A 10-Lead Long Duration Ambulatory ECG Design

-Minimizing power consumption-

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ABSTRACT

The ECG(Electrocardiograph) ambulatory test as called Holter is performed usually to diagnose several heart diseases causing different arrhythmias. This paper exposes the insights of the design of a 10-lead ambulatory ECG recorder. Reducing the size and minimizing the power consumption of the ECG recorder are crucial to allow long recording time without causing discomfort to the patient. This paper proposes lower hardware design and differential compression algorithm to extend the maximum 72 hours recording time in consideration of smaller and light-weighted recorder size. The performance results by newly introduced compression algorithm are shown and discussed.

Keywords : *Ambulatory ECG, Holter, Long term ECG recording, 3 axis accelerometer*

Ⅰ. Introduction

Despite of the heart diagnosis advances, heart rhythm disorders remain a major cause of mortality and morbidity in United States and in other parts of the world. Sudden cardiac death(SCD) continues to claim more than 250,000 ∼400,000 U.S. lives annually[1],[2] accounting for 15∼20 percent of all deaths[3][4].

The early diagnostic for heart disease is essential to reduce the mortality caused by heart diseases. The ambulatory test known as Holter is a very common noninvasive test widely used to diagnose cardiac diseases mainly related with sporadic rhythm alterations. The patient ECG signal is recorded[5] during normal day activity and to be evaluated and validated by a cardiologist, and then recorded patient data is transferred to PC via USB or SD card memory automatically analyzed on PC based computer algorithm. This is an ambulatory test which is usually carried out for 24 hours or more.

Design technology for power solution, small size and light weight has mainly been focused on hardware study by using lower power electronic components. To help better heart diagnosis for some patients, 48 or 72 hours recording time is recommended. Since the ambulatory recorder must have ECG signal powered by small batteries for long term, it is very important to consider the minimum power consumption. This article focuses in all the precautions and techniques applied during the ambulatory recorder design to achieve the lower possible energy consumption and smaller size.

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Ⅱ. Electronic components selection

The ambulatory ECG recorders besides comply with the safety and ECG monitoring standards need to include a minimum of features required by the state of the art technology. The following summary shows some of the more common features of an ambulatory recorder nowadays.

- Record 72 hours of 3 ECG channels(7-lead patient cable)
- Record 24 hours of 12 ECG channels (10-lead patient cable)
- Pacemaker detection
- LCD to configure and signal display
- Fast data download to PC
- Accessible event hot key by the patient
- Size is usually less of 10×6×2 cm
- Storage in Compact Flash, SD or Micro SD card
- USB connectivity
- Powered by 1×AAA to 2×AA batteries
- Built-in real-time clock

To comply with above features, the electronics components are used in the recorder hardware design. To acquire and digitalize 8-lead of ECG simultaneously, the integrated analogue front-end ADS1298[6] from Texas Instruments which offers better solution issued by power consumption and small size was applied. Before making the final decision, the ADAS1000-1 and ADAS 1000-3[7] chips from Analog Devices were also evaluated but to get 8-lead ECG data, it was necessary to use the two chips and this will need additional PCB space which is critical in this required design.

The Micro SD card are widely used in mobile phones and many of IT devices are the cost effective storage media. Its size is adequate for the ambulatory recorder and its power consumption is acceptable for this application.

Since the Micro SD card power consumption is not particularly low, especially during writing process, special care must be taken during this operation. The standby power consumption of a Micro SD card can be as low as 0.2mA[8], so it is preferable to stay in this mode as long as possible. To minimize the power consumption caused by the writing operation in the Micro SD card, the following applications and algorithms are performed:

- Use the low power mode of CPU.
- Lossless real-time compression of the ECG signal.
- Buffering the compressed data.
- Write the buffered data as fast as possible and go back to low power consumption mode.

The data saving on Micro SD card can be accessed through an SPI port but the data rate is lower compared to the access using the SD bus with 4 data bits while using the same clock speed. So the decision of the CPU to use was marked by the following parameters:

- Low power consumption during active.
- Flexible low power modes.
- SDHC controller supporting SD bus with 4 data bits.
- SPI port to handle the ADS1298.
- Enough I/O lines to handle a parallel LCD.
- 1 PWM to control the backlight brightness.

One of the most energy savers MCU families is the MSP430 from Texas Instruments which is a 16-bit MCU specialized for low power consumption systems typically using 195uA/MHz in active state[9]. Unfortunately there are no variant of this family including SDHC controller.

