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Synchronous acquisition of multi-channel signals by single-channel ADC based on square wave modulation

Xiaoqing Yi,[1] Liling Hao,[2] Fangfang Jiang,[2] Lisheng Xu,[2] Shaoxiu Song,[1] Gang Li,[1] and Ling Lin[1,a)]
[1]*State Key Laboratory of Precision Measurement Technology and Instruments, Tianjin University, Tianjin 300072, China*
[2]*The Department of Sino-Dutch Biomedical and Information Engineering School, Northeastern University, Shenyang 110004, China*

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Synchronous acquisition of multi-channel biopotential signals, such as electrocardiograph (ECG) and electroencephalograph, has vital significance in health care and clinical diagnosis. In this paper, we proposed a new method which is using single channel ADC to acquire multi-channel biopotential signals modulated by square waves synchronously. In this method, a specific modulate and demodulate method has been investigated without complex signal processing schemes. For each channel, the sampling rate would not decline with the increase of the number of signal channels. More specifically, the signal-to-noise ratio of each channel is n times of the time-division method or an improvement of $3.01 \times \log_2 n$ dB, where n represents the number of the signal channels. A numerical simulation shows the feasibility and validity of this method. Besides, a newly developed 8-lead ECG based on the new method has been introduced. These experiments illustrate that the method is practicable and thus is potential for low-cost medical monitors. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4998990]

I. INTRODUCTION

Multi-channel biopotential signals, such as electrocardiograph (ECG) and electroencephalograph (EEG), include lots of physiology and disease information, which is of important action for doctors to judge pathological changes.[1–4] Synchronously acquiring multi-channel biopotential signals with high precision by a relative simple method remains a huge challenge.

In order to simplify the analog circuit, the published research works used a high resolution $\sum$ - Δ ADC to acquire ECG, without the use of instrument amplifiers. This reduced the complexity of hardware, the power consumption, and the system cost.[5–8] However, when this method is used in multi-channel signal acquisition, the use of multi-$\sum$ - Δ ADC will lead to an obvious increase of system cost and power consumption. When $\sum$ - Δ ADC is combined with an analog multiplexer, it will cause the sampling rate of each channel to drop to $1/n$, where n represents the number of signal channels. Worse yet, this approach will result in cross talk among channels because of its long settling time. When SAR ADC[9] is combined with an oversampling technique, it also can realize high resolution and avoid a long settling time. Though this is suitable for wearable health care devices, it does not solve the above problem. As a result, a series of analog front-end (AFE) chips have been developed and are popularly used in the detection of biopotential signals in wearable medical monitors. It can synchronously acquire multi-channel signals and reduce the volume of monitoring to meet the requirements of wearable medical monitors, where the designers do not care about the higher cost. For example, the ADS129x series chips by Texas Instruments, low-power, 8-channel, 24-bit analog front-end,[10] are integrated signal conditioning blocks for ECG and other biopotential measurements. Multi-lead ECG detection is a main application of AFE.[11–14] Gaxiola-Sosa *et al.*[11] used 8-channel AFE, ADS1298, to design a wearable 12-lead ECG wireless medical system. There is no doubt that the system is small, but the cost of system is much more expensive.

Therefore, compared with the above multi-channel ADC acquisition methods, in this paper, a new acquisition method that synchronously acquires multi-bioelectric signals by a single-channel ADC is proposed. The core of this method is to modulate the signals by frequency doubled square waves, respectively, and add up the signals to obtain a single channel signal (further labeled as mixed signals). The mixed signal is then sampled by a single-channel ADC to finally acquire multi-channel biopotential signals through the digital demodulation method. In this method, the sampling rate of each channel remains unchanged for each channel with the increase in the number of channels. According to the oversampling technique,[15] the signal-to-noise ratio (SNR) of each channel is n times of the conventional time-division multiplex (TDM) or an improvement of $3.01 \times \log_2 n$ dB, where n represents the number of channels.

II. PRINCIPLE AND ALGORITHM

A. Square wave modulation and demodulation method

The acquisition device consists of (1) modulation circuit, (2) addition circuit, and (3) single-channel ADC and microcontroller; Fig. 1 shows a structure schematic of the acquisition device.

