A Low-Power Photoplethysmography Sensor using Correlated Double Sampling and Reference Readout Circuit

Kana Sasai[1], Shintaro Izumi[1], Kento Watanabe[1], Yuji Yano[1], Hiroshi Kawaguchi[2], and Masahiko Yoshimoto[1]
[1]Graduate School of System Informatics, Kobe University, Kobe, Japan
[2]Graduate School of Science, Technology and Innovation, Kobe University, Kobe, Japan
sasai.kana@cs28.cs.kobe-u.ac.jp

***Abstract*—This paper describes a low-power photoplethysmography (PPG) sensor circuit using a current integration circuit. PPG sensors are widely used in modern healthcare products for monitoring cardiovascular information. However, the PPG circuits generally have a large power consumption because the LED driver consumes considerable energy to obtain the required amount of reflected light from the human body. A simple way to reduce the power requirements of PPG circuits is to lower the duty cycle of the LED through intermittent operation of the LED. However, this causes accuracy degradation because the target signal is susceptible to interference from various noises. To reduce the power consumption while maintaining accuracy, the correlated double sampling (CDS) method that we introduced in our previous work was used. In our previous work, wherein the PPG was placed on fingertips, the heartbeat error was 5 ms. This paper presents a signal-to-noise ratio improvement method for CDS by using a PPG sensor with current integration circuits. This enables SNR improvement and measurements to be taken from any part of the body. In the proposed method, the target PPG signal is extracted by canceling noise and DC components using two sensors. The proposed circuit was evaluated using actual measurements and the total consumption current was 26.9 µA. The root mean square error of the heartbeat interval was 4.27 ms, even though the sensor was worn on the wrist during the experiment.**

Keywords—noise reduction; PPG; pulse wave; low-power

I. INTRODUCTION

In recent years, cardiovascular diseases such as cerebral infarction and myocardial infarction have become the main causes of death in the world [1]. There is a need for not only prevention by improvement of lifestyle but also early detection through individuals monitoring their biological signal on a daily basis. It is important to routinely measure heart rate variability (HRV) which is determined using the R-R interval (RRI) of an electrocardiogram (ECG) [2], [3]. However, taking routine measurements frequently using an electrocardiogram maybe challenging as individuals have to attach electrodes to their chests. The RRI is often measured using the PPG sensor attached to an electrocardiograph.

The PPG sensor measures the volume change of an artery over time by irradiating a green LED light onto the blood vessels when placed on the skin, and measuring the reflected light using a photodiode (PD) as shown in Fig. 1 [4]. The PPG sensor is small and can be placed on parts of the body such as fingertips, earlobes and on the wrist. This may allow for more frequent HRV routine monitoring. However, the primary limitation of the PPG sensor is high power consumption because of the driving LEDs. Therefore, in order to realize daily monitoring of biological signal using a PPG sensor through a wearable device its power consumption must be lowered.

II. CIRCUIT DESIGN OF THE PPG SENSOR

A. *Transimpedance Amplifier Based Readout Circuit and Intermittent LED Driving*

The PPG sensor circuit mainly consists of an LED driver and readout circuits. The current obtained from the PD is very small and requires conversation and amplification to a voltage in the readout circuit. Transimpedance amplifiers (TIA, see Fig. 2(a)) are generally used for voltage conversion in circuits [5-9]. The TIA converts the current I_{in} from PD into a voltage having a transimpedance R_f . Therefore, the output voltage V_o is expressed as $V_{\mathrm{o}} = R_f * I_{\mathrm{in}}$. C_f in Fig. 2(a) is essential for negative feedback stability and can be calculated using the following equation [10].

$$C_f = \sqrt{\frac{C_{PD} + C_{\mathrm{in}}}{2\pi \mathrm{R_f}(GBW)}}$$

In the above equation, C_{PD} is a parasitic capacitance of the PD; C_{in} and GBW denote an input capacitance and a gain bandwidth of an operational amplifier, respectively; and R_f is a resistance determined by transimpedance gain.