The Kinetis Family from Freescale offers several processors with this SD bus controller with 4 data bits [10]. These are 32bits ARM Cortex M4 processor with a very flexible scheme of 10 different low power modes. It can be used with Processor Expert software to speed up the firmware development by using its components and module drivers.

The ARM Cortex M4 processor includes real-time clock which will be used to keep the date and time even if the unit will be off. A tri-axis accelerometer is included to allow patient activities studies in correlation with the acquired ECG signal.

Ⅲ. The compression algorithm

The Analogue Front-End(AFE) ADS1298 features 24 bits ADC samples[6]. The Table 1 shows the approximate file size of ECG signal on Micro SD card based on different configuration of the recorder if no compression or packing where applied.

Table 1. ECG file size without compression

Channels	Sampling frequency	Recording time	Filter size
3	500Hz	24hours	~495MB
3	1000Hz	24hours	~989MB
12	500Hz	24hours	~1.318GB
12	1000Hz	24hours	~2.636GB

Notice that the file size changes according to the number of leads and the sampling frequency. To acquire 12-Ch ECG, standard 8-lead ECG signal will be captured and then the remaining of 4-lead ECG will be derived and computed by Einthoven' s theory.

These file size of ECG signal will have a negative impact in the download time to PC before the record analysis. If the ECG signal where will be compressed and packed, the file size will be smaller, and so will be reduced the amount of write cycles of the Micro SD card. This means that less power consumption will be resulted and the recording time will be increased.

The ADS1298 works as a DC coupled amplifier without high pass filter. Its gain range is relatively small compared to high-pass filtered ECG amplifiers. It is necessary to comply with the ±300mV of DC offset that may be presented in the electrodes according to the IEC 60601-47[11] standard requirement. DC offset voltage will relatively be very high level compared with original ECG signal only. So it will normally be filtered out by high pass filter, 0.05Hz[10] before ECG signal processing. The digitized 24-bit ADC data which is combined with the original ECG signal and DC offset will be derived with bigger numbers of bits even if high resolution 24-bit ADC has the strong point which should not be necessary to apply such high pass filter which may be caused to signal distortion. This will be caused to require high memory space and delaying processing time. To eliminate the drift ECG signal, high pass filter will be applied on the PC analysis.

On the other hand, the typical signal morphology of ECG suggests that for an average cardiac frequency the signal remains most of the time in base line. If the differentiated data between the current and previous sampled data is packed and stored instead of the original digitized raw data, the number of bits to store will be smaller and so will be resulted to reduce the file size.

By storing the differentiated ECG, the bits are used so as to absorb the possible offset introduced by the electrodes contact with the skin will also be removed.

The Figure 1 shows an original ECG signal, the differentiated signal and the reconstructed ECG signal after decompression.

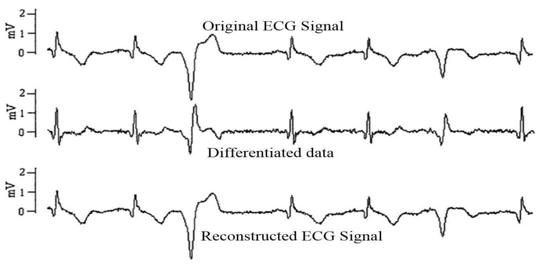

Fig. 1. Original ECG, Differentiated data and Reconstructed ECG Signal

Notice how the amplitude of differentiated signal is smaller than the original ECG signal. The decompressed data is exact to the original one since this algorithm does not introduce any loss during compression.

The Figure 2 shows a block diagram of the designed ambulatory recorder.

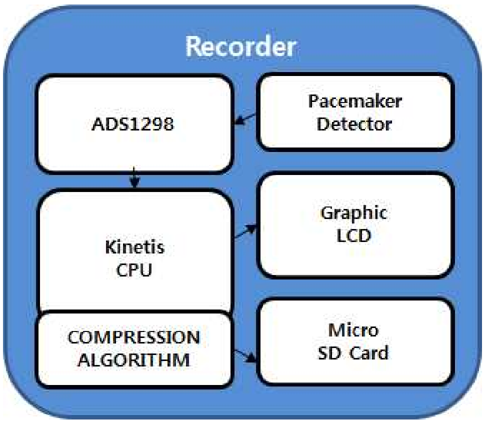

Fig. 2. Ambulatory recorder block diagram

This compression algorithm is fairly simple and it can be implemented with few computational resources. The timing for the acquisition is directly controller by the ADS1298 which wakes up the CPU from sleep when there is a sample ready to read and compress. The CPU is also responsible for controlling the LCD and access the Micro SD card using FAT32 file system to store the compressed data.

