# A 5-ms Error, 22-μA Photoplethysmography Sensor using Current Integration Circuit and Correlated Double Sampling*

Kento Watanabe, *Student Member, IEEE*, Shintaro Izumi, *Member, IEEE*, Yuji Yano, Hiroshi Kawaguchi, *Member, IEEE*, and Masahiko Yoshimoto, *Member, IEEE*

***Abstract*— This paper presents a low-power Photoplethysmography (PPG) sensing method. The PPG is commonly used in recent wearable devices to detect cardiovascular information including heartbeat. The heartbeat is useful for physical activity and stress monitoring. However, the PPG circuit consumes large power because it consists of LED and photodiode. To reduce its power consumption without accuracy degradation, a cooperative design of circuits and algorithms is proposed in this work. A straightforward way to reduce the power is intermittent driving of LED, but there is a disadvantage that the signal is contaminated by a noise while circuit switching. To overcome this problem, we introduce correlated double sampling (CDS) method, which samples an integration circuit output twice with short intervals after the LED turns on and uses the difference of these voltage. Furthermore, an up-conversion method using linear interpolation, and an error correction using autocorrelation are introduced. The proposed PPG sensor, which consists of the LED, the photodiode, the current integration circuit, a CMOS switch, an A/D converter, and an MCU, is prototyped. It is evaluated by actual measurement with 22-year-old subject. The measurement results show that 22-μA total current consumption is achieved with 5-ms mean absolute error.**

## I. Introduction

Cardiovascular disease occupies the largest portion of the causes of death in the world. In the statistics of 2015, 17.7 million people die of cardiovascular disease, which is 31% of the total deaths. It is important to detect and prevent cardiovascular disease at the early stage to suppress the decrease of working population in aging society. In this work, ultra-low-power Photoplethysmography (PPG) sensor is proposed with sufficient accuracy that can be applied for prevention and early detection of cardiovascular diseases.

Physical activity and stress can be monitored by measuring the fluctuation of heartbeat interval in daily life. The heartbeat variability is also used for diagnosis of cardiovascular disease [1, 2]. In recent years, wearable devices have attracted attention as a method for long-term monitoring such biometric information. Particularly, we focus on the PPG sensor, which is commonly used in recent wearable devices to detect cardiovascular information including heartbeat.

The PPG sensor irradiates green light to the body surface and measures the amount of light absorption by hemoglobin related to the volume change of blood vessels [3] (see Fig. 1). However, measuring the pulse wave signals consumes large amounts of power, because the PPG requires one or more LEDs and a photodiode to measure the reflected light. Since the battery capacity of the wearable device is strictly limited, the power consumption should be reduced to realize an easy-to-use daily life monitoring system.

To overcome this drawback, this study proposes a low-power hardware design and accurate heartbeat extraction algorithm for PPG sensor.

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K. Watanabe, S. Izumi, Y. Yano, H. Kawaguchi, and M. Yoshimoto are with the Graduate School of Science, Technology and Innovation, Kobe University, Kobe, Japan (e-mail: watanabe.kento@cs28.cs.kobe-u.ac.jp).

## II. Low-Power Hardware Design

This section describes about hardware architecture of PPG and its power reduction method.

### *A. Circuit configuration for PPG sensor*

As illustrated in Fig. 1, PPG sensor detects the reflected light from the human body using photodiode. Then, an electric current is generated by the photodiode according to the intensity of the reflected light. This small current is converted to a voltage and it will be amplified. Fig. 2 shows two kinds of photo detection circuits used in PPG.

Transimpedance amplifier (TIA, see Fig. 2(a)) is commonly used in recent PPG sensors [4, 5, 6]. The TIA converts the minute current $I_{in}$ generated by photodiode into a voltage with the transimpedance $R_f$. The amplified output voltage of this circuit $V_o$ is expressed as below.

$$V_o = R_f * I_{in}$$

$C_f$ in Fig. 2 is indispensable for negative feedback stability and can be calculated by the following equation [7].

