A Real Time ECG Preprocessing System Based on ADS1298

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Abstract

The aim of this paper is to discuss the main characteristics of a real time ECG pre-processing multichannel system designed by the authors of the paper. It is based on the multichannel high-resolution ADS1298 integrated circuit and the MSP430F5529microcontroller, both from Texas Instruments. The developed acquisition system complies with the international standard IEC60601-2-25:2011 {ed2.0} and provides improvements in parametric characteristics of the signal with respect to previous solutions. The recovery times decreased to 1.33 seconds and the common mode rejection ratio (CMRR) has been increased to 94.3 dB in lead I and 93.71dB in lead II as compared to the corresponding values 91.12 and 90.86 obtained by the authors in previous solutions. Noise level decreased from 11μV to 9μV. The present solution is more compact and reliable so it can be used in different equipments for real time ECG pre-processing.

1. Introduction

Nowadays, considerable human and material resources are aimed to research and develop tools for the prevention and treatment of heart disease. An example of this is the use and improvement of non-invasive techniques such as the electrocardiogram (ECG), which is the most widely used clinical test to study the cardiac activity [1].

Multichannel electrocardiographs have advantages over single-channel ones because printed or visual recording of multiple derivations allows observing how an electrical phenomenon manifests itself in time.

Depending on the resolution of the ADC (Analog digital converter) used in the acquisition channel, there are two different approaches to process the ECG signal. One approach is to use low-noise amplifiers and increase amplifier gain (approximately 500), and thus use a low-resolution (approximately 12-bit) ADC. In this case, care must be taken so that the intrinsic noise of the amplifier does not dominate the overall system noise. The other approach would be to use a lower gain value (approximately 5) and a high-resolution (approximately 24-bit) ADC. In both approaches, the noise-free dynamic range at the ADC output remains the same [2].

Noise in the amplification channels distorts the integrity of the ECG signal. The use of amplifiers with a high CMRR will reduce the noise influence. The signal preprocessing should eliminate low-frequency noise that results from baseline wander movement and respiration and higher-frequency noise that results from muscle artifacts and power-line or radiated electromagnetic interference.

Once the ECG signal is acquired, the remaining noise should be minimized as much as possible by using digital filters. Digital filters designed for ECG processing must have linear phase characteristic, at least in the bandwidth of interest. This prevents phase distortion introduced in the ECG signal by the classic analog filter [3].As a result of the filtering process, the ECG signal obtained is limited to the frequency range of interest.

The goal of this paper is to present and discuss the main characteristics of a system for preprocessing the ECG signal in real time, based on the multichannel integrated circuit ADS1298. This system has been designed to be implemented in multichannel electrocardiography, as the signal acquisition module. Its design was focused to improve parametric characteristics of the ECG signal as obtained by the authors in a previous work [4].It also allows reducing cost, size and power consumption of the electrocardiographs, guaranteeing the compliance with the international standard IEC60601-2-25:2011 [5] without affecting patient safety.

2. Materials and methods

The proposed system acquires and digitizes the ECG signal by means of the ADS1298multichannel high-resolution integrated circuit. Real time preprocessing of the ECG signal is accomplished using the MSP430F552916-bit microcontroller, with an external 12 MHz clock. The system has a dynamic input range of 11 mV and 3.10 μV/LSB.

Solutions based on high resolution A/D converters, like the ADS1298, provide an increase in system reliability due to the reduction of discrete components and soldering points. It also allows decreasing the size and power consumption as compared to solutions based

on low resolution A/D converters.

Reducing the number of discrete components leads to a greater complexity because signal conditioning and processing must be performed by the firmware running on the microcontroller. Figure 1 shows the PCB of the system presented in this paper for ECG preprocessing.

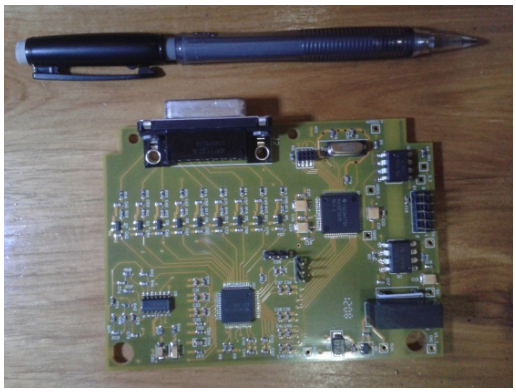

Figure 1. ECG preprocessing experimental system with small size dimensions (7.5 x 10.5 cm).

The system design was focused on the compliance of international standards for patient safety, by improving electrical insulation [5].

2.1 Firmware

Signal conditioning consists in eliminating low and high frequency noise and limiting the system bandwidth from 0.05 to 150 Hz. Signal conditioning is performed using analog filters in solutions based on low resolution A/D converters, while in high resolution solutions this is carried out using digital filters.