The ambulatory recorder has the ability to record 8 leads of 3 leads only. In the case of the 3 leads configuration, the unused channels of the ADS1298 are power off to reduce power consumption. This helps to extend the recording time when only 3 leads are recorded.

Ⅳ. Data file structure

The differentiated data is stored as the file data. In order to take advantage from this signal morphology, it is needed a file structure that allows to use a variable sample size in bits. While compressing the corresponding part to the QRS complex(bigger amplitude), more numbers of bit will be resulted per sample.

The differentiated data is stored in frames. Each frame will have a header in which will be information of the amount of bits used per samples. The amount of bits will changed from frame to frame according to the needs. Each frame will be store a maximum of 75 samples. Along with every sample there is 1-bit to assign the pacemaker spike information. The electrodes status such as encoded off is encoded in the frame header.

The Figure 3 shows the frame structure. It also holds the accelerometer information if it will be enabled at the beginning of the test. The patient even mark is encoded in the frame structure since so it could have in the worst case 0.3sec of delay but this delay is acceptable for the purpose of this information.

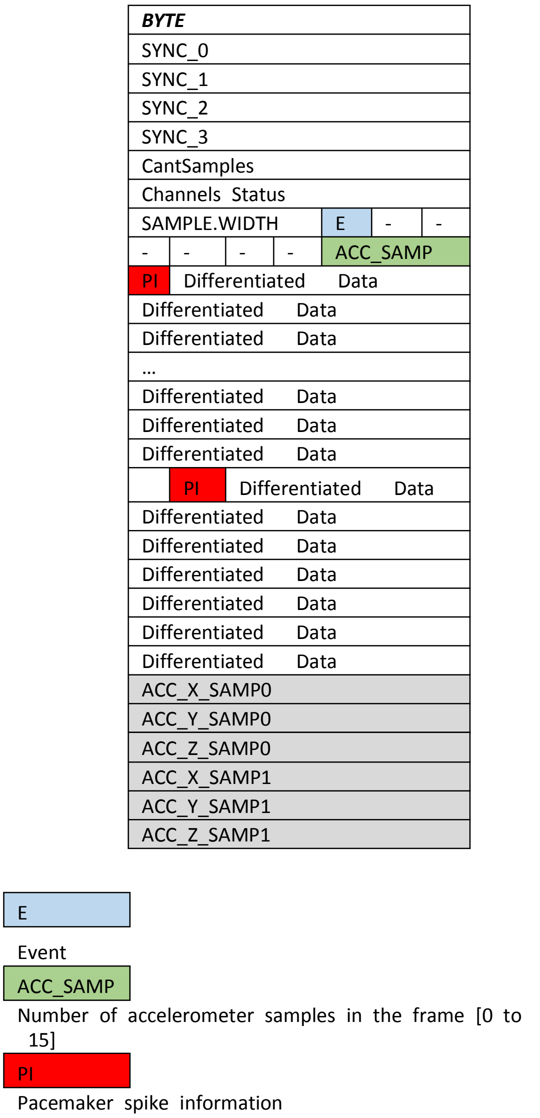

Fig. 3. Signal frame structure

The pacemaker spike information is encoded with 1-bit indicating the presence of the spike in the sample. If the pacemaker function is disabled, this bit is removed to save on SD space for power saving.

Since the number of samples per frame is variable, the amount of accelerometer samples per frame is variable too. The number of bits needed, each sample per lead is calculated on the fly. If the calculated number of bits exceeds the number of bits of the frame being filled, this frame is completed. And a new frame is created with 2-bit more than the amount actually needed by the current sample. These two extra bits help to reduce some overhead generated by too small frames with less than 15 samples.

The Figure 4 shows a simplified block diagram of the compression process. This algorithm is applied to every sample during all the recording time.