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

Here, $C_{PD}$ is a parasitic capacitance of the photodiode. $C_{in}$ and $GBW$ respectively denote a input capacitance and gain

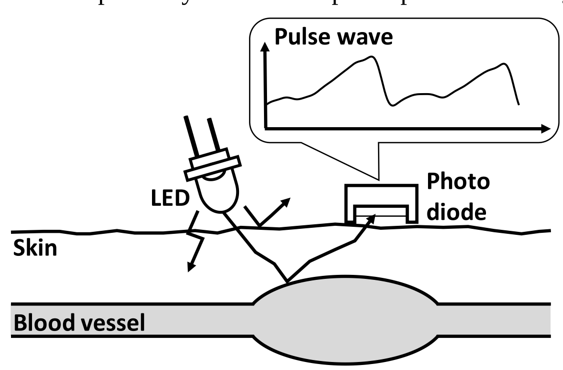



Fig. 1. Overview of PPG sensor.

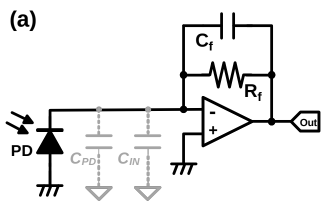



Fig. 2. Photo detection circuits for PPG: (a) Transimpedance amplifier (TIA) and (b) current integration circuit.

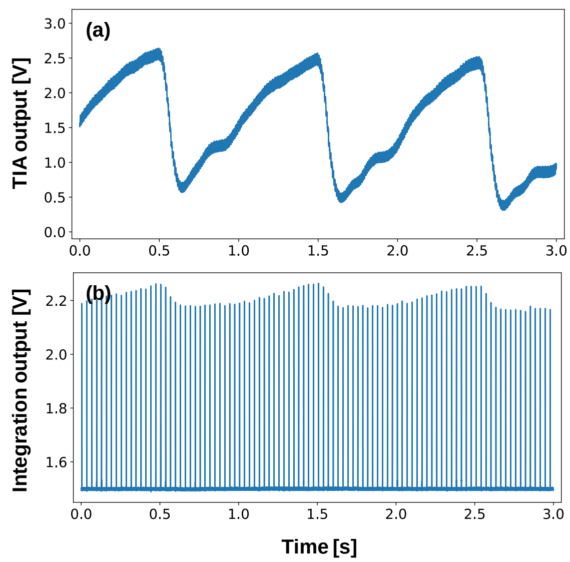



Fig. 3. Measured example of PPG waveform with (a) TIA and (b) current integration.

band width of an operational amplifier. $R_f$ is a resistance determine transimpedance gain.

As a different circuit configuration, a current integration circuit can be used as shown in Fig. 2 (b). This circuit outputs a voltage which obtained by integrating the charge generated from the photodiode using a feedback capacitor $C_f$. To prevent the saturation, a switch $SW$ is periodically turned on and the integrated electric charge in $C_f$ is reset. Then, the output voltage $V_o$ is expressed as below.

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

Here, $T_{sw}$ denotes the time duration to open the switch, which means the integration time.

Fig. 3 depicts measured examples of PPG waveform with each circuit configuration. Note that the integration circuit is reset periodically and it should be sampling with the synchronized timing using an analog-to-digital converter.

### B. Low-Power PPG Sensing Methodology

The LED consumes the largest power among the components of conventional PPG sensor circuit. To reduce its power dissipation, intermittent LED driving is used in prior works [5, 6]. The active rate of LED is expressed as $T_{LED}/T_{sample}$. Here, $T_{sample}$ and $T_{LED}$ respectively denote a sampling interval and time duration to turn on the LED for each sample. Since the current consumption of the LED is linearly proportional to this active rate, the basic strategy of

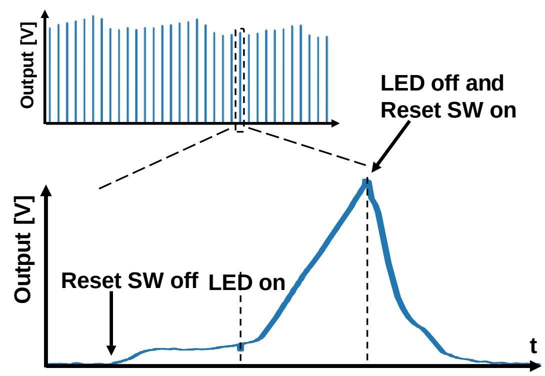



Fig. 4. Enlarged integration circuit output waveform for one sampling period. Reset switch and LED are controlled periodically.

power reduction is to shorten $T_{LED}$ and lengthen $T_{sample}$. However, when lowering the active rate of the LED, the signal-to-noise ratio of the obtained PPG deteriorates. It degrades the accuracy of the extracted heartbeat interval from PPG. Therefore, the objective of this research is to realize a measurement method that can keep accuracy even at low active rate.

