Adaptive Noise Cancellation Method for Capacitively Coupled ECG Sensor using Single Insulated Electrode

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Abstract— **This paper describes a noise reduction method for capacitively coupled ECG sensors. Capacitively coupled sensors using an insulated electrode have been proposed to obtain ECG signals without pasting electrodes directly onto the skin. It can achieve better usability than conventional ECG sensors. However, it is difficult to remove noise contamination, because the high input impedance and low input capacitance are required to realize the capacitively coupled ECG sensor. Especially, base-line drift and power-line noise are more serious problem when using a single electrode structure. To address this problem, we propose a noise cancellation technique using an adaptive noise feedback approach, which can improve the availability of the capacitive ECG sensor using a single electrode. An instrumental amplifier is used in the proposed method for the first stage amplifier instead of voltage follower circuits. A microcontroller predicts the noise waveform from an ADC output. To avoid saturation caused by base-line drift and power-line noise, the predicted noise waveform is fed back to an amplifier input through a DAC. We implemented the prototype sensor system to evaluate the noise reduction performance. Measurement results show that the proposed method can suppress both of base-line drift and power-line noise simultaneously.**

Keywords—electrocardiogram (ECG); heart rate; capacitively coupled; noise reduction;

I. INTRODUCTION

Electrocardiography (ECG) and heart rate are important bio-signals used for heart disease detection, heart rate variation analysis, and exercise intensity estimation. Recently, long-term ECG monitoring systems using paste-type wearable devices have been developed [1-3].

In the long-term monitoring, conventional ECG and heart rate sensors present shortcomings in terms of usability. These systems require pasting of wet electrodes directly onto the skin. Dry type electrodes have been developed to replace wet type electrodes, but they should be contacted electrically to the skin. These electrodes also affect the sensor device size. At least two electrodes are necessary to measure ECG. These difficulties have hindered the progress of wearable sensors.

Photoplethysmographic (PPG) sensor, which consists of LEDs and photodetectors, have been used in watch-type wearable sensors to detect HR,. The HR can be measured using reflected light from human skin and blood vessel, which include information related to the hemoglobin concentration variation of blood. This PPG sensor does not require electrical contact, but it requires direct skin contact for light exposure and for the reflected light detection. Power consumption is also a shortcoming of the PPG sensor because the LED requires at least 10 mA. Although recent PPG sensors employ intermittent LED drive, they still consume several milliamperes of current on average.

To avoid direct skin contact during ECG measurement, a capacitively coupled noncontact measurement method has been proposed [4–6]. This method can obtain the ECG signal through insulators such as clothing (see Fig. 1). The electrode, which is capacitively coupled to the human body, can record the biopotential from the heart. Various applications have been

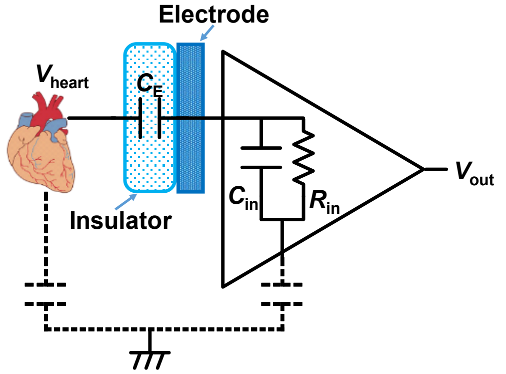

Fig. 1. Capacitively coupled ECG sensor overview [11].

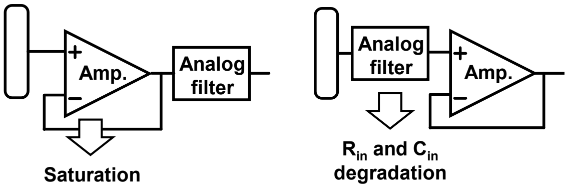

Fig. 2. Conventional noise reduction approach.

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developed using the capacitively coupled sensor: it can be implemented for a chair [7], a bathtub [8], a lavatory seat [9], and a driver seat [10].

A salient concern related to the capacitively coupled sensor is strong noise contamination. Therefore, a noise-reduction technique for these sensors is proposed in this work to improve both usability and availability of ECG measurements.

II. CAPACITIVE-COUPLED SENSOR

Fig. 1 depicts the principle of the capacity-coupled ECG sensor. To detect biopotential using the insulated electrode, very high input impedance and small input capacitance (R_{in} and C_{in} in Fig. 1) are necessary for the first stage amplifier. Generally, a voltage follower circuit, which has very high input impedance amplifier (> 1TΩ) and a high bias resistance (> 1GΩ), is used in the first stage.

These features cause strong noise interference. Body motion artifacts and the environmental electrical field interference are the primary causes [12]. This work specifically focuses on base-line drift and power-line interference. These noises cause saturation problems in the first stage amplifier.