[a)]E-mail: linling@tju.edu.cn

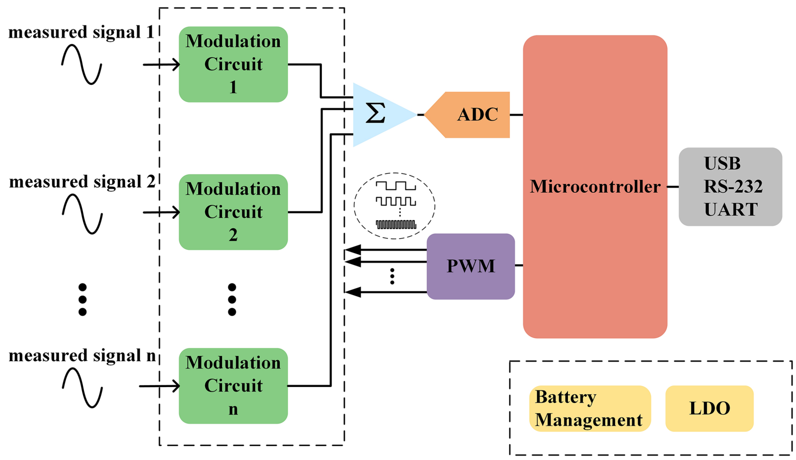

FIG. 1. The structure schematic of the device that synchronous acquisition of multi-channel signals by the single-channel ADC based on square wave modulation.

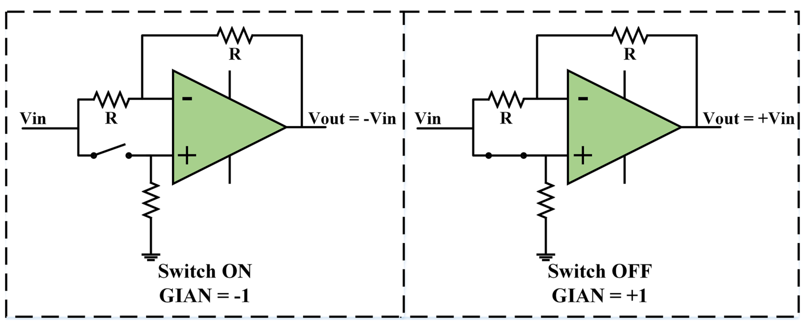

FIG. 2. The realization of square wave modulation.

The implementation of the square wave modulation and demodulation method contains three steps:

(1) The micro controller unit (MCU) produces n-channel square waves as carrier signals with a frequency ratio by multiples of two. That is, the frequency of the carrier signals is f, $2f$, $4f$, . . . , $2^n * f$ (n = 0,1,2,. . .), where f is the lowest frequency of the carrier signals. The modulating signals V_{in} are modulated by square waves with the circuit showed in Fig. 2.

(2) V_{out}, the modulated signals of each channel, are added together by an addition circuit, and then the mixed signal is sampled by a single-channel ADC whose sampling frequency is f_s, $f_s = 2^{n+1} * f$ (n = 0,1,2,. . .).

(3) In order to simplify the illustration, the demodulation takes 2-channel signal acquisition, for example. Actually, this method can be applied in the acquisition system with more channels. Suppose f, the lowest frequency of the carrier signals, is much higher than the frequency of modulating signals. Thus, the level of each modulating signal and DC offset, V_1, V_2, and V_B, can be approximately regarded as invariant within one period of the lowest frequency of the carrier signal. So the sampling sequence in one period can be expressed as

$$\mathrm{SP1} = +V_1 + V_2 + V_B, \tag{1}$$

$$\mathrm{SP2} = -V_1 + V_2 + V_B, \tag{2}$$

$$\mathrm{SP3} = +V_1 - V_2 + V_B, \tag{3}$$

$$\mathrm{SP4} = -V_1 - V_2 + V_B. \tag{4}$$

Consequently, the two-channel modulating signals can be demodulated according to the following equations:

$$\mathrm{SP}_1 - \mathrm{SP}_2 + SP_3 - SP_4 = 4V_1, \tag{5}$$

$$\mathrm{SP}_1 + \mathrm{SP}_2 - SP_3 - SP_4 = 4V_2. \tag{6}$$

The DC offset is also eliminated during the demodulate process. It is easy to find that the sampling rate of each channel is determined by f, the lowest frequency of the carrier signals. Figure 3 shows the carrier signals and ADC sampling sequence for 2-channel signal acquisition.

