A Holter of Low Complexity Design Using Mixed Signal Processor

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Abstract

A 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 60Hz noise from power line, we use the MSP to implement a finite impulse response (FIR) filter which is equiripple design. We also integrate the ringed buffer for the input samples and the symmetrical characteristic of the FIR filter for efficiently computing convolution. The experimental results show that the output ECG signal with the PQRST feature is easy to be distinguished. This ECG signal is recorded for 24hr using a SD card. Furthermore, the ECG signal is transmitted with a smartphone via Bluetooth to decrease the burden of the Holter recorder.

1. 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.

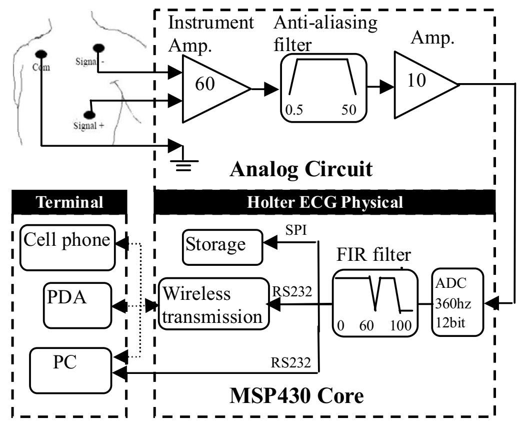

Figure 1. Signal-flow graph representation of this Holter System.

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.

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2. Methodology

A block diagram is depicted with ECG signal-flow shown in figure 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.

2.2. 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 an anti-aliasing filter. The HPF is designed to avoid the DC power of ECG signals exceeding the 0~3.3V limit. The anti-aliasing filter is designed to satisfy Naquist sampling theory. A valid bandwidth for signal with 360Hz sampling is 180Hz. Thus, we have to cut down the signal over 180Hz 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.

2.3. 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. Thus, the specification for the filter is show in Table 1.

Sampling frequency	360Hz
Stopband	60Hz 110-180Hz
Passband	0-50Hz 71-100Hz
Passband ripple	0.5dB
Stopband attenuation	30dB

Table 1. Filter Spec.

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).

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

In this paper, the number of coefficients—N is 63 taps which are estimated by well known Parks-McClellan algorithm, the sampling frequency and the resolution of the x[n] is 360Hz and 12bits 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 mixed signal processor (MSP) which is slower than DSP. Thereby, we use a ringed 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:

$$h[N-1-k] = h[k] \qquad 0 \le k < N \quad (2)$$

This symmetrical characteristic can be used to reduce the MAC computation load.

Ringed 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:

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

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

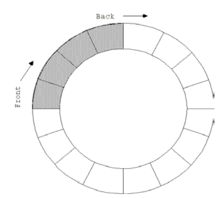

Figure 2. Ringed buffer

The placed order as a circle for input samples is called a ringed 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 ringed buffer and the symmetrical characteristic to implement a convolution, the program is more complex then using Eq.(1), but a batter efficiency can be obtained. We use pseudo code to describe the algorithm as shown in figure 3.

```
Globol 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
```

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        y[n] = y[n] + h[k] ×x[n-k]
    End If
    n = n + 1
    If n = N
        n = 0
    End If
End procedure
```

Figure 3. 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 109us which is far fewer than sampling interval (2.7ms) 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.

2.4. Processor

The advised mixed signal processor (MSP) is the MSP430[8] which is a 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.
(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.

2.5. Storage

Holter recorders must have a storage media to record ECG signals from the body of patients within 24hr. Therefore, there are two kinds of digital storage cards to be used in the previous papers : the SmartMedia card is used by Segura-Jucire[2] and the CF card is advised by Kong[3]. However, we will utilize the SD card to storage ECG signals.

SD Cards can be controlled with SPI mode which is a serial communication. The all operations for a SD card can be finished by manipulating three control lines: Serial Out (SO), Serial In (SI), and Clock (CLK) as shown in Figure 4. The SPI communication can be implemented with embedded peripheral in the MSP430. Thus, storing the ECG signal in the Holter recorder with a SD Cards is simpler than with a CF card. The storage size is about 64M for recoding in 24h without compression in this paper.

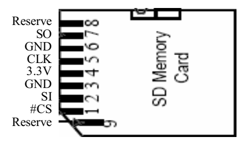

Figure 4. Schematic diagram of the memory card
In this Holter recorder, a SD Card is used.

2.6. 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.

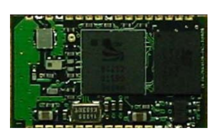

Figure 5. Bluetooth module with top view

2.7. Terminal

The Holter recorder equips with a keyboard and a LCD to be controlled and display the ECG information of a patient respectively in Segura-Jucire[2]. However, no meter a keyboard or a LCD is very large, so that it is hard to carry. Moreover, these components are useless for patient who is recording ECG. 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 do you want for Holter recorders without adding a keyboard and a LCD. The filtered ECG signal is displayed on the smartphone in real time as shown in figure 6.

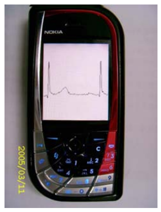

Figure 6. The filtered ECG signals display with smartphone in real time.

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 50Hz low pass, 100Hz low pass, 0.5 Hz high pass, or 60Hz 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 figure 7.

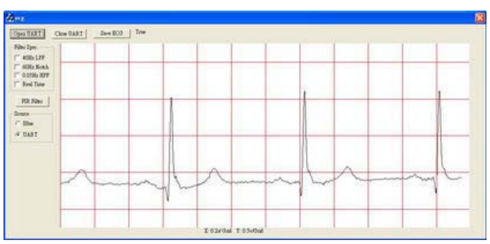

Figure 7. The filtered ECG signals display in real time on PC.

3. 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 ringed 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 figure 7, 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.

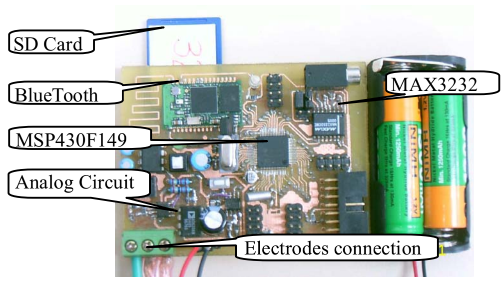

Figure 8. Holter system prototype

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