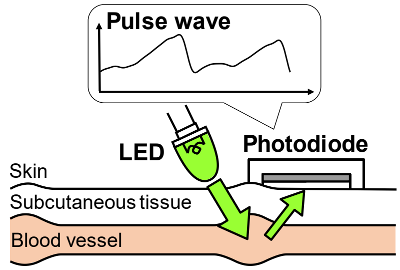

Fig. 1. Overview of PPG sensor.

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Active rate reduction methods using intermittent LED drivers have been used to reduce the power consumption of PPG sensors[5-9]. However, when the active rate is lowered, the SNR of the obtained PPG and the heartbeat error are degraded. In addition, it is difficult to follow the change of the offset of DC resulting from movement or changes in pressure. To eliminate the offset of the DC of the PPG signal with intermittent LED drivers, an additional feedback loop circuit for current compensation (see Fig. 2(b)) is required.

B. Current Integration Based the Readout Circuit and Correlated Double Sampling (CDS)

In our prior work [11], we introduced a current integration circuit shown in Fig. 3(a) instead of conventional TIA. This circuit outputs a voltage which obtained by integrating the charge generated from the PD with a feedback capacitance C_f. The output voltage V_o is expressed by the equation below.

$$V_o = I_{\mathrm{in}} * T_{\mathrm{sw}} * \frac{1}{C_f}$$

In the above equation, T_{sw} represents the time period when the switch is open, and it also the integration time. When the switch is closed, the integrated charge is reset. This allows for an effective reduction of the power consumption by synchronizing the LED activation timing and the sampling operation of the analog-to-digital converter. Some examples of measurements of the PPG waveform using the current integration circuits with intermittent LED drivers are given in Fig. 3(b). The primary disadvantage of the integration circuit is that it makes noise every time the switch is turned on and off. The CDS method [12] was introduced in our prior work [11] to overcome the aforementioned disadvantage. In the CDS method, the offset is sampled at time t_1 immediately after turning off the switch. It is sampled again at time t_2 after the charge is integrated. The difference of these two sampling results can be used as an output, allowing for the switching noise to be removed as shown in Fig. 4.

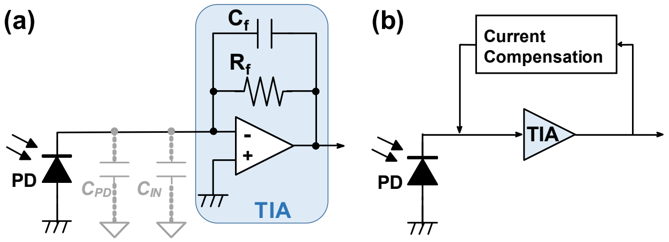

Fig. 2. (a) Readout circuit using TIA and (b) Current compensation feedback for intermittent LED driving.

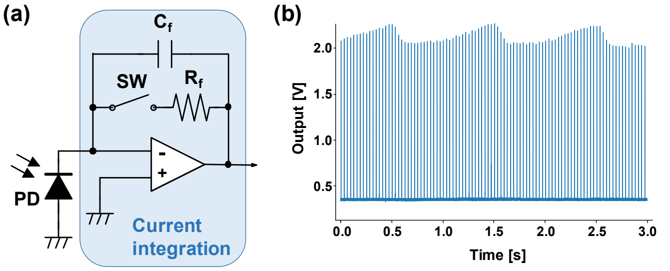

Fig. 3. (a) Readout circuit using current integration and (b) An example of current integration output including a pulse wave.

III. PROPOSED READOUT CIRCUIT

The current integration circuit and CDS method can achieve an ultra-low active rate (0.24%) of LED and a 5 ms heartbeat interval error [11]. However, previous studies showed that this method could only conduct measurements through contact with fingertips.

The signal obtained by the PPG sensor is mostly a DC component from skin tissue and veins, and the pulse wave signal is very small at less than about 5% [13]. The output of the current integration circuit consists of various noises as shown in Fig. 5. The noise produced when switching on and switching off can be suppressed by the CDS as described in Sect. II, however, the other noise such as a hum noise cannot be removed using current integration methods. When the sensor is placed on the wrist, it is assumed that the noise level is relatively constant despite the decrease in the level of signal of the pulse wave in comparison to the fingertips. Furthermore, it is challenging to suppress the noise using an analog filter because the signal and noise are modulated as shown in Fig. 4. It is also difficult to apply a digital filter after conducting CDS because the objective of the design is to allow for ultra-low sampling rates.