Unfortunately, implementing analog filters in front of the first stage amplifier is difficult because of requirements for high impedance and low capacitance input (see Fig.2). To address this problem, differential input and signal injection approaches have been proposed in earlier works [13]. However, these require multiple electrodes, which spoil the usability benefits of capacitively coupled sensors.

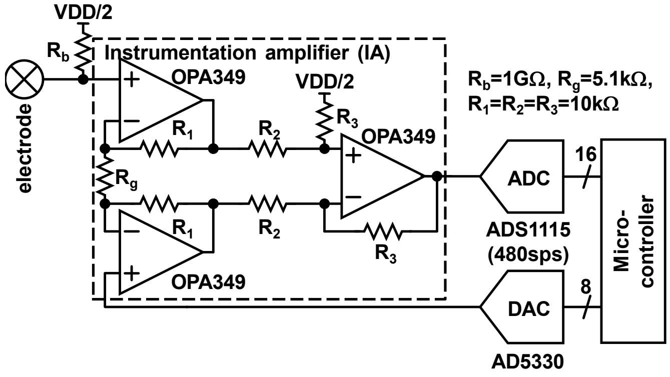

Fig. 3. Proposed architecture using noise feedback for capacitively coupled ECG sensor.

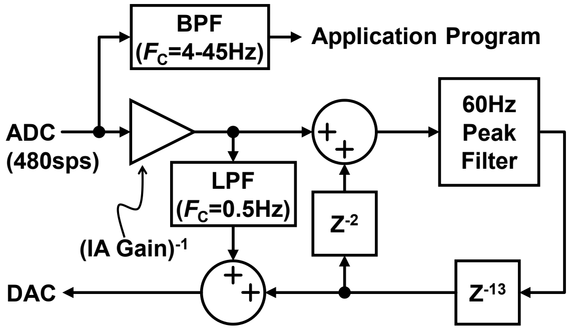

Fig. 4. Digital filters implemented in MCU for base-line drift and power-line noise extraction.

III. PROPOSED METHOD

The objective of this work is realizing the noise reduction without degradation of the input impedance and the input capacitance only using single electrode. Fig. 3 presents a block diagram of the proposed sensor. An instrumentation amplifier (IA) is used as the first stage amplifier. The insulated electrode and the bias resistance are connected to an IA input. The predicted noise waveform is generated by the DA converter (DAC) and the microcontroller, which are connected to another input of IA. The IA output is connected to an AD converter (ADC).

The microcontroller predicts the base-line drift and the power-line noise waveform using ADC output. Because the power-line noise frequency is already known as 50 Hz or 60 Hz, its waveform can be predicted using the previous ADC output. Under most circumstances, the phase and amplitude of the power-line noise are almost same as one period prior. The base-line drift can also easily extract using a low pass filter (LPF). We implemented the digital filters using the microcontroller unit (MCU) to predict these noises continuously.

Fig. 4 shows details of the digital filters implemented in the MCU. This implementation assumes 60-Hz power-line noise and 480-Hz sampling rate of ADC. A 60-Hz peak filter (see Fig. 5) and LPF with 0.5-Hz cutoff frequency (see Fig. 6) are implemented to extract the noise component from the sum of the ADC output and the previous DAC output. Then, previous DAC output is required because the IA input (+) equals the sum of the DAC output and the IA output. The ADC output includes only the IA output.

The proposed method can suppress the noise without degradation of the input impedance and the input capacitance, because this method does not require the analog filter in front of the first-stage amplifier (IA). Even if the gain of the IA is greater than 0 dB, the proposed method can still prevent saturation caused by the noise.

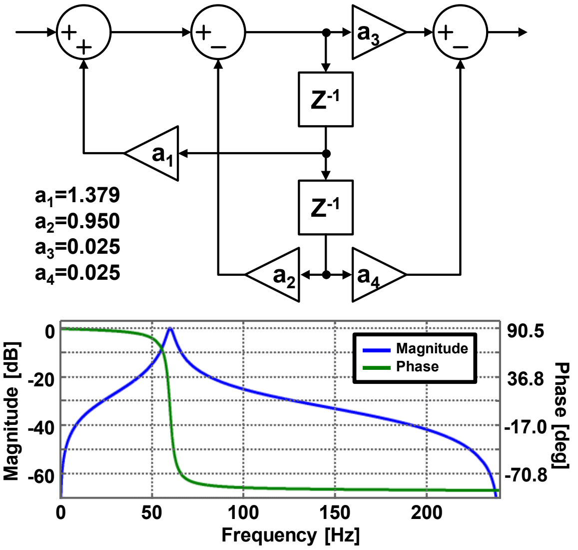

Fig. 5. Implementation of 60-Hz peak filter for power-line noise extraction..