The skin-electrode interface introduces an additional dc offset of approximately 300 mV [2]. This offset must be eliminated to avoid amplifier saturation using a high pass filter with a cut-off frequency between 0-0.05 Hz. The value of 0.05 Hz is established in the ECG standard [5]. Once the ECG signal is acquired, a first order high pass IIR Butterworth filter, with a cutoff frequency of 0.045Hz is applied. The equation is shown below:

$$y_n = x_n - x_{n-1} + 0.99939\, y_{n-1} \quad (1)$$

Where:
x_n: input signal,
y_n: filtered signal.

The IIR filters have a nonlinear phase response in certain frequency ranges, which causes phase distortion of the ECG signal. The designed filter has a linear phase characteristic in the bandwidth of interest, from 0.05 to 150 Hz. Figure 2 shows the magnitude and phase response versus frequency of the IIR filter designed:

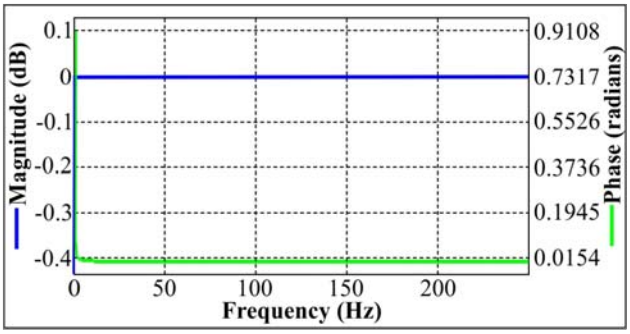

Figure 2. First order high-pass IIR filter.

The proposed preprocessing system will be used as the acquisition module in eight-channel electrocardiograph types, which signal layer processing 12bit/channel samples. In addition, processing 24bit/channel data on 16bit microcontrollers, represents a high computational cost and there is no need of such high resolution for the application. Therefore, it is profitable to reduce the signal from 24 bits/channel to 12bits/channel without introducing significant distortion of the acquired signal.

An internal ADS1298 test signal was used. This signal is offset free and has known amplitude. The reduction factor was calculated using the maximum thresholds corresponding to the system's input dynamic range values and establishing a direct relation between the input 24 bit dynamic range and the 12 bit converted signal. The reduction process consists in multiplying the 24 bit samples by the reduction factor, resulting in equivalent 12 bit samples.

After reducing the signal it is necessary to limit the system bandwidth to 150Hz in order to remove the high frequency signal components, which do not provide useful information for the application. A 28thorder high-pass FIR filter, equiripple type, with a 150 Hz cutoff frequency was designed. The filter's equation is shown below:

$$y_n = \sum_{k=0}^{N-1} b_k\, x_{n-k} \quad (2)$$

Where:
N: filter order
b_k: filter coefficients
x_n: input signal
y_n: filtered signal

The FIR filters are characterized by having a linear phase response, so there will be no phase distortion [5]. Figure 3 shows the magnitude and phase response versus

frequency of the FIR filter designed:

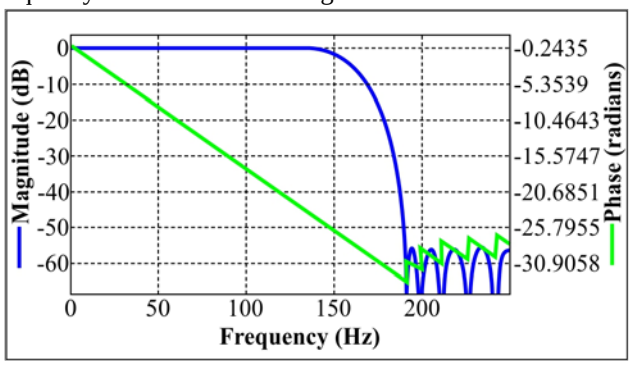

Figure3. 28th order equiripple Low pass FIR filter.

Both filters were designed and simulated using MatLab2009 software. In order to validate the digital filters several frequency response tests were carried out, all of them complying with the standard IEC60601-2-25:2011.

All non-battery powered equipment can pick up large interference signals from power lines, fluorescent lights, and so forth. This interference signals have frequency components of 50 or 60 Hz, depending on the country. A notch filter is used to mitigate these signals. It is implemented in the processing layer to get a better performance and to allow enabling/disabling it in real time whenever it is necessary [2].

