The design of a power-efficient 12-ch ECG ambulatory recorder

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Abstract

The ambulatory ECG test so called Holter is widely performed to diagnose several heart diseases that cause different arrhythmia. This research presented the design of a power-efficient 12-ch ECG ambulatory recorder. Reducing the size and minimizing the power consumption of the ECG recorder played a critical role in increasing its usability with longer recording time without causing any discomfort to patient. To that end, various power saving techniques such as DMA transfer, efficient use of processor specific low power mode and data compression, etc. have been proposed in this paper. With the focus on reducing the power consumption of the acquisition system, our proposed techniques extend the recording time up to 72 hours. The performance test result of the proposed differentiated compression algorithm is also presented and discussed. The experimental results demonstrated that the proposed compression algorithm significantly improves overall battery life-time up to 3 times.

Keywords: Holter, ambulatory ECG recorder, differentiated compression algorithm

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Introduction

Despite of the advances in heart disease diagnosis, Sudden Cardiac Death (SCD) continues to occur in the range of 250,000 and 400,000 annually in U.S.A. (Benjamin *et al*., 2009; Fishman *et al*., 2010), accounting for 15 to 20% of all deaths (Gillum, 1990; Myerburg *et al*., 2004). Early diagnosis of heart disease is crucial to reduce the mortality rate caused by heart disease. The ambulatory ECG test known as Holter is a very commonly used, non-invasive test that diagnoses cardiac diseases primarily related with sporadic rhythm alterations. Patient's ECG signal is recorded during normal day activity and evaluated by a cardiologist. The recorded patient data is transferred to PC via USB or SD card memory and analyzed using a computer algorithm (Kim and Lee, 2011).

Typical ambulatory analysis usually takes at least 24 hours. For better diagnosis required for certain patients, 48 to 72 hours of recording time is desirable. Since the ambulatory recorder operates on a small battery, the power efficiency of the device plays an important role in extending battery life and satisfying a recording time requirement. The most common approach to improving the power efficiency as well as size and weight of ECG recorder is to change hardware that uses lower power and smaller electronic components. Departing from such brute-force, costly hardware approaches, this paper presents a design of a power-efficient 12-ch ambulatory recorder that carefully integrates both efficient hardware and software algorithms.

The total power consumption of each Holter is best estimated when both sampling rate and recording channel are considered properly. In comparison with other existing devices, our high design requirements such as 12-ch recording, 1000 Hz sampling rate, 24-bit ADC resolution and 72 hours of operation impose substantially bigger challenges in extending recording time. (Table 1) shows the detailed comparison of different models.

Methodology

1. Related work

The modern ambulatory ECG recorders include the following minimum state-of-art features in addition to complying with the safety and ECG monitoring standards (IEC 60601-2-47, 2001):

- Record 72 hours of 3 ECG channel (7-lead patient cable)
- Record 24 hours of 12 ECG channel (10-lead patient cable)
- Pacemaker detection
- LCD that displays configuration and signals
- Fast data download to PC
- Accessible event hot key by patient

Table 1 The detailed comparison of different models.

model / details	FM180	MICROVIT MT-101/200	Burdick 4205	proposed technique
recording channels	2/3 channel	3 channel	3 channel	3/12 channel
recording time	24 hours	72 hours	24/48 hours	72 hours
capacity	MMC 64 MB	SD memory card 64 MB	SD card 512 MB	4 GB Micro SD Card
sampling frequency (Hz)	125	500	200	250, 500, 1000
a/d resolution	-	12bit	8bit	24 bits
color display	NO	NO	NO	YES
power	AAA Alkaline (LR-03)x1	1 x AA/LR6 alkaline 1.5 V or 1 × accumulator NiMH 1.2 V, > 2100 mAh	AAA alkaline IEC-LR3	Alkaline batteries: DC 3.0 V (2*AA type)
dimensions (mm)	65×18×62	94×61×20	60.95×60.95×17.02	90.5×65×24
weight	78 g (include battery and MMC card)	110 g (with battery)	56 g with batteries	80 g (without battery)

- Pocket size usually less than 10×6×2 cm
- Storage in compact Flash, SD or Micro SD card
- USB connectivity
- Batteries of 1×AAA to 2×AA
- Built-in real-time clock

In order to acquire and digitalize 8-lead of ECG simultaneously, the integrated analogue front-end ADAS1298 (Texas instruments, 2014) from Texas instruments is used. This offers a small compact form factor and power consumption. Two chips from Analog Devices (ADAS1000-1 and ADAS1000-3) (Analog Devices, 2014) were also investigated but not selected because both chips were required to get 8-lead ECG data, which requires additional PCB space.

