Capacitively Coupled ECG Sensor System with Digitally Assisted Noise Cancellation for Wearable Application

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***Abstract*—This paper describes a digitally assisted noise cancellation method for a capacitively coupled electrocardiogram (ECG) sensor. This sensor using an insulated electrode can measure ECG through an insulator such as clothing without direct skin contact. In wearable applications, this type of ECG sensor is superior in terms of usability compared with the pasted type ECG sensor. However, noise immunity is an important difficulty related to capacitively coupled ECG sensors because it requires very high input impedance and small input capacitance for the first-stage amplifier. This circuit characteristic considerably degrades its noise immunity for the power line noise and motion artifact. To address this difficulty, we propose the noise feedback method, which can improve the availability of a capacitively coupled ECG sensor. Noise caused by body movement and the surrounding environment included in the output of the AD converter is extracted by digital filters. DC offset, baseline fluctuation, and low-frequency component of body motion noise are extracted using a variable-gain loop filter. Power line noise is also extracted using a peak filter. Then the noise waveform is estimated from the result of the previous cycle. This noise information is DA converted and given feedback to the first stage amplifier. The proposed method was evaluated using prototype sensor in an actual environment. ECG measurements were confirmed in both two-electrode configuration and single-electrode configuration. Measurement results show that the power line noise can be suppressed to -29.2 dB at maximum.**

Keywords*—*capacitively coupled ECG sensor; digitally assist; electrocardiogram (ECG); noise feedback; wearable

I. Introduction

In recent years, an increase in the number of and need for caregivers because of aging has become a social problem. Lifestyle-related diseases are the main reasons requiring nursing care. Consequently, prevention and early detection of such diseases are important. Reduction of medical expenses is also possible if diseases can be treated before becoming severe. Routine monitoring of biological information and analysis of data contributes to lifestyle disease prevention. Among the many kinds of biological information, electrocardiography is important for early detection of cardiovascular disease, analysis of heart rate variation, evaluation of exercise intensity, and stress evaluation. Wearable sensors that measure and analyze such data in real time have attracted attention.

To widen the use of daily measurement of ECG using the wearable sensor, the burden on the user must be lightened. Conventional ECG sensors require direct contact of the electrodes with the skin. Although dry electrodes have also been developed in recent years, their necessity to make direct contact has not been confirmed. Such contact, the cause of discomfort and rash, hinders the wider use of pasting wearable sensors.

As an ECG measurement method that requires no electrodes directly on the skin, a noncontact measurement method using capacitively coupled electrodes has been proposed [1–3]. The capacitively coupled ECG sensor has high usability because it can take measurements even if an insulator such as clothing is interposed between the electrode and the human body. Applications such as a chair [4], a bathtub [5], a toilet seat [6], and a driver's seat [7] have been proposed.

However, capacitively coupled sensors have an important shortcoming: they are strongly affected by body movement noise and power line noise. To overcome these difficulties, this paper presents a proposal of a noise cancellation method and realizes a capacitively coupled type ECG sensor that is useful for wearable applications.

II. Capacitively Coupled ECG Sensor

Fig. 1 shows an equivalent circuit of a capacitively coupled ECG sensor. High input resistance (R_{in}) and small input capacitance (C_{in}) are necessary to measure the potential of the body surface using a capacitively coupled electrode, which is

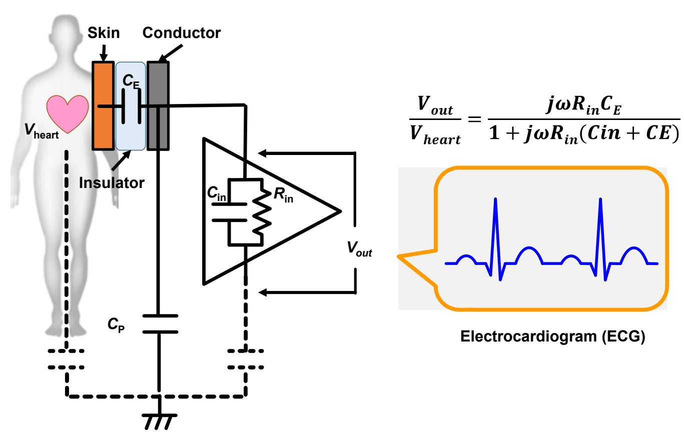

Fig. 1 Equivalent circuit of capacitively coupled ECG sensor [8].