The ADS1298 is configured to convert ECG signal to digital values at a 500 Hz sampling rate, as recommended in [5]. This sampling frequency implies a conversion time of 2 ms and during this interval the ECG signal must be acquired and conditioned. Besides, it is necessary to package the ECG signal according to a defined protocol and transmit this information via the serial port to the processing layer. The Data Ready signal from the ADS1298 is connected to an interrupt pin of the microcontroller. Once an interrupt is received, the digitized ECG signal is acquired using the serial port interface (SPI) interface.

This acquisition is done by configuring the SPI interface to work with the integrated DMA module (Direct Memory Access), because transfers using the DMA module reduce acquisition times. The digital filters are executed using the hardware multiplier microcontroller module to increase their performance.

Initially all the coefficients of both filters were floating numbers and the filtering process could not be completed in real time with an acceptable processing time. To solve this problem, filters with integer coefficients multiple of two were implemented. Multiplying integer numbers in the microcontroller is much faster than multiplying floating numbers; furthermore, filter coefficients also are multiples of two.

The previously mentioned transformation allowed solving most of the multiplications with rotation, addition and subtraction instructions, allowing the two digital filters to be executed in real time within the MSP430f5529 microcontroller.

Once the filtering process is over, the resulting signal is transmitted over the serial port to the processing layer, according to a defined protocol.

This protocol starts each data frame with the hexadecimal value 55H. It provides a synchronization method with the signal processing layer. The frame also includes the digitalized and conditioned ECG signal, lead states and information about any pacemaker present. This protocol was tested during 12 consecutive hours and there was no loss of information detected at all.

The basic principle for disconnected leads detection consists to inject an excitation signal and measure its circuit response [6]. The system uses the constant current method for the detection of loose or disconnected electrodes. This method provides greater input impedance than the pull-up resistors method, improving system noise immunity [7].

The ECG preprocessing system must be able to detect the presence of pacemaker pulses with amplitudes between 2 mV to 250 mV and durations between 0.1 ms to 2.0 ms [5]. Pacemaker detection is performed using an external circuit connected to the ADS1298digital output. This hardware detection pacer circuit is designed to monitor any occurrences of a pace maker signal in an electrocardiogram (ECG) application by providing an alert to a GPIO. The circuit combines three individual circuits: a differentiator circuit used for slope detection, a window comparator to monitor for any event and SR latch to indicate an event had occurred. A pacemaker signal at the input will latch a digital I/O pin high to indicate the signal is present in the waveform [7]. This information is sent to the processing layer in the data frame. Pacemaker detection was tested using a triangular waveform digital generator, since this method provides an easy way to input different simulated signals, which are summarized in Table 1.

Table 1. Triangular test signals used to evaluate the pacemaker detection circuit.

Test signal	
ms	mV
0.1	2.0
0.5	2.0
1.0	2.0
1.5	2.0
2.0	2.0
0.1	250
0.5	250
1.0	250
1.5	250
2.0	250

All of these different signals were detected by the preprocessing system, indicating the pacemaker presence.

3. Results

Three prototypes of the system presented in this paper have been manufactured and tested; successfully passing the parametric and electric safety tests established in the standard IEC 60601-2-51. Some of the main results and a comparison with previous solutions are summarized in Table 2:

Table 2. Main results and a comparison with previous solutions

Parameter	Previous solutions	ADS1298	IEC
Frequency response (Hz)	0.05-150	0.05-150	0.05-150
Recovery time (s)	1.44	1.33	< 2
CMRR (dB)	90.86	93.71	> 89
Intrinsic channel noise (μV)	11	9	< 30
Crosstalk (%)	< 2	< 2	< 2
Amplitude quantization (μV/LSB)	3.45	3.10	< 5

The system was tested acquiring and preprocessing simulated ECG signals continuously for 12 hours. For signal evaluation, previously developed software was used. This software allows verifying compliance with the standard [5].

The recovery time of a channel, associated with amplifier saturation or fall of one of the electrodes associated to the channel, decreased 0.11 s. This reduction is important because the signal returns quickly to the baseline and allows obtaining the electrocardiogram in less time.

CMRR was improved by 4dB which influences quality positively since it increases the noise immunity of the preprocessing system.

Crosstalk interference remained with the same approximate values. This means that the signal value obtained from each A/D converter, is closer to its true value because the effect of other channels has no noticeable influence.

The proposed system has been evaluated with simulated signals. All results comply with the parameters established in IEC 60601-2-25:2011.

4. Conclusions

A real time ECG preprocessing system has been designed by the authors, built and tested. It provides a more compact and reliable solutions, which will be used as acquisition module in multichannel electrocardiographs.

Further improvements were obtained with the increase in CMRR value and the decrease in noise, recovery time and amplitude quantization values, as compared with previous solutions.

The proposed system has been built and tested with satisfactory results. As demonstrated through the analysis of the main results obtained, the real time ECG preprocessing system complies with the international standard IEC 60601-2-25:2011.

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