Micro SD card is widely used in mobile devices and many other IT devices as a cost-effective storage media. Its size is adequate for the ambulatory recorder and its power consumption is acceptable. In order to further reduce the power consumption of micro SD card, special care must be taken to especially data writing process as it is the most power consuming operation. The standby power consumption of a micro SD card is as low as 0.2mA (Dtt8, 2006), therefore it is preferable to stay in this mode as long as possible. To minimize the power consumption caused by the writing operation of micro SD card, the following techniques are used:

- Use low power consumption mode whenever possible
- Lossless real-time compression of ECG signal
- Buffer the compressed data before writing it to SD card
- Use DMA transfer to write data to SD card
- Write the buffered data as fast as possible and return to low power consumption mode

The data stored on micro SD card can be accessed through SPI port but the data rate is lower compared to using the SD bus with 4 data bits for the same clock speed. Therefore, deciding which CPU to use is made by the following parameters:

- Dynamic (non-standby) power consumption
- Fine-grained low power mode support
- SDHC controller that supports 4 data bits SD bus
- SPI port to handle the ADS1296
- Enough I/O lines to handle a parallel LCD
- 1 PWM to control backlight brightness

One of the most energy saving MCU families is the MSP430 series from Texas instruments which is a 16-bit MCU specialized for low power systems and typically uses 195uA/MHz in active state (Texas instruments, 2013). Unfortunately, there is no variant of this family that supports SDHC controller.

The Kinetis Family from Freescale offers several processors with this SD bus controller with 4 data bits (Freescale Semiconductor, 2010). These are 32 bits ARM Cortex M4 processors 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 a real-time clock which can be used to keep the date and time even if the unit is off. A tri-axis accelerometer is included to allow patient activity studies in correlation with the acquired ECG signal.

2. Compression algorithm

The ECG signal compression has been studied for several years. Several techniques have been developed and tested (Singh *et al*., 2015). However, given a specific application and its constraints in computational power and memory, none of them satisfy this particular project.

A custom implementation using the Delta Encoding principle (Singh *et al*., 2015; El B'charri *et al*., 2016) was also developed to achieve lossless compression with small computational power and memory footprint.

The Analogue Front-End (AFE) ADS1298 from Texas instruments features 24-bits ADC sampling (Texas instruments, 2014). (Table 2) shows the approximate file size of ECG signal on micro SD card based on different configuration of the recorder without any compression or packing.

Table 2 ECG file size without compression.

channel	sampling frequency	recording time	file size
3	500 Hz	24 hours	~ 495 MB
3	1000 Hz	24 hours	~ 898 MB
12	500 Hz	24 hours	~ 1.318 GB
12	1000 Hz	24 hours	~ 2.636 GB

Note that the file size changes depending on the number of leads and sampling frequency. To acquire 12-ch ECG, standard 8-lead ECG signal is captured and the remaining 4-lead ECG is derived and computed by the Einthoven's theory.

The large file sizes of ECG signal imposes a negative impact on the download time to PC before the record analysis process. If the ECG signal is compressed and packed, the file size becomes smaller, and so the amount of write cycles of the micro SD card is reduced. This results less power consumption and increased recording time.

The ADS1298 filter works as a DC coupled amplifier without high-pass filter. Its gain range is relatively small compared to high-pass filter, 0.05 Hz (Freescale Semiconductor, 2010) before ECG signal is processed. The digitized 24-bit ADC data which is combined with the original ECG signal and DC offset is derived with bigger numbers of bits. Even if high resolution 24-bit ADC has the strong point, it is not necessary to apply such high-pass filter which may cause signal distortion. This requires high memory space and causes long processing time. To eliminate the drift ECG signal, high-pass filter is applied for the analysis on PC.

On the other hand, the typical signal morphology of ECG suggests that the signal remains in base line for an average cardiac frequency most of the time. 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 becomes smaller, which reduces the file size.

By storing the differentiated value of ECG, the bits are used to absorb the possible offset introduced by the electrodes contact with the skin.

(Figure 1) compares an original ECG signal, differentiated signal and reconstructed ECG signal after decompression.