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insulated from the human body. The coupling part capacitance (C_E) must be sufficiently greater than C_{in}. In this circuit, C_{in} and R_{in} are mainly determined by the characteristics of the operational amplifier and the resistance value for the bias. The parasitic capacitance (C_P) between the electrode and GND is also a difficulty: amplification becomes impossible when C_P becomes large.

For that reason, it is necessary to design a front-end circuit to satisfy these constraint conditions. When these conditions are satisfied, the input of the amplifier (V_{out}) becomes almost equal to the ECG signal (V_{heart}). Therefore, it is obtainable. Fig. 2 presents simulation results of the influence of C_E and C_P on the gain of the circuit. An OPA 349 is used as an amplifier. The simulation result shows that C_E is expected to be higher than 100 pF. The simulation result also shows that C_P is suppressed to 100 pF or less.

As described above, countermeasures against noise are indispensable for the capacitively coupled ECG [9] because it is susceptible to noise. Particularly, it is strongly affected by baseline drift, body movement noise, and power line noise. In a typical ECG, such noise is reduced by placing an analog filter in front of the first stage amplifier. However, the heartbeat component contained in the ECG is distributed in the range of several Hz to 40 Hz. To suppress noise while maintaining this signal, a filter with a large time constant is required. Therefore, satisfying the condition in Fig. 2 is difficult. Furthermore, the output might be saturated depending on the dynamic range and gain of the first-stage amplifier. In such a case, it is insufficient to put a filter behind the first-stage amplifier.

Therefore, we introduce a digitally assisted noise elimination method. In our previous work [10], a noise feedback method using a peak filter and a low-pass filter was proposed for single-electrode configuration of capacitively coupled ECG. For this study, we use the peak filter used in our previous work and improve these methods especially for low-frequency noise extraction. Furthermore, we investigate application of the noise feedback to both a single-electrode configuration and a two-electrode configuration.

III. Proposed Method

A capacitive coupling ECG can be configured with either a single electrode or two electrodes. Fig. 3 depicts the circuit of the analog front-end and the whole block diagram when applying the proposed method to each configuration. An instrumentation amplifier (IA) is used in the first stage of the single-electrode configuration. Then the electrode is connected to one input of the IA. The noise feedback from a DAC is connected to the other input of the IA. In the two-electrode configuration, the noise feedback is connected to a bias resistor in front of the first-stage unity-gain buffer (see Fig. 3(a)). When the bias resistance is 1 GΩ and the input capacitance is 2 pF, they constitute a low-pass filter with 80-Hz cutoff frequency. That configuration meets the noise feedback requirement unless the input capacity increases. Even when the input capacity increases, low-frequency feedback is available.

Fig. 4 portrays a block diagram of filters for noise extraction. They are implemented in a microcontroller. The ADC output is obtained by subtracting DAC from the first-

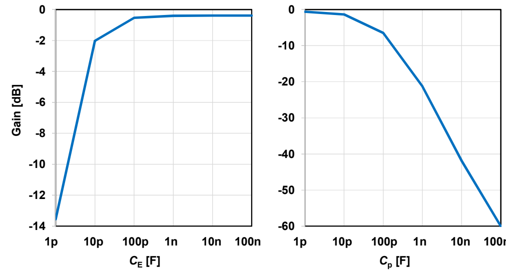

Fig. 2 Simulation result of C_E and C_P influences on the circuit gain.

