Capacitive Coupled Electrodes based Non-contact ECG Measurement System with Real-time Wavelet Denoising Algorithm

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***Abstract*—A non-contact electrocardiograph (ECG) measurement system based on capacitive coupled electrodes is proposed. Unlike conventional wet electrode, the capacitive coupled electrode is designed to measure ECG signal both in contact with skin and through clothes. The hardware part of the system includes two capacitive coupled electrodes, a reference electrode, a signal processing module and a transmission module, and the software part includes data extraction, signal processing, data storage, and waveform display. A real-time ECG denoising algorithm is developed based on wavelet transform with a moving window. To verify the performance of proposed system, two different conditions of the ECG measurement are experimentally tested in comparison with Ag/AgCl electrode. One is in a contact condition in which capacitive coupled electrodes touched the skin. Another is the non-contact condition in which ECG was measured through thin clothes. The results show that the capacitive coupled electrode is better than the conventional Ag/AgCl electrode when it is attached to the skin, and the clear ECG waveform can be obtained under non-contact measurement. The results demonstrated the feasibility to measure high resolution ECG waveform with real-time denoising algorithm in a non-contact way.**

I. Introduction

ECG is one of the most commonly used examinations in clinic. It has a wide range of applications, including recording the electrical activity of normal human heart and diagnosing cardiovascular diseases[1]. Therefore, it is very meaningful to study the ECG signal measurement system.

Nowadays, the most widely used wet electrodes, such as Ag/AgCl electrodes, could acquire high-quality ECG signals, but they have certain limitations, mainly reflected as follow. Firstly, skin preparation such as removing thick hair and the cuticle of the skin is needed[2]. Secondly, wiping alcohol or applying conductive gel may cause skin irritation, especially in infants and sensitive people[3]. Thirdly, it may cause panic and nervousness in patients, which indirectly affects the reliability of the measured result[4]. Fourthly, it couldn't be reused, so the measurement cost is high. The above limitations of traditional ECG measurement systems restrict their development towards long-term monitoring and daily monitoring.

Other than textile electrode, capacitive coupled electrode provides a means of non-contact ECG measurement which could be used in many applications and it is therefore being further studied in recent years. The ECG recording in the bathtub was studied using the capacitive coupled electrode, but only the R peaks in the recorded signals were large enough to be auto-detected, and other details were completely contaminated by noise[5]. Similar results were obtained in toilet applications, where the capacitive coupled electrodes composed of the Cu plate and the PTFE film was used[6]. A wearable ECG measuring system was designed based upon capacitive coupled electrode, and good quality ECG signal was obtained through thin clothes after the algorithm based on a singular spectrum analysis and designed for noise reduction was applied [7]. But clear ECG signal couldn't be obtained in real time because the algorithm was carried out in Matlab off-line. The concept of a wireless wearable device through the use of non-contact capacitive based electrode was designed and implemented[8]. Both ECG and respiration rate were measured using only the capacitive coupled electrodes and an analog conditioning circuit, but it wasn't minimized to a surface mount level on a printed circuit board (PCB).

In this paper, an ECG measurement system based on capacitive coupled electrode is propose. It can acquire ECG signal both in contact with skin and through clothes with real-time denoising algorithm and automatically store ECG data for later analysis. To verify the performance of proposed system, two different conditions of the ECG measurement are experimentally tested in comparison with Ag/AgCl electrode. One is a contact condition in which capacitive coupled electrodes touched the skin. Another is the non-contact condition in which ECG was measured through clothes.

The rest of this paper is organized as follows: Section II explains the proposed system. Section III describes a real-time denoising method based on wavelet transform. After that, we verify ECG signal quality by proposed system in Section IV. And Section V concludes the paper.

II. System design

The non-contact ECG measurement system consists of two parts, hardware and software. The hardware part includes two capacitive coupled electrodes, a reference electrode, a signal processing module and a signal transmission module.

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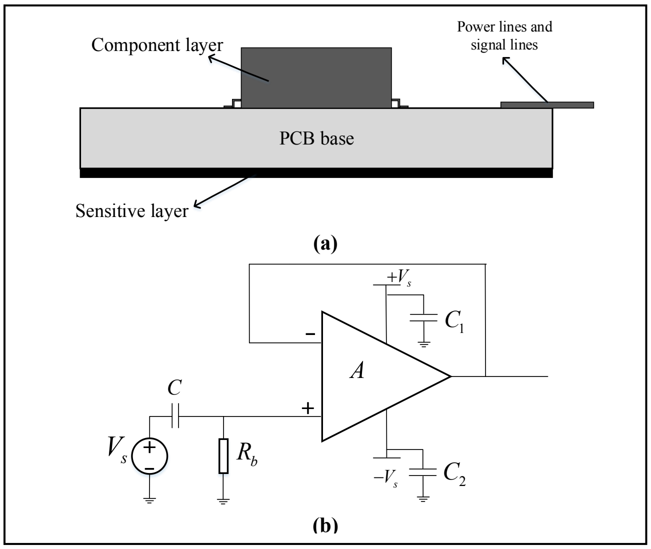
The software part includes data extraction, signal processing, data storage, and waveform display.