To overcome challenges posed by potentially applying a digital filter after conducting CDS, we propose a circuit with a new architecture that combines CDS and a reference circuit illustrated in Fig. 6. The proposed readout circuit will consist of a PD and an integrating circuit, with the same configuration as that of a current integration circuit will be added as a reference circuit. The input light of the PD of the reference circuit will be degraded by a Neutral Density (ND) filter. Light reflected by the blood in vessels will be eliminated using the ND filter. Furthermore, light reflected from the tissues and ambient light will only be attenuated by adjusting the filter. The difference between the outputs of the two integration circuits will be amplified by an instrumentation amplifier (IA) composed of three operational amplifiers. The CDS of the IA output is calculated by a microcontroller unit (MCU) including an AD converter (ADC).

IV. PERFORMANCE EVALUATION

The proposed PPG sensor was prototyped to evaluate the potential for power reduction and accuracy. The prototype sensor comprised of PDs, an ND filter, current integration circuits, CMOS switches, LEDs, an A/D converter, and a MCU as shown in Fig. 6. The operating voltages of the analog circuits

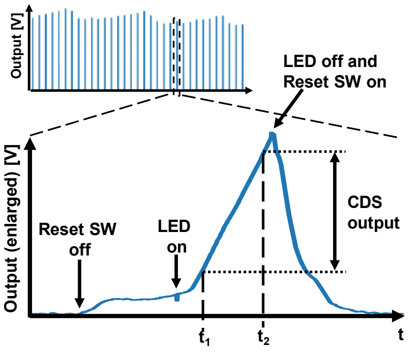

Fig. 4. Enlarged integration circuit output wave for one sampling period. Reset switch and LED are controlled periodically. CDS is adopted to integrate the circuit output, and differences in voltage is used as PPG signal.

and the MCU were all 3.3 V, and were generated by a power supply output and independent LDOs. A photograph of the prototype sensor and the setup of the test environment is given in Fig. 7.

The experimental subject was a 22-year-old woman. Measurements were taken over a period of 10 seconds for each of the settings. The tests were conducted in duplicate. The root mean square error (RMSE) of the interval of a heartbeat and the electric current used by the PPG sensor were evaluated and presented as an average of all the recorded measurement. A commercially available PPG sensor using TIA [14] and current single integration circuit type PPG sensor [11] were evaluated for comparative purposes. The current and the interval of a heartbeat were simultaneously measured using the three devices.

The results of the measured pulse waves are presented in Fig. 8. The sampling rate of the reference sensor was set at 400 Hz and the sampling rate of the current integration PPG sensor and proposed PPG sensor were set at 20 Hz. The results showed that the SNR of the integration circuit was improved in the proposed PPG.

In Fig. 9(a), the RMSE was determined as the difference between the extracted heartbeat intervals of the proposed PPG sensor in comparison to the reference PPG sensor [14]. The current integration PPG sensor [11] showed unacceptable RMSE because of the degradation SNR as shown in Fig .8. However, the proposed PPG sensor achieves 4.27 ms RMSE despite it being worn on the wrist. The interval error was less than 5 ms, which is acceptable for heart rate variability analysis [2].

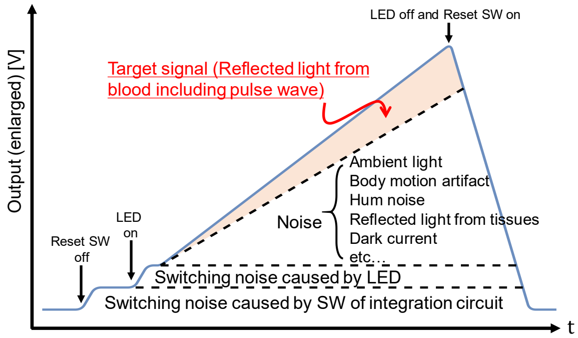

Fig. 5. Signal and noise components contained in current integration output.