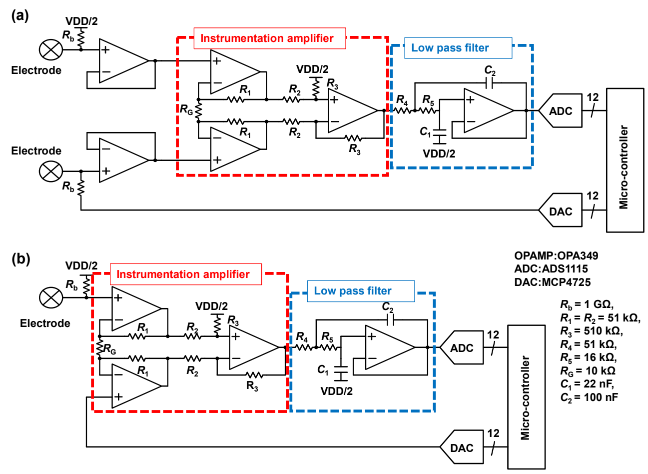

Fig. 3 Analog front-end circuits and block diagram of proposed sensor: (a) dual electrode model and (b) single-electrode model.

stage amplifier input and by then multiplying it by the gain. This filter block consists of a peak filter for power line noise extraction and a loop filter for low-frequency noise extraction.

Because the power line noise is limited to 50 Hz or 60 Hz, the frequency is extracted using a simple peak filter. Fig. 5 shows the peak filter configuration. This peak filter has an input of the sum of the DAC and the ADC to give the power line noise waveform of one cycle prior to the first-stage amplifier. The noise waveform can be predicted easily using the waveform of one cycle prior. This prediction is necessary because the delay occurs as a result of the conversion operation in the microcontroller, ADC, and DAC.

Next, low-frequency noises including DC offset, baseline variation, and low-frequency component of body motion noise are extracted using a filter as depicted in Fig. 6. This loop filter controls the noise feedback to adjust the output of the ADC to the bias voltage (VDD / 2). The ADC is directly input to the loop filter to bring the input closer to zero. In almost all cases, the input to the ADC is saturated at the start of operation because the input signal is amplified at least 100 times to measure the ECG. Noise feedback is started from that state with a large loop gain. After the input to the ADC falls within the dynamic range, the loop gain of the filter is reduced gradually. According to this control, the saturation of ADC is eliminated in a short time. The influence of the filter on the ECG signal is minimized.

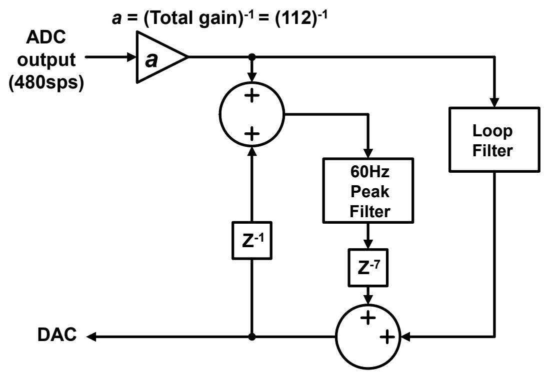

Fig. 4 Digital filters in MCU used for noise extraction.

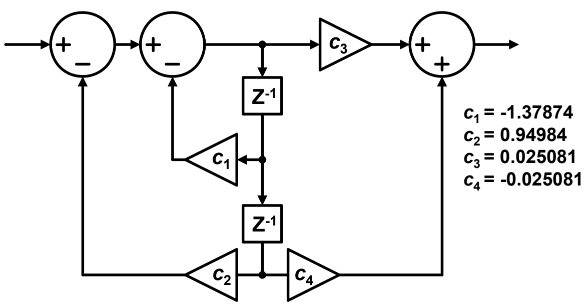

Fig. 5 Implementation of 60-Hz peak filter for power-line noise extraction.

As portrayed in Fig. 4, the outputs of the two filters are finally added and given feedback through the DAC. Then, the value of DAC input is stored in the register. This value will be added to the next ADC output, which is divided by the total gain of the system. This result represents the true input signal of IA, excluding the influences of gain and noise feedback.

Operation of the proposed filter was confirmed by simulation. Then, a measured ECG signal with 1 mV amplitude was used as test input, which is biased to VDD / 2. The total gain of the system was set to 40 dB. Fig. 7 depicts the response when the offset voltage is shifted 200 mV from VDD / 2. In this simulation, 60-Hz power line noise with 120-mV amplitude is simultaneously added when the offset voltage shifted. The ADC input falls within the dynamic range. The power line noise is suppressed to about 0.7 s after the offset fluctuation. Then the ECG signal is obtained.