TIA (Fig. 2(a)) is generally used in PPG. However, the TIA has a disadvantage that the influence of the dark current of the photodiode increases when the LED's active ratio decreases. On the other hand, current integration circuit (Fig. 2(b)) can mitigate this effect because it has reset operation and it can integrate the current only while the LED is activated. Thus the integration circuit is employed in this work.

## III. Signal Processing for Heartbeat Extraction

As described in Section II, the combination of the intermittent driving of LED and the integration circuit are effective for power reduction. Unfortunately, the integration circuit also has disadvantage that a switching noise is generated at the moment of the reset switch turns on and off. The influence of this noise becomes larger when reduce the LED turn on duration $T_{LED}$. Furthermore, the sampling interval $T_{sample}$ also affects to the accuracy, because long $T_{sample}$ causes large sampling error. This section describes control methods and algorithms to solve these problems.

### A. Switching Noise Reduction using Correlated Double Sampling

Fig. 4 shows the waveform obtained by enlarging the measurement example of Fig. 3(b). The voltage output is contaminated by the switching noise when the reset switch is turned on and off. In particular, the noise when the switch is turned off is integrated and the peak value included the noise component. This noise component is not constant, and it has enough large fluctuation compared with the signal at low active rate. On the other hand, the influence of the switching noise is limited in other period of LED driving.

Therefore, we introduce a correlated double sampling (CDS) technique. CDS has been used for image sensor circuits. In this method, a noise component affecting the output as an offset is sampled at first sampling, and second sampling is conducted after charge is accumulated. The difference of these two sampling result is used as a signal [8].The switching noise in the proposed PPG can be suppressed by same manner,

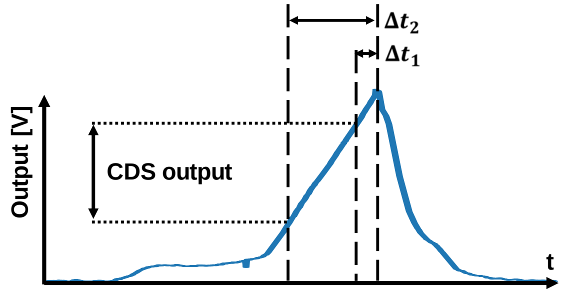



Fig. 5. Applying CDS to integration circuit output. Difference voltage is used as PPG signal.

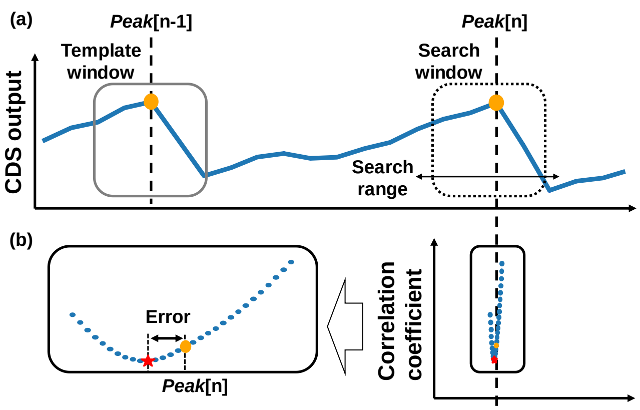



Fig. 6. Error compensation technique using autocorrelation: (a) peak detection result of CDS output and window definition, (b) peak error estimation using correlation coefficient.

which samples the integration circuit output twice with short intervals, and the difference of these voltages is used as shown in Fig. 5. In other words, it uses the slope of integral waveform instead of its peak voltage to obtain the PPG.

## *B. Sampling Error Compensation using Autocorrelation*

Next, to lengthen the sampling interval $T_{\text{sample}}$, the sampling error is compensated. Generally, when extracting the heartbeat interval from the PPG, the peak of the waveform is detected as shown in Fig. 6(a), and its interval is calculated. The sampling error that correlates with $T_{\text{sample}}$ is superimposed on this peak interval.