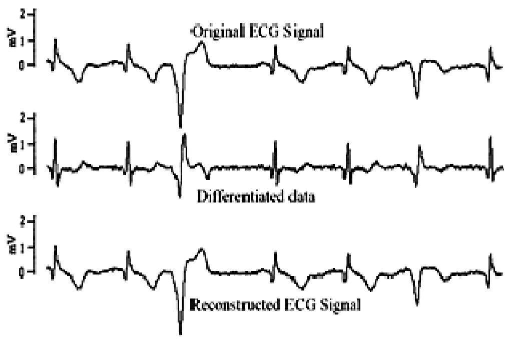
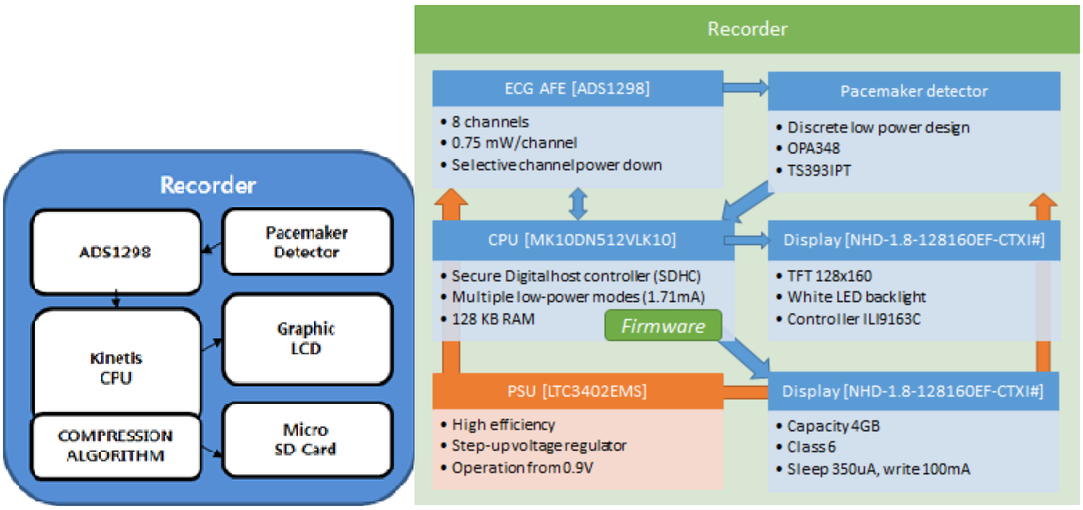


Figure 1 Original ECG, differentiated data and reconstructed ECG signals.

Notice that how much the amplitude of differentiated signal is smaller than the original ECG signal. The decompressed data is exactly same as the original one since this algorithm does not introduce any loss in accuracy during compression.

(Figure 2) shows the block diagram of our designed ambulatory recorder and the details of each block.



(a) block diagram (b) details of each component

Figure 2 Block diagram and details of the proposed ambulatory recorder.

This compression algorithm is fairly simple and can be implemented with a few computational resources. The acquisition timing is directly controlled by the ADS1298 which wakes up the CPU from sleep when there is any 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 an ability to record either 8 leads or 3 leads. In the case of the 3leads configuration, the unused channels of the ADS1298 are powered off to reduce power consumption. This helps extend the recording time when only 3 leads are recorded.

3. Data file structure

The differentiated data is stored as a file. In order to take advantage of the signal morphology, a file structure that allows variable sample bit sizes is required. When compressing the corresponding part to the QRS complex, more numbers of bits are used per sample as amplitude gets bigger. The differentiated data is stored in frames. Each frame has a header which contains information about the number of bits used per sample. The number of bits changes from frame to frame depending on the needs. Each frame can store up to 75 samples. Each frame also has 1-bit to assign the pacemaker spike information. Electrodes status such as encoded off is encoded in the frame header.

(Figure 3) shows the frame structure. It can also hold the accelerometer information if it is enabled at the beginning of the test. The patient event mark is encoded in the frame structure with 0.3 seconds delay in worst case, which is acceptab

The single-bit pacemaker spikes in the sample. If the pacemaker function is disabled, this bit is removed to save SD space and power consumption.

E

Event

ACC_SAMP

Number of accelerometer samples in the frame [0 to 15]

PI

Pacemaker spike information

BYTE						
SYNC_0						
SYNC_1						
SYNC_2						
SYNC_3						
CantSamples						
ChannelsStatus						
SAMPLE.WIDTH				E	-	-
-	-	-	-	ACC_SAMP		
PI	Differentiated Data					
Differentiated Data						
Differentiated Data						
…						
Differentiated Data						
Differentiated Data						
Differentiated Data						
	PI	Differentiated Data				
Differentiated Data						
Differentiated Data						
Differentiated Data						
Differentiated Data						
Differentiated Data						
Differentiated Data						
ACC_X_SAMP0						
ACC_Y_SAMP0						

Figure 3 Signal frame structure.

As the number of samples per frame is variable, the amount of accelerometer samples per frame changes as well. If the calculated number of bits exceeds the number of bits in the frame being filled, this frame is completed. Then a new frame is created with 2-bit more than the number of bits actually needed by current sample. These two extra bits help reduce some overhead generated by two small frames with less than 15 samples.