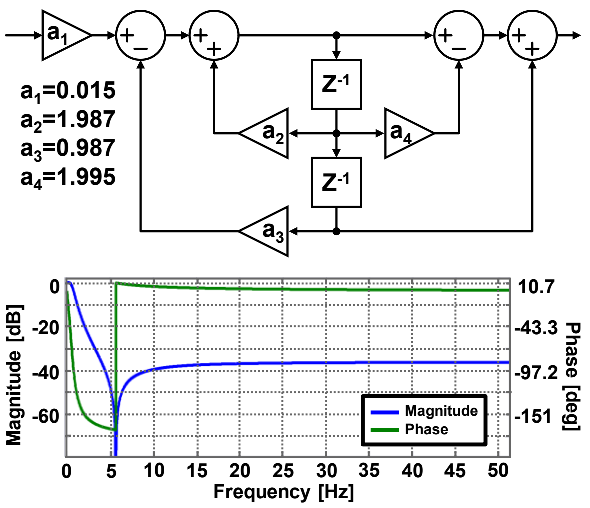

Fig. 6. Implementation of LPF for base-line drift extraction.

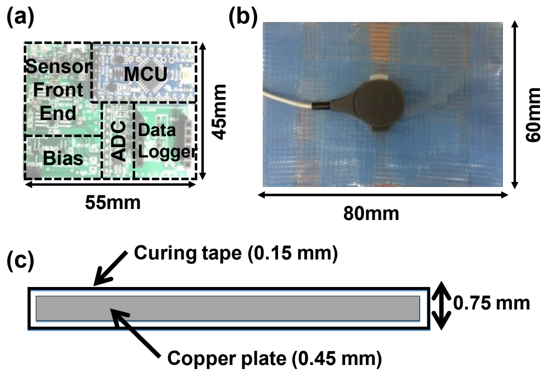

Fig. 7. (a) Prototype sensor board, (b) Insulated electrode, and (c) Cross section of insulated electrode.

IV. PERFORMANCE EVALUATION

To evaluate the proposed method, a prototype sensor board is implemented as portrayed in Fig. 7. The prototype sensor consists of a 16-bit resolution ΔΣ ADC (ADS1115; Texas Instruments Inc.), an 8-bit resolution DAC (AD5330; Analog Devices Inc.), and an 8-bit 8-MHz MCU (Arduino Pro Mini; SparkFun). The sensor front end, which has 2.5 V single supply voltage, consists mainly of an IA circuit using operational amplifiers (OPA349; Texas Instruments Inc.). The gain of IA is set to 14 dB.

First, the noise reduction performance was verified using a signal generator (SG) as portrayed in Fig. 8. The SG output 60-Hz sine wave with 0.2- Vpp amplitude and 1.09-V offset. Fig. 9 present the measurement results. Then, the DAC output and the IA output are observed simultaneously. When the DAC feedback is enabled, the 60-Hz frequency component is suppressed about 15 dB. In contrast, the high frequency component at 480 ± 60 Hz is increased when the DAC feedback is enabled. These high-frequency components can be suppressed sufficiently using the LPF in front of the ADC.

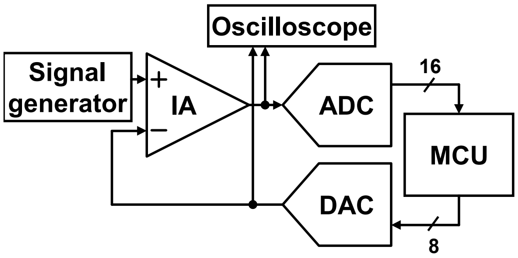

Fig. 8. Experimental setup for 60-Hz sine wave input from signal generator.