A. Capacitive Coupled Electrode

Fig. 1(a) shows the structure of the capacitive coupled electrode. The proposed capacitive coupled electrode consists of three layers, including sensitive layer, PCB base and component layer. The PCB base is used to carry the sensitive layer on one side and the electronic components on the other. The sensing layer is coated with copper and then plated with gold to ensure its electrical conductivity and smooth surface. The sensing layer can form a coupling capacitance with the human skin to sense the ECG changes of the skin.

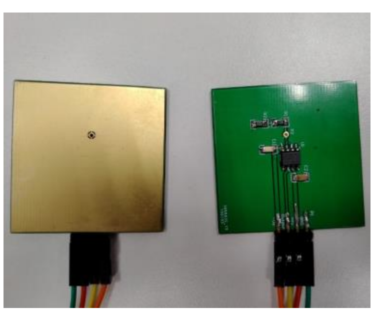
Figure 1. Capacitive coupled electrode.



The component layer is mainly composed of a resistor and an operational amplifier OPA124 (Texas Instruments). The schematic of this electrode is shown in Fig. 1(b). The resistor R_b is used for current biasing and the operational amplifier is used as a voltage follower.

The prototype of the capacitive coupled electrode is shown in Fig. 2.

Figure 2. Prototype of the capacitive coupled electrodes

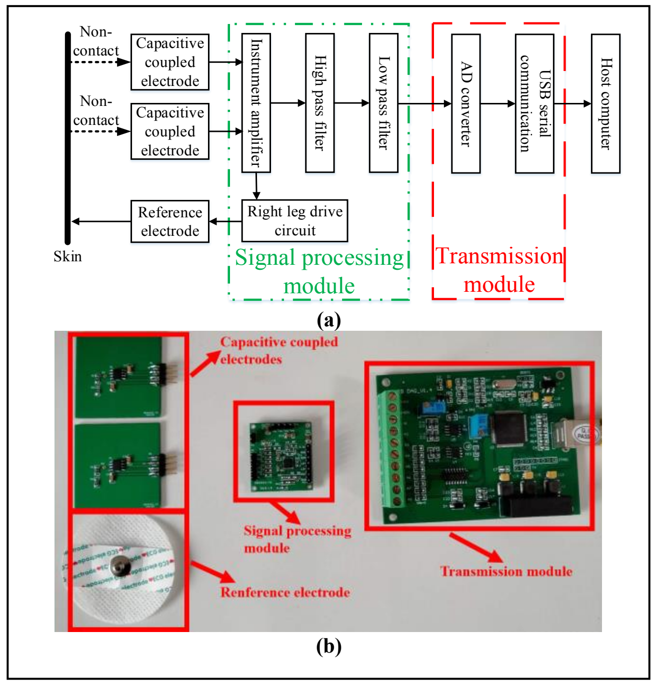


B. Hardware Design

Hardware part of the system includes the capacitive coupled electrode aforementioned, a signal processing module and a signal transmission module based on modular designing method, as shown in Fig.3(a).

The signal processing module is composed of an instrument amplifier, a high pass filter, a low pass filter and a driving right leg circuit. The ECG signal in human skin is sensed by two capacitive coupled electrodes in a non-contact manner, and then are differentially amplified by an instrumentation amplifier. Then the baseline drift of the signal is reduced by the high-pass filter and the high-frequency noise is reduced by the low-pass filter. In addition, due to the function of the driving right leg circuit, the common mode signal of the two capacitive coupled electrodes is led back to the human skin through the reference electrode, and being suppressed[9, 10]. Finally, the ECG signal is converted from analog signal to digital signal by an analog to digital converter (ADC), and then transmitted to the host computer by USB serial communication. Fig.3(a) shows the prototype of hardware system.

Figure 3. (a)Block diagram and (b)prototype of hardware system.



C. Host Computer Software

The host computer software facilitates the human-computer interaction of the operator[11, 12], as well as monitoring the real-time ECG waveform while storing the data for later analysis, as shown in Fig.4.