The demodulation method is particularly simple just using addition and subtraction operation, which is appropriate for low-cost and real-time embedded systems. The whole process of modulation and demodulation for 2-channel signal

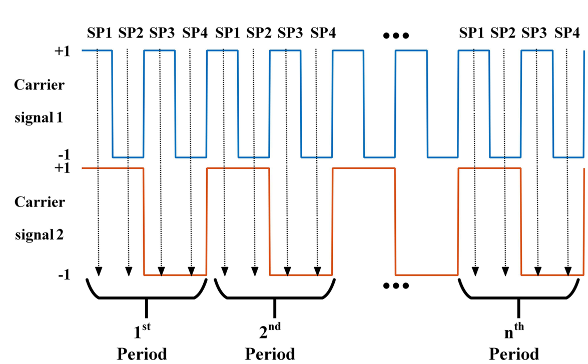

FIG. 3. The carrier signals and ADC sampling sequence for 2-channel signal acquisition.

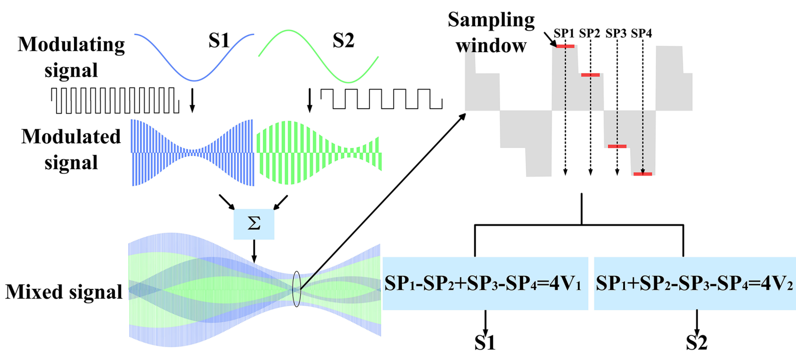

FIG. 4. The whole process of the modulation and demodulation for 2-channel signal acquisition.

acquisition is shown in Fig. 4. Likewise, the principle for more channel signal acquisition is similar.

B. Oversampling technique

The oversampling technique is to use k times of the actual required sampling frequency, i.e., Fo = k * f_o, where *Fo* is the oversampling frequency, k is the oversampling rate, and f_o is the actual required sampling frequency according to the Nyquist sampling theorem.[16] After sampling, the frequency is restored equivalently to f_o through the down-sampling which means to take the average of the k sampling value. As the quantization noise, the thermal noise and the external disturbance introduced in the data acquisition process mostly belong to the white noise. Thus the sum-average arithmetic has a good performance of noise immunity and improves the SNR because oversampling makes the bandwidth of the quantization noise increase k times, so the quantization noise after down-sampling in the effective frequency band reduces to $\sqrt{1/k}$ times of the origin, which shows that oversampling can reduce the quantization noise of the ADC and improve the system resolution.[17–19] Based on theoretical derivation,[20] the SNR can be improved by 3.01 dB with every two times increase of the sampling rate, which is equivalent to the increase in 1/2 effective bit of the ADC.

For an n-channel signal acquisition system, each channel's sampling rate of the new method is n times than that of the TDM. Based on oversampling theory, the SNR of each channel is n times of TDM or an improvement of $3.01 \times \log_2 n$ dB, where n represents the number of the signal channels.

III. EXPERIMENTAL VERIFICATION

A. Simulation experiment

1. Methods

In order to assess the validity of the new modulation technique, simulation experiments were carried out with matrix laboratory (MATLAB) software. Two sine signals of 1 Hz were employed as modulating signals, with a different phase and amplitude to distinguish each other. Square signals of 200 Hz and 400 Hz represented the carrier signals. The 2-channel modulating signals were multiplied by the two corresponding carrier signals, respectively. Then random noises were added to the mixed signal as quantizing noise, whose amplitude was 1/1000th of modulating signals. The mixed signal was sampled and demodulated according to the method mentioned above. The sampling rate is 200 Hz, and 4000 sampling points for each channel were obtained.