IV. Performance Evaluation

The proposed method is implemented on a prototype board to evaluate its performance for actual measurements. Fig. 8 shows PCBs of the prototype of the capacitive coupling ECG sensor with noise feedback. It shows boards of two kinds. The small board has a first-stage amplifier; the base board consists of other analog circuits, ADC, DAC, MCU, and wireless communication circuit (BLE). Two small boards are used for the two-electrode configuration. By dividing the board, the distance between the first-stage amplifier and the electrode is minimized. Then, the wraparound of noise and unnecessary coupling are suppressed. A 16-bit resolution ADC (480sps ADS 1115; Texas Instruments Inc.) and a 12-bit resolution DAC (MCP 4725; Microchip Technology Inc.) are used in this implementation. The power supply for the front end circuit is

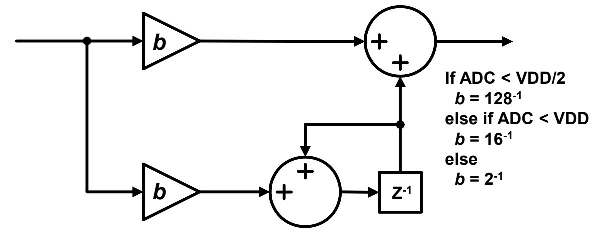

Fig. 6 Loop filter implementation for low-frequency noise extraction.

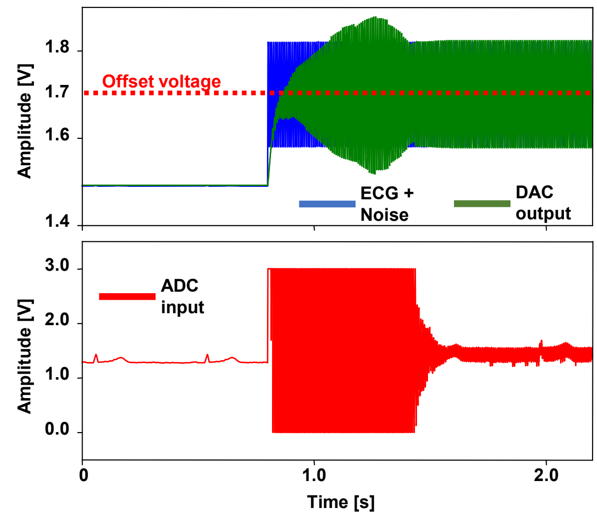

Fig. 7 Simulation result of noise feedback with ECG input.

2.5 V. Amplifiers are configured mainly with an OPA 349 operational amplifier (Texas Instruments Inc.). The total gain is set to 41 dB.

Fig. 9 shows an electrode used for the evaluation and experimental setup. The electrodes are made of aluminum foil insulated with dressing film. They are attached inside of a rubber band, and attached on clothing. The electrodes were placed at the A, B, and C positions as shown in Fig. 9. With the two-electrode configuration, three inductions are measured: between A and B (I-induction), between A and C (II-induction), and between B and C (III-induction). In the case of a single-electrode configuration, measurements were performed for each electrode.

First, to evaluate noise feedback effects, I-induction with the two-electrode configuration was measured at three places with different noise environments. Fig. 10 shows the measurement results obtained with and without noise feedback. When the noise feedback is not applied (Without FB in Fig. 10) measurement result is not stable. When only low-frequency noise feedback is applied (With Loop Filter FB in Fig. 10), the ECG is obtained in each place. Furthermore, when the power line noise feedback is applied (With Loop Filter + 60 Hz Peak Filter FB in Fig. 10), noise is suppressed to -29.2 dB at maximum.

Next, Fig. 11(a) shows the ECG waveform measured using each induction of the two-electrode configuration. Even when

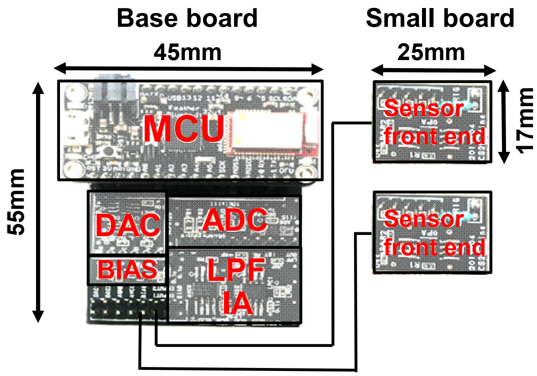

Fig. 8 Prototype sensor boards.