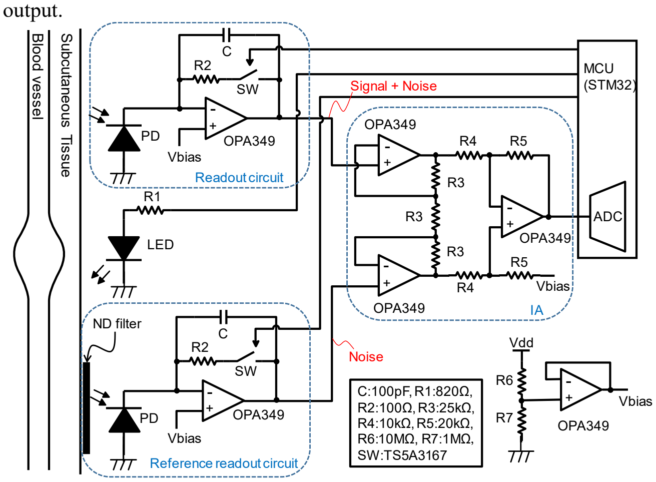

Fig. 6. Detailed circuit diagram of proposed PPG sensor. Outputs of two integration circuits are subtracted and amplified by instrumentation amplifier.

The current measurements of the PPG sensors were evaluated and compared to the results of previous studies, and are presented in Fig. 9(b). The total current consumption was 26.9 μA.

V. CONCLUSION

In this paper, we proposed a low-power and noise-tolerant PPG sensor comprising a CDS and a circuit with a new architecture. The proposed circuit achieved 89.7 % RMSE, an improvement with 5 μA current consumption overhead.

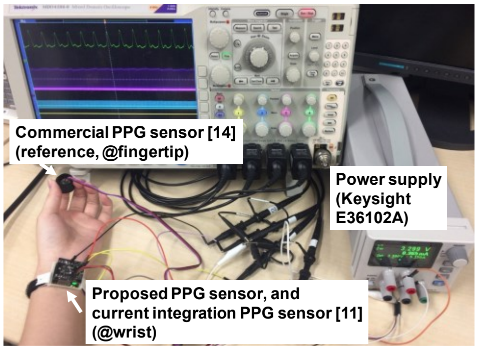

Fig. 7. Experimental setup.

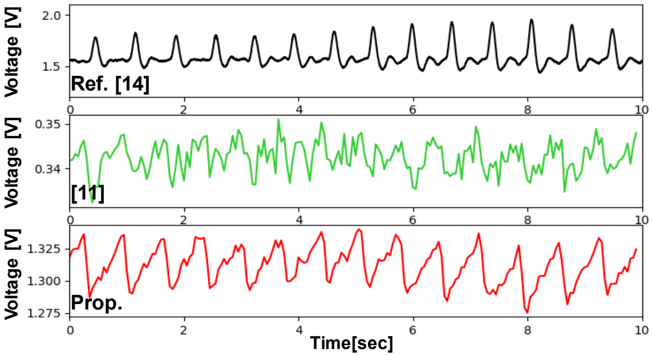

Fig. 8. Measured pulse waves. Reference sensor using TIA [14] was measured at a 400 Hz sampling rate. current integration [11] and proposed current integration based on PPG sensors were measured at a 20 Hz sampling rate.

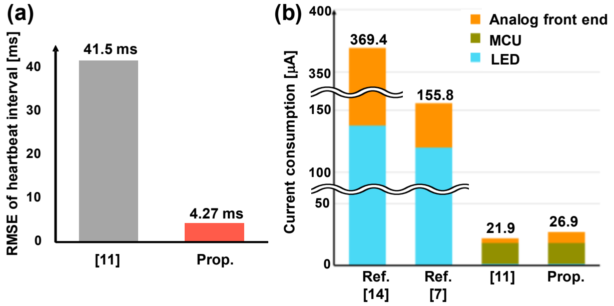

Fig. 9. (a) A comparison of the extracted heartbeat interval error of the proposed PPG sensor in comparison to a current integration PPG sensor [11]. Both PPG sensors were placed on the wrist of the test subject. (b) A Comparison of the current consumption of the proposed PPG in comparison to a current integration PPG sensor [11]. Proposed PPG sensor has 5 μA overhead compared with current integration PPG [11]. Note that the current integration sensor shows unacceptable heartbeat interval error at wrist as shown in Figs. 8 and 9(a).

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