Figure 4. Host computer software interface

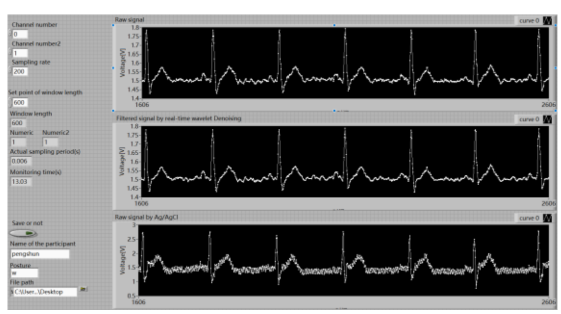
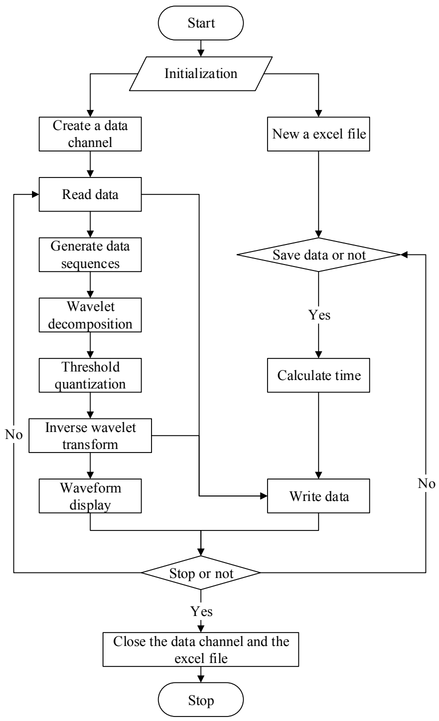


Fig. 5 shows the flow diagram of the host computer software. The whole process includes the following contents.

Firstly, the parameters are initialized, then the virtual data channel is created and an excel file is created for data storage. Then enter a main loop for data processing. Finally, both the data channel and the excel file are closed after the main loop ends.

Figure 5. Work flow diagram of the host computer software



In the main loop, the data flow is divided into two paths. One of them is used for real-time signal filtering and denoising. Firstly, the data is read from the virtual data channel. Then a real-time signal denoising is applied based on wavelet transform. Finally waveform is displayed.

Another path of data flow is used for data storage. Before execution, it is necessary to determine whether the user saves the data or not. When the data need to be saved, the time, the raw signal and the filtered signal are written into the created excel file.

III. ALGORITHM

ECG signal acquired by capacitive coupled electrodes will contain a lot of noise. We propose a real-time denoising algorithm based on wavelet transform. A moving window is set to get the latest raw ECG data named as $x(k-l+1)$, $x(k-l+2),\cdots x(k-1)$ together with the current data point to be filtered $x(k)$, where l is the length of the window. Multi-scale decomposition based on Daubechies wavelet is applied to process the data in one moving window at the specific moment. The order of wavelet transform is 5 with 3 decomposition layers. Thus, an approximate vector cA_3 and 3 detail vectors cD_1, cD_2, cD_3 are obtained.

Threshold quantization is performed on the three detail vectors aforementioned [13]. Taking cD_1 as an example, we sort the absolute value in ascending order and square each element to have a new vector NV. For each element k in vector NV, we calculate the risk vector $Risk$ based on the equation (1) below. Then we find a k_0 to minimize $Risk$ and obtain the threshold $Tr_1 = \sqrt{NV(k_0)}$.

$$Risk(k) = \frac{n_1 - 2k + \sum_{j=1}^{k} NV(j) + (n_1 - k)NV(k)}{n_1} \tag{1}$$

where, n_1 is the length of cD_1.

For each value in detail vectors, when the absolute value is larger than or equal to this given threshold, it remains unchanged. Otherwise, it is set to 0.

Finally, the filtered detail vectors are performed wavelet inverse transform with approximate vector thus to get the ECG signal sequence $y(k-l+1)$, $y(k-l+2),\cdots y(k-1)$. And $y(k)$ is the real-time output for one sampling input $x(k)$.

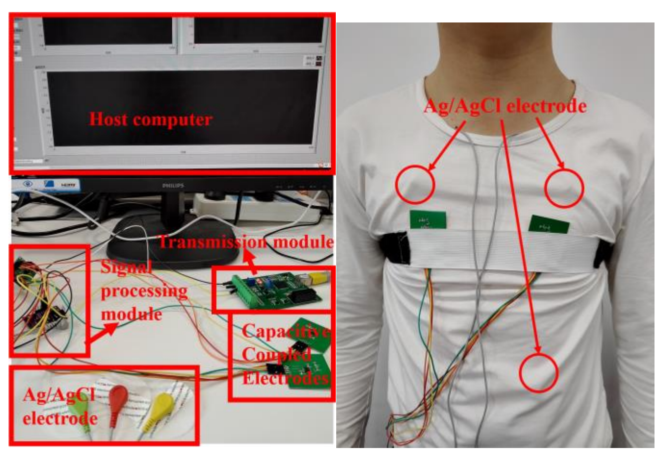
IV. EXPERIMENTS AND RESULTS

The experimental procedures involving human subjects described in this paper were approved by the Institutional Review Board.