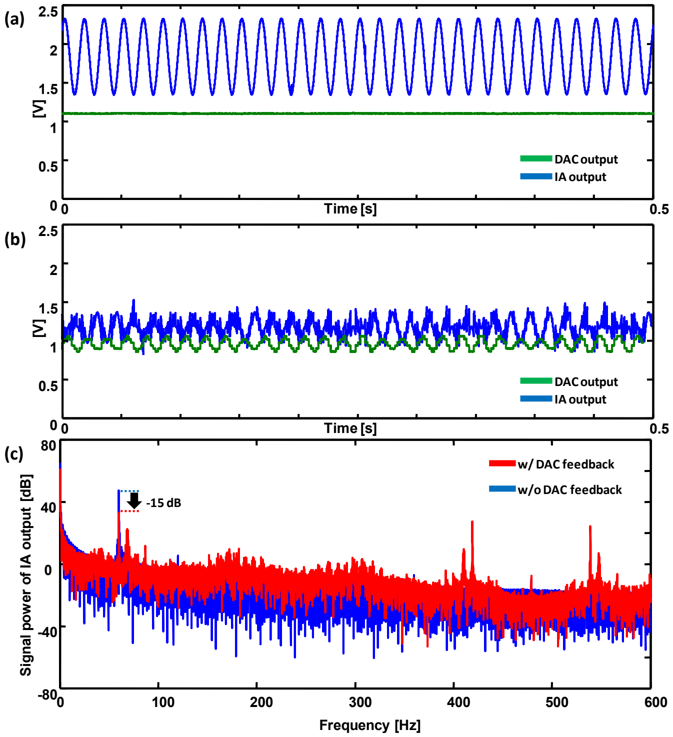

Fig. 9. Measurement result with 0.2-Vpp 1.09-V offset 60-Hz sine wave; (a) w/o DAC feedback, (b) w/ DAC feedback, and (c) signal power comaprison.

Fig. 10 presents the transient waveform of 0.4-Vpp 60-Hz sine wave input with several offset voltages. In this experiment, the DAC output was fixed to VDD / 2 in the first 5 s. Subsequently the proposed feedback scheme was activated. After that, the offset voltage is swept from 0.5 V to 2.0 V with 100-mV step at every 5 s. As presented in Fig. 10, the saturation of IA can be successfully prevented using the DAC feedback.

Next, to evaluate the performance of the proposed system, we conducted ECG measurement from a human body using the prototype sensor board. This experiment was conducted in a laboratory, which is not shielded. To evaluate the accuracy, the measured ECG using the proposed sensor is compared with those of the reference sensor (CamNtech Actiwave Cardio). The proposed sensor and reference sensor record the ECG signal and heart rate simultaneously as depicted in Fig. 11. The proposed sensor board and the insulated electrode are pasted on the clothing surface. As shown in Fig. 12, the saturation of the IA caused by base-line drift and power-line noise can be suppressed in proposed sensor.

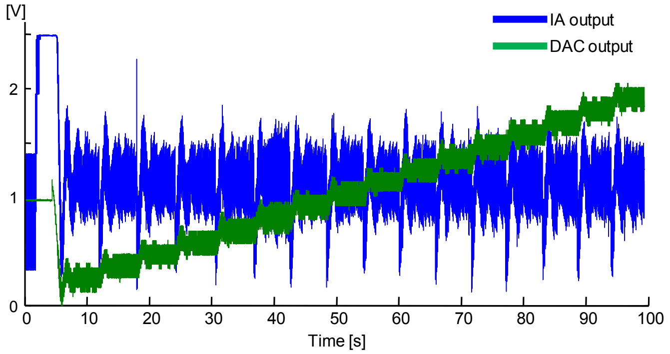

Fig. 10. Transient waveform of 60-Hz sine wave input with several offset voltages. The offset voltage is swept from 0.5 V to 2.0 V with 100-mV step at every 5 s.

V. CONCLUSION

The objective of this work is realizing the noise reduction for the capacitively coupled ECG sensor without degradation of the input impedance and the input capacitance only using single electrode. The proposed method employs the estimated noise waveform and DAC to mitigate the noise interference in the first-stage amplifier. The measurement result using the prototype sensor shows that both of the base-line drift and the power-line noise is reduced without R_{in} and C_{in} degradation.

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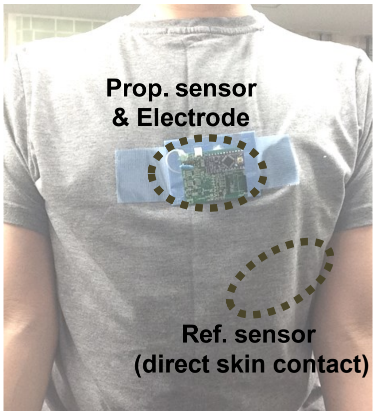

Fig. 11. Experimental setup for ECG measurement. ECG is measured by both of proposed sensor and reference sensor simultaniously.

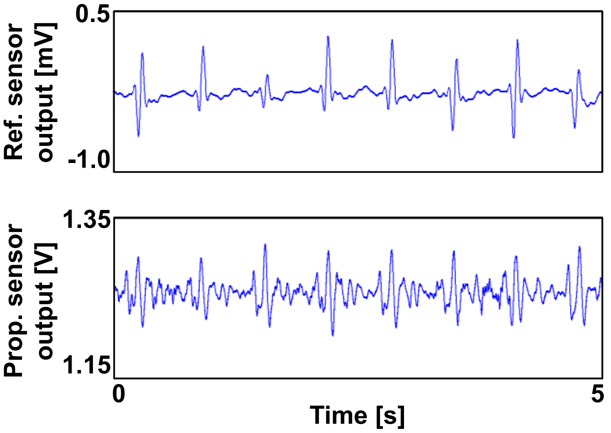

Fig. 12. Measurement result of ECG.