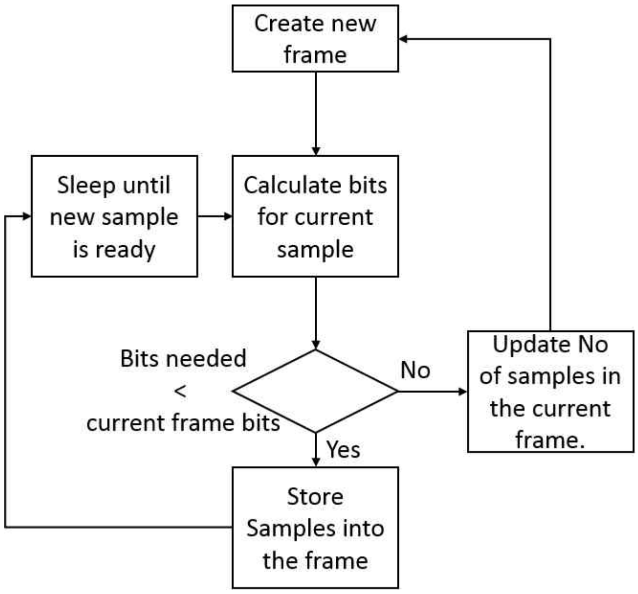

Fig. 4. Simplified compression algorithm block diagram

The Table 2 shows the ECG file size now filled with the ECG differentiated data using variable bits per samples. All of the test was performed by recording 24 hours of ECG signal using an ECG patient simulator.

Table 2. ECG file size with compression

Channels	Sampling frequency	Recording time	Filter size
3	500Hz	24hours	~220MB
3	1000Hz	24hours	~440MB
12	500Hz	24hours	~600GB
12	1000Hz	24hours	~1.2GB

As expected the different sampling frequencies and number of leads impact in file size but using the compression algorithm, the file size is reduced to less than half of the uncompressed size.

Ⅴ. The Micro SD card file system

To be able to access the data to be analyzed by the analyzer software it must be saved by using some standard file system. It brings the additional complexity to the firmware incrementing the resources consumption. Fortunately the FatFs[12] library is capable of handle different FAT12, FAT16 and FAT32 file systems with very low memory requirements. This library has implemented all the functionalities needed to save the signal data without data corruption.

The data writing process to the file must be made as fast as possible. During the development stage the file was firstly created and its size was dynamically allocated. The writing operation is not optimal because every time the file is growing and the file allocation table will be updated. This means that there were some additional write operations besides the data writing process. Also the library need to look for free cluster to expand the file, this adds some read operation, consuming more energy and time than those of the actual needed. This is not a library limitation it is supposed to work in that way, but this behavior is no to good enough for this application.

The file is pre-allocated with the maximum size to overcome this problem, for FAT32 it is 4GB. After this, the file pointier is moved to the beginning of the file and the data writing process starts. When the acquisition is completed, the file is truncated to its actual size. In this way the FAT is updated only once at the beginning and once at the end of the recording. The search for free clusters to make the cluster chain is done all at the beginning of the recording, this will save a lot of time and power during the rest of the test.

The frames are assembled into a 16KB buffer which is written to the Micro SD card using a DMA channel, allowing the CPU to remain in low power mode. While the 16KB buffer is being wrote, another 16KB buffer is being filled to no signal get lost so.

By storing the ECG differentiated signal, the original ECG signal can be reproduced without any loss. This algorithm will not degrade the signal in any way.

Ⅵ. Experimental Results

The Table 3 shows the battery operation time before and after using the compression algorithm.

Table 3. Battery operation results

Channels	Sampling frequency	Without compression	With compression
3	500Hz	~40hours	~80hours
3	1000Hz	~20hours	~72hours
12	500Hz	~24hours	~76hours
12	1000Hz	~12hours	~24hours

The compression ratio will be varied according to the cardiac frequency. The presence of substantial noise will also affect the compression ratio. For a patient with the average cardiac frequency of 80 bpm, the algorithm compression ratio is 0.42 with respect to the original 24 bits signal. The download time can be reduced to half. The decompression algorithm is simple and it does not affect the processing time.

Several tests performed to check for possible data lost originated by power failure. In all the cases the save information was valid and usable until the moment of the power failure.

By using highly the integrated Analog Front-End ADS1298 from Text Instruments the final ambulatory recorder size didn't exceed the dimensions 9×5.5×2.5 cm including the 2×AA battery holder.

Ⅶ. Conclusions

The ECG(Electrocardiograph) ambulatory test as called Holter is performed usually to diagnose several heart diseases causing different arrhythmia. This paper exposes the insights of the design of a 12-ch ambulatory ECG recorder. Reducing the size and minimizing the power consumption of the ECG recorder is crucial to allow long recording time without causing discomfort to the patient. In this paper, we presented the hardware design and differential compression algorithm to extend the maximum 72 hours recording time under considering smaller and light weighted recorder size. The performance result by newly introduced compression algorithm was shown and discussed.

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