To mitigate this problem, it is effective to adopt autocorrelation using not only peaks but whole heartbeat waveforms. In our prior work [9], a sampling error compensation algorithm for Electrocardiogram (ECG) using upconversion and autocorrelation has been proposed. We apply this algorithm to PPG.

Fig. 6 (b) illustrates the sampling error compensation algorithm. First, the PPG waveform with low sampling rate is upconverted using linear interpolation. Next, correlation between two windows within the search range centered on the detected peak is calculated, and a time at which the correlation coefficient becomes maximum is used as corrected peak. In this work, the search range is set to $\pm 2T_{\text{sample}}$. Since the waveform of PPG has similarity, the sampling error can be corrected by this method.

# IV. Performance Evaluation

The proposed PPG sensor is prototyped to evaluate the power reduction and the accuracy. Fig. 7 illustrates the detail

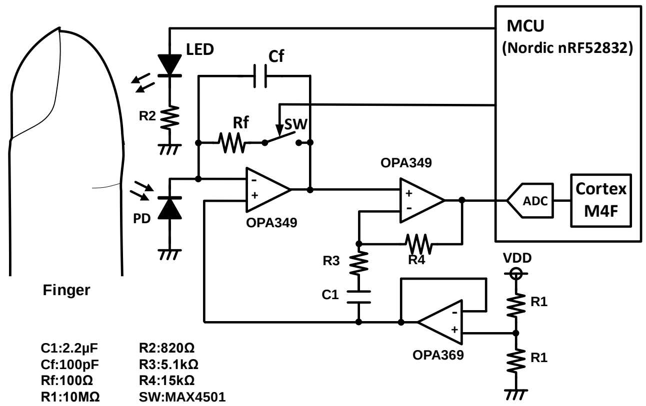



Fig. 7. Circuit block diagram of prototype sensor.

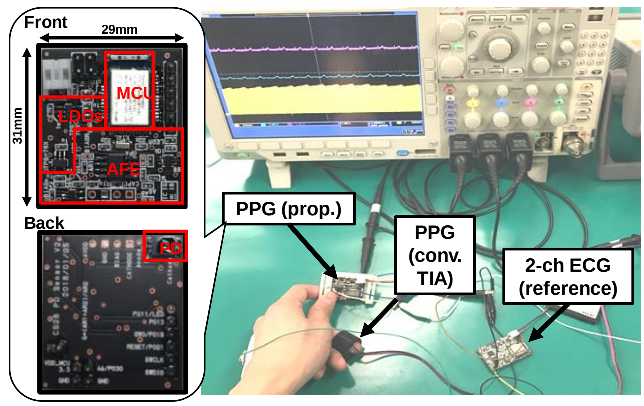



Fig. 8. Experimental setup for performance evaluation.

circuit diagram of the prototype sensor, which consists of a photodiode, a current integration circuit, a CMOS switch, LED, A/D converter, and MCU. The operating voltages of analog circuits and MCU are both 3.0V, which generated by a 3.7V lithium-ion battery and independent LDOs. Fig. 8 depicts the photograph of the prototype sensor and its test environmental setup.

In this experiment, the subject is 22-year-old man. Totally 10 sets of 10 seconds duration measurement are conducted for each setting parameter. Mean absolute error (MAE) of heartbeat interval and the current consumption of the PPG sensor are evaluated by averaging all sets of measurement. The ECG is simultaneously recorded and its heartbeat interval is calculated as reference value. A commercially available PPG sensor using TIA [10] is also measured simultaneously to compare with proposed sensor.

First, Fig. 9 shows the relation between sampling interval $T_{\text{sample}}$ and MAE of heartbeat interval. Then, the LED driving duration $T_{\text{LED}}$ is set to 150 µs. The CDS timing $\Delta t_1$ and $\Delta t_2$ (see Fig. 4) are respectively set to 7 µs and 125 µs. The MAE is calculated by the difference of heartbeat intervals between ECG and PPGs. Note that an error of several milliseconds occurs for all PPGs due to a pulse wave velocity variation. The proposed sensor achieves less than 5-ms MAE when $T_{\text{sample}}$ is longer than $1/16$ s. The result shows that the MAE of the proposed PPG is improved using CDS and autocorrelation comparing to using only peak detection, especially with long $T_{\text{sample}}$. 5-ms MAE is sufficiently small value for heart rate variability analysis [1].