A. Experimental Setup

Experimental setup of the ECG measurement system proposed is shown in Fig. 6. When measuring ECG, the electrodes can be placed either as standard leads or as non-standard leads. In this experiment, two capacitive coupled electrodes were placed in the right chest and left chest, and the reference electrode was placed in the left waist.

Figure 6. Experimental setup of the ECG measurement system

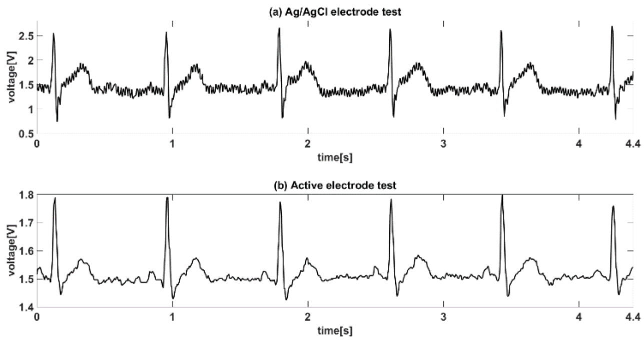


To verify the performance of proposed system, two different conditions of the ECG measurement are experimentally tested. One is a contact condition in which capacitive coupled electrodes touched the skin. Another is the non-contact condition in which ECG was measured through a simple cotton underwear (about 1 mm in thickness). In addition, in order to better test the performance of capacitive coupled electrodes, conventional Ag/AgCl electrodes were used for comparison in the experiment. Two similar signal processing modules are used in two measurement systems to avoid their different effects on the experimental results.

B. Experimental Results

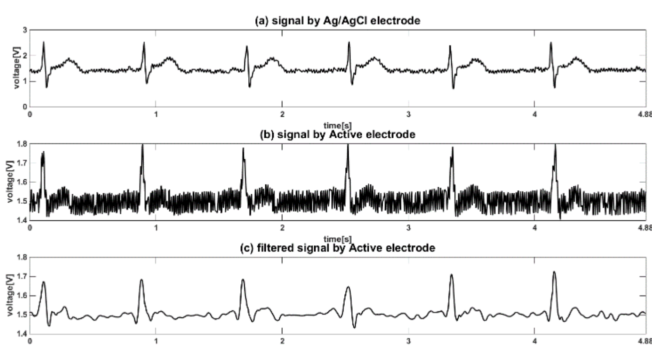
Firstly, the performance of the system was tested when the capacitive coupled electrode was attached to the skin. Fig. 7(b) shows the ECG signal which has not been filtered by the host computer software. Because of the hardware filtering, the signal has almost no noise. Compared with the results of conventional Ag/AgCl electrodes measured using the same acquisition system in Fig. 7(a), it can be seen that the performance of the capacitive coupled electrodes proposed is better than that of traditional Ag/AgCl electrodes when the capacitive coupled electrode was attached to the skin.

Figure 7. Experimental results in contact condition



The experimental results in non-contact condition, in which ECG was measured by capacitive coupled electrodes through a simple cotton underwear (about 1 mm in thickness), are shown in Fig. 8(b) shows the ECG signal which has not been filtered by the host computer software. Because the sensor impedance increases dramatically in the non-contact case, the ECG signal acquired contains a lot of noise, causing T wave is not very clear in ECG waveform. Fig. 8(c) shows the ECG waveform which has been filtered by the host computer software, in which T-wave is very clear. Compared with the results of conventional Ag/AgCl electrodes measured in Fig. 8(a), it could be verified that ECG signals are obtained by the proposed system in non-contact condition.

Figure 8. Experimental results in non-contact condition



V. DISCUSS AND CONCLUSION

A non-contact ECG measurement system based on capacitive coupled electrode is designed and modularized. It consists of signal acquisition module, signal processing module, signal transmission module and host computer software. The signal acquisition module includes two capacitive coupled electrodes and a reference electrode, and the ECG changes in human skin could be sensed by capacitive coupled electrodes both with touching skin and through clothes. We also propose a real-time ECG denoising algorithm based on wavelet transform with a moving window. To verify the performance of proposed system, two different conditions of the ECG measurement, including contact condition and non-condition, are experimentally tested in comparison with Ag/AgCl electrode. The results show that the capacitive coupled electrode is better than the conventional Ag/AgCl electrode when it is attached to the skin, and the clear ECG waveform can be obtained under non-contact measurement. In addition, the system proposed could measure ECG waveform in real time and store data for later analysis because of the host computer software.

The limitation of this system is that although the reference electrode could be placed in a simple manner, such as being held in the hand, it still needs to touch the skin. In the later stage of work the reference electrode should also be made into a non-contact electrode.

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