter efficiently since the hardware multiplier in a MSP430 can perform the MAC operation in fewer clocks than a conventional MCU. Furthermore, the cost is cheaper than a DSP. Hence the MSP430 has capability to process low frequency signal such as ECG. The control system and the signal processing for ECG signal can be co-designed with a MSP so that the complexity of the Holter recorder is reduced. Meanwhile, the low powered and portable features are satisfied. In this paper, we use embedded peripherals in the MSP430 for the Holter recorder as following: (1) the raw ECG is acquired from 12bits ADC; (2) a FIR filter is implemented with 16bit MAC unit; (3) a Bluetooth module is controlled by a RS232 interface; (4) the ECG signal is saved into a SD card via SPI interface, and (5) the low power consumption is achieved by selecting five power saving modes. This shows that a Holter recorder can be implemented by using the integrated components in MSP430. For these reasons, the MSP430 is very suitable to implement a Holter recorder.

Wireless transmission. In the past, the conventional heart diagnosis using Holter recorders needs back to the hospital and waits for the reports with doctors. But now, the ECG can be accessed from the internet in real-time [3], so that patients can wait for the reports of ECG diagnosis at home. A smartphone with the Bluetooth function is more and more popular now. The data transmission between the smartphone and our Holter recorder is achieved by using Bluetooth module. The

physician at a hospital can monitor the ECG from patient at home via GPRS with the smartphone. Since the Bluetooth protocol is really complex, we adopt the instantly usable Bluetooth module which is controlled easily by MSP430 with build-in RS232 interface.

Terminal. A smartphone as a terminal can improve the situation which needs large components for special functions in Holter recorders. We control the Holter recorder via Bluetooth by programming the J2ME [12], because the smartphone has many application program interface (APIs), such as user interface, Bluetooth transmission, data storage and GPRS. Therefore, using a powerful smartphone can provide what any software features you want for Holter recorders without adding a keyboard and a LCD.

When we emulate the FIR filter on PC, the ECG signal from the prototype via RS232 is no filtered by MSP430. This software can select specifications of FIR filter like 50 Hz low pass, 100 Hz low pass, 0.5 Hz high pass, or 60 Hz notch filter. Therefore, the digital filter for ECG can be implemented fast by software on PC, but burns the MSP430 when the filter is tuned. If the FIR filter coefficients are decided and implemented on PC, the filter can be done by using MSP430 as well. The filtered ECG signal from our Holter recorder is shown in Fig. 3.

Fig. 3 The filtered ECG signals display in real time on PC.

Heart Rate Variability Analysis

Heart Rate Variability (HRV) is an important tool of heart diagnosis. We can observe the balance of autonomic nervous system (ANS) rely on a subtle variation of heart rate. The sympathetic nervous system (SNS) is one of the three parts of the autonomic nervous system, along with the Enteric Nervous System (ENS) and parasympathetic nervous system (PSNS). SNS is to speed up the heartbeat, and PSNS is to slow down the heartbeat. Due they cooperate such that the heartbeat could keep steady. There are a lot of papers discuss about HRV analysis [13][20] etc. HRV analyzing is on Time domain or frequency domain. By using Power Spectral Density (PSD), frequency domain method divide heart rate variability's frequency domain into three regions: High Frequency (HF): 0.15 ~ 0.4 Hz, Low Frequency (LF): 0.05 ~ 0.15 Hz, and under the Very Low Frequency (VLF): 0.05 Hz. In recent years, the scholars find that a normal person's age is related to ANS in certain degree. We can also observe the active degree of ANS by HRV. Therefore William [17] proposed to analyze frequency domain of HRV for measuring physiological age of ANS. The major analyze of HRV's time domain is that records each RR interval time and then become a RR sequence. PSD is which the RR sequence uses by Fourier Transform for getting energy distribution on frequency domain. The frequency scale of PSD calculates by sampling frequency. Suppose a digital signal's sampling frequency is 8K, 1024 points, the biggest frequency can analyze to 4K after FT. That is the half of sampling frequency. If we want to analyze each point on the discrete frequency spectrum, let the sampling frequency divided by FT point number 8K / 1024 = 7.8125 Hz, that means the each value is 7.8125 Hz gap.