In addition, we expanded the channel number and contrasted the SNR of each channel between the new method and TDM, in the case of 2-channel, 4-channel and 8-channel signal acquisition.

2. Results and discussions

Figure 5 shows a piece of (a) modulating signals, (b) mixed signals, and (c) demodulated signals in a 2-channel modulation and demodulation experiment.

From these figures, It can be seen that the modulating signals are identical with demodulated signals. Therefore, the results illustrate that the new method could accurately recover the modulating signals.

In the contrasting experiment, the fast Fourier transform (FFT) was adopted to compute SNR, using the modulus of frequency of modulating wave as useful signals, using the modulus of other frequency as noises. Results are summarized in Table I.

From the table, the SNR of each channel in the new method was nearly unchanged when the channel number varied, since the sampling rate of each channel declined. While the SNR of each channel in the TDM declined with the increase in the channel number because the sampling rate dropped to 1/n of the channel number. More specifically, the SNR improvements between the new method and TDM were 2.9412 dB, 5.9681 dB, and 9.0569 dB for 2-channel, 4-channel, and 8-channel signal acquisition, which were very close to theoretical values 3.01 dB, 6.02 dB, and 9.03 dB, respectively.

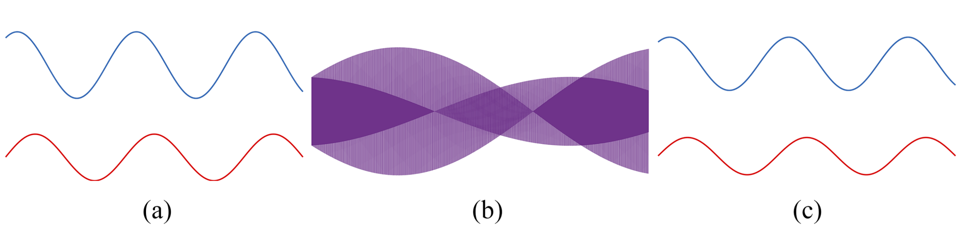

FIG. 5. A piece of (a) modulating signals, (b) mixed signals, and (c) demodulated signals.

TABLE I. Comparison of the performances of two acquisition methods at a different number of channels.

Number of channels	$SNR_{new\ method}$ (dB)	SNR_{TDM} (dB)	SNR improvement (dB)
2	75.9650	72.0238	2.9412
4	76.0218	70.0536	5.9681
8	76.0017	66.9454	9.0569

The results proved that the new method on the one hand can acquire multi-channel signals effectively and on the other hand can improve the SNR of each channel compared with TDM.

B. Practical application

1. Methods

We have developed an 8-lead ECG acquisition device to illustrate the new method for the biopotential signal detection as showed in Fig. 6(a). The device consists of a bioelectric preamplifier circuit, modulation circuit, and MCU PSOC4 (CY8C4247LQI-BL483, Cypress, USA) with Bluetooth Low Energy (BLE).

Five channels of signals, including limb lead V_R V_L V_F and thoracic lead V_1 V2, were acquired by the bioelectric pre-amplifier circuit. Then the MCU controls the modulation circuit to realize modulation by square waves produced by the timer in MCU; the frequency of the carrier signals was 200 Hz, 400 Hz, 800 Hz, 1.6 KHz, and 3.2 KHz, respectively. Then the mixed signal was sampled by the on chip 12-bit ADC(1MSPS). In this system, the sampling rate of the ADC is much higher than the required sampling rate (200SPS); thus the oversampling technique can be used to improve the precision of the ADC. That is, 32 continuous analogue-digital conversions are executed in every sampling window, and then averaged to one single sampling value. According to oversampling theory, the precision of ADC can be improved by 2.5 bits. As mentioned in Fig. 4, to avoid the potential influence of jitter and oscillation at the rising or falling edge, the location of the sampling points should be in the middle of each pulse. That is, the sampling window locates in the middle of each pulse. ECG signals were viewed and stored in a smart phone or a laptop via BLE. An ECG signal emulator (SKX-2000D, Mingsheng Co. Ltd., China) was employed to act as the source of ECG signals. The consumption of the device was evaluated by a 6_1/2-digit digital multimeter (34401A, Agilent Technologies Inc., USA).