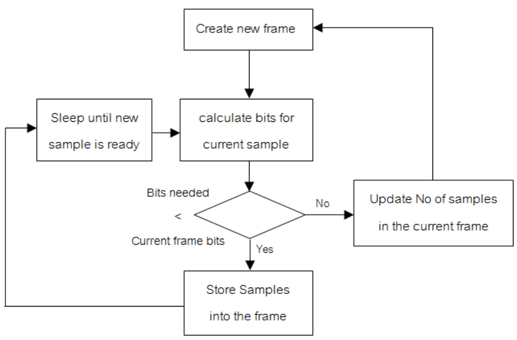


Figure 4 Block diagram of the simplified compression algorithm.

(Figure 4) shows the simplified block diagram of the compression process. This algorithm is applied to every sample during entire recording time.

Table 3 ECG file size with compression.

channel	sampling frequency	recording time	file size
3	500 Hz	24 hours	~ 220 MB
3	1000 Hz	24 hours	~ 440 MB
12	500 Hz	24 hours	~ 600 MB
12	1000 Hz	24 hours	~ 1.2 GB

(Table 3) shows the ECG file size filled with the ECG differentiated data using variable bits per sample. All tests were performed by recording 24 hours of ECG signal using an ECG patient simulator.

As expected, the different sampling frequencies and number of leads affect file size but the proposed compression algorithm helps reduce the size to less than half of the uncompressed.

4. Micro SD card file system

For the analyzer software to be able to access the data, it must be saved in some standard file systems. It brings additional complexity to the firmware and increases the resource consumption. Fortunately, the FatFs (Elm-chan, 2005) library is capable of handling different FAT file systems (e.g., FAT12, FAT16 and FAT32) with very low memory requirement. This library has implemented all the functionalities required to save the signal data without any data corruption.

The file writing process must be made as fast as possible. During the development stage, the file is first created and its size is dynamically allocated. As the file grows the file allocation table must be updated. Therefore, there are some additional write operations besides the data writing itself. Also, the library needs to search for free cluster to expand the file, which adds a file read operation, consuming more energy and time than what is actually needed. Although this is not a library limitation, this behavior is certainly not optimal for this application. As a workaround, the file is pre-allocated with its maximum size to overcome this problem (4 GB for FAT32). Once pre-allocated, the file pointer is moved to the beginning of the file and the data writing process starts. When the acquisition completes, the file is truncated to its actual size. In this way the FAT is updated only twice: one at the beginning and the other at the end of recording. The search for free clusters to make the cluster chain is performed at the beginning of recording. This will save a lot of time and power during the rest of the test.

The frames are assembled into a 16 KB buffer and written to the micro SD card using a DMA channel. This allows the CPU to remain in low power mode. While the 16 KB buffer is assembled, another 16 KB buffer is filled with the acquired ECG signal simultaneously in order to optimize the overall processing time.

By storing the differentiated signal, the original ECG signal can be reproduced without any loss. This algorithm does not degrade the signal integrity.

Results and discussion

Table 4 Battery operation results.

channel	sampling frequency	without compression	with compression
3	500 Hz	~40 hours	~ 80 hours
3	1000 Hz	~20 hours	~ 72 hours
12	500 Hz	~24 hours	~ 76 hours
12	1000 Hz	~ 12 hours	~ 24 hours

(Table 4) shows the battery operation time before and after using our proposed compression algorithm.

The compression ratio varies depending on cardiac frequency. The presence of substantial noise also affects the compression ratio. For a patient with the average cardiac frequency of 80 bpm, the algorithm compression ratio is 0.42 for the original 24-bits signal. The download time is therefore reduced to half and the decompression time is negligible due to smaller size and its relatively light-weight algorithm.

Several tests are performed to check for any data loss caused by possible power failure. In all tests, the information saved before the moment of the power failure is valid and usable.

By using the integrated Analogue Front-End ADS1298 from Texas instruments the final ambulatory recorder size does not exceed the dimensions of 9×5.5×2.5 cm including the 2×AA battery holder.

Table 5 Impact of each technique on power consumption.

	3 channels [500 Hz]				12 channels [500 Hz]			
	none	low power modes and DMA	ECG compression	all	none	low power modes and DMA	ECG compression	all
power [mA]	25.64	20.9	21.02	16.3	32.7 mA	29.7	23.1	20.7

(Table 5) shows the impact of each technique on reducing the power consumption. The table demonstrates that average power consumption using proposed techniques such as device low power modes, DMA transfer and signal compression is reduced by 36.9%.

Conclusion

This paper presents the design of a power-efficient 12-ch ECG ambulatory recorder with a small form factor. Our proposed hardware design and differentiated compression algorithm extend its recording time to up to 72 hours, and make the device smaller and light-weight. Our proposed techniques reduce the average power consumption of the recorder by up to 16.3 mA for a 3-channel recording with 500 Hz sampling frequency. Our experimental results demonstrate that the proposed compression algorithm in conjunction with DMA transfer and low power modes remarkably extends battery operation time by up to 3 times depending on the number of channels being digitalized.

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