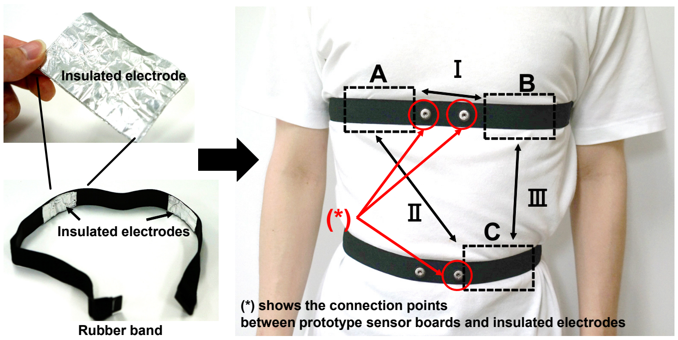

Fig. 9 Insulated electrodes and experimental setup.

clothes are sandwiched between the human body and the lectrodes, the same waveform as the usual ECG was obtained.

Finally, Fig. 11(b) shows the ECG waveform measured by each electrode with the single-electrode configuration. Compared to the two-electrode configuration, although the influence of noise is stronger, the heartbeat component is visible. The influence of low-frequency noise is suppressed.

V. CONCLUSION

This study examined a digitally assisted noise-canceling approach used for capacitively coupled ECG sensor to improve its availability for wearable applications. The proposed noise feedback method extracts power line noise and low-frequency noise using digital filters. We evaluated the single-electrode and two-electrode configurations using a noise feedback approach in actual environments. The prototype sensor showed high availability for all environments.

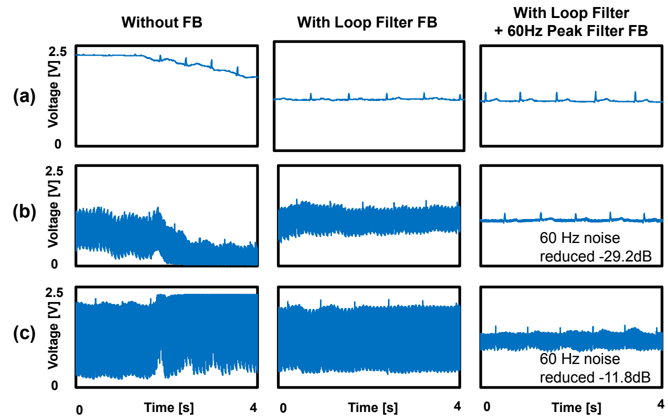

Fig. 10 Mesurement result of with and without noise feedback: (a) outside the room, (b) inside the room, and (c) nearside of power line noise source.

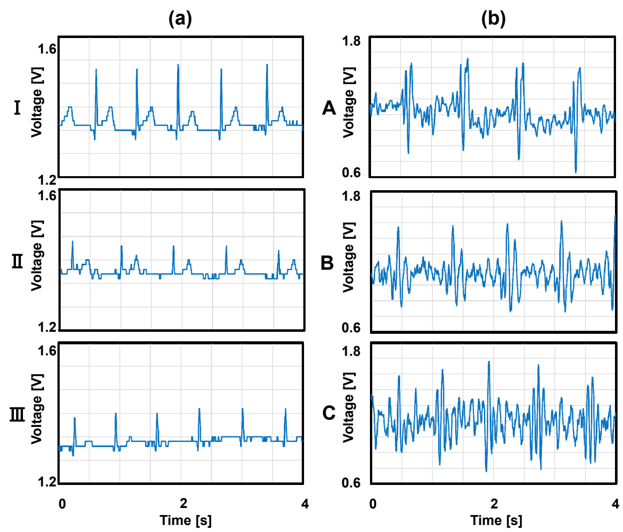

Fig. 11 Measurement result with each electrodes: (a) two electrode configuration and (b) single electrode configuration.

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