The interval of heartbeat, each sample interval of RR sequence, and sample frequency are not fixed. Taking RR sequence by FT directly, so PSD's result is not correct and result analysis is also not correct. Therefore, before doing FT to RR sequence, we need take interpolation and resample action.

These processes will affect the distribution of HF [19]. In contrast with FT, the Lomb method [18] of this system eliminates interpolation and resample processes. It can make RR sequence transform to Frequency spectrum directly, and reduces the processer's loading efficiently.

Lomb method. In the past 20 years, there are many researches [16]-[18] which have used for HRV frequency analysis concerning the Lomb periodogram. In the beginning, Lomb [14] proposed a transformation base on frequency spectrum, it can find out weak periodic signal in the signal x(i) which sampling interval is not the same. The method is the signal x(i) projected onto a basis function $b_i(t)$ then obtains c, using c could let the convert $c*b_i(t)$ integral value and x(i) average of MSE reaches to minimum. The Lomb-Scargle method make the unfixed interval sample perform Fourier transform $b_i(t)=e^{j2\pi f_i t}$, the transformed result and actual frequency spectrum difference reach to minimum, and no symptom of frequency aliasing and leakage [19]. The Lomb transformation was defined as eq. (4):

$$c\ (i)\ = \int_{-\infty}^{\infty} x(t)\ b_i(t)dt \tag{4}$$

Where, c(i) is a coefficient from an original signal x(t) through orthogonal basis $b_i(t)$ transforms, and it make the $e(c_i)$ of the eq. (5) reach to minimum:

$$e(c_i)\ = \int_{-\infty}^{\infty} (x(t)-c(i)b_i(t))^2\, dt \tag{5}$$

In the discrete domain, signal samples by a fixed time d(t-nT). If the T duration is inconsistent, it can obtain a frequency spectrum by using the Lomb-Scargle method directly, and this frequency spectrum approaches the actual one very much. The past method was used interpolation and resample first to solve, but this method would destroy the frequency spectrum [15]. In order solve this problem; Lomb method has brought up a derivative eq. (6):

$$x(t_n)\varepsilon_n = \alpha \cos(2\pi f_i t_n) + \beta \sin(2\pi f_i t_n) \tag{6}$$

Both the time complexity of Lomb method and FFT are $O(n\log n)$. The variation of heart rate causes inaccuracy of sampling time. Therefore, after interpolation method and resampling, then it executes FFT. This not only caused spectrum distortion, but also increasing the transform time. As a result, this paper uses the Lomb method for the spectral analysis of HRV, and this method is implemented in this system.
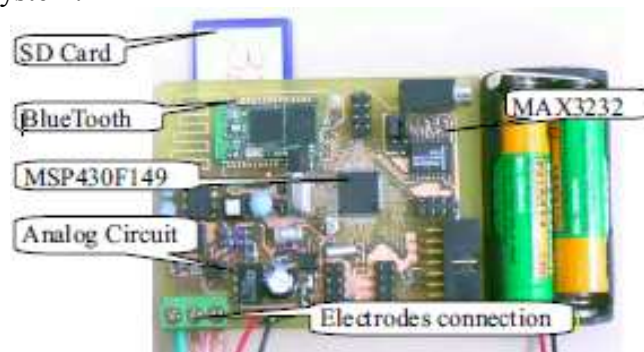

Fig. 4 Holter system prototype

Conclusion

In this paper, we realize a Holter recorder of low complexity using a MSP. We use the MSP430 to implement a FIR filter which can replace the most analog circuits. So that the analog circuits only have a BPF and an amplifier for the preprocessing of ECG signals. An efficient MAC in a MSP430 is used to perform the convolution which is faster than the conventional MCU. We utilize the ring buffer for the input samples and the symmetrical characteristic of FIR filter for reducing the number of coefficients to perform the convolution. As experimental result in Fig. 3, the processed ECG signal is clear. Then the ECG signal is saved in the SD Card, transmitted wirelessly through Bluetooth or transmitted fixedly via RS232. To avoid a keyboard and a LCD consisting in the Holter recorder, we use the smartphone with Bluetooth as a terminal to minimize the volume of the Holter recorder.

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