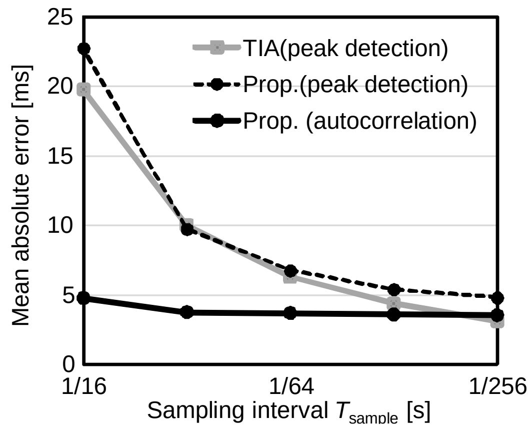


Fig. 9. Relation between sampling interval and MAE.

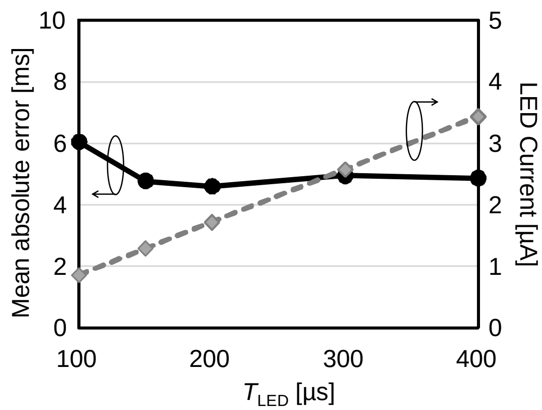


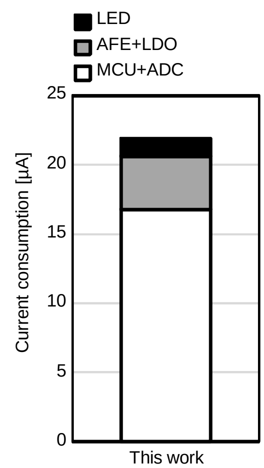
Fig. 10. Effect of LED driving duration $T_{LED}$.

Next, the effect of $T_{LED}$ on MAE of heartbeat interval and the current consumption of LED are evaluated as shown in Fig. 10. Then, $T_{sample}$ is set to $1/16$ s. The results show that the MAE can be suppressed to 5 ms or less when $T_{LED}$ is longer than 150 μs. The current consumption of LED is reduced to 1.29 μA when 150-μs $T_{LED}$ and $1/16$-s $T_{sample}$ are selected.

Finally, the entire current consumption of the proposed PPG sensor is evaluated and it compared with prior works as shown in Fig. 11. 22-μA total current consumption is achieved including analog circuit blocks, LED, LDOs, A/D converter (ADC), and MCU for signal processing. The active rate of LED is set to 0.24% with 150-μs $T_{LED}$ and $1/16$ s $T_{sample}$. As shown in Fig. 11, the proposed PPG sensor achieves at least 85.9% reduction in current consumption compared with conventional low-power PPG sensors [5, 6].

## V. Conclusion

As described herein, we proposed the power and noise reduction method for PPG sensor. The combination design using the current integration circuit, CDS, and autocorrelation based compensation was introduced. The prototype sensor achieved 22-μA current consumption and 5-ms MAE with 0.24% LED active rate. This current consumption is 85.9% smaller than conventional PPG sensor. Furthermore, the achieved MAE is comparable to conventional PPG sensors. Note that the proposed methods were implemented in the prototype PPG sensor using discrete components. Therefore, the proposed sensor has the possibility of further lower power




| | This work | [5] | [6] |
|---|---|---|---|
| Photo detection circuit | Current integration | TIA | TIA |
| Sampling Freq. | 16 Hz | 128,16,13 and 4 Hz | N/A |
| Feature Extraction | Pulse Interval | Pulse Interval | Pulse Interval |
| Error rate | 4.77 ms (MAE) | 2bpm | N/A |
| Supply voltage | 3V