2. Results and discussions

An example of 8-lead ECG signals gathered by the newly designed device is shown in Fig. 6(b). To verify the practicability of this device, a comparative experiment was designed; we adopted a multi-function data acquisition card (myDAQ, National Instruments, Inc., USA) to acquire ECG signals from the ECG emulator directly. The ECG signals acquired by the data acquisition card could be seen as reference signals or real signals, which is shown in Fig. 6(c). Compared with Figs. 6(b) and 6(c), it can be seen that the ECG signals acquired by the newly designed device and that by the data acquisition card are nearly the same. That is, the ECG signals acquired by the newly designed device have no significant distortion. The comparative experiment demonstrates that the new modulation method and the newly designed device based on that method are suitable for multi-channel biopotential signal acquisition. Thanks to the new method, 8-lead ECG signals can be acquired accurately by a single channel on-chip ADC with no high performance. Besides, the architecture of the circuit is simple only including operational amplifiers and analog switches. The power consumption was as low as 9.6373 mA at 3.3 V, mostly dominated by the requirements of the MCU. Concretely, the

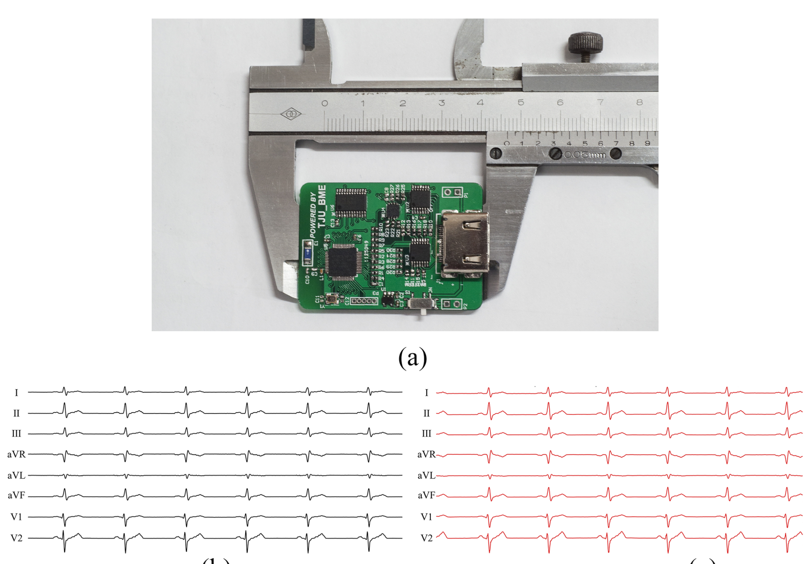

FIG. 6. (a) The circuit of the newly designed 8-lead ECG acquisition device. (b) An example of 8-lead ECG signals measured from an ECG emulator by the newly designed device and (c) by the NI data acquisition card, see text for details.

consumption of the MCU was 9.1326 mA in the case of BLE and ADC working at full load. Thus the working current of the analog circuit was just nearly 500 μA. Besides, the size of the printed circuit board was 46.9 mm × 32.7 mm. These results indicated that we have successfully applied the new method in the ECG signal acquisition, with small volume, low power consumption, and low cost.

IV. CONCLUSION

In this paper, a method that synchronous acquisition of multi-channel signals by single-channel ADC based on square wave modulation is proposed, which has a great performance in multi-channel biopotential signal acquisition. The corresponding demodulation method is very simple only including addition and subtraction operation, which is suitable for real-time and low-cost embedded systems. We adopt a simulation experiment to prove that the SNR of each channel can be improved by 3.01 dB with every two times increase of the channel number under the same condition, compared with TDM. The newly designed 8-lead ECG acquisition device is characterized by small volume and low power consumption. Thus this new method has a superior prospect in the design of low-cost medical instruments. While the new method does have its limitation, with the increase of the number of channels, the needed frequency of carrier signals grows exponentially. Higher frequency of carrier signals means higher sampling rate and more frequently data processing, which may increase the power consumption or requires higher performance. That is, the number of channels and power consumption interact and affect each other. These factors should be taken into consideration when adopting this new modulation technique. Modifying this modulation technique to decrease the needed frequency of carrier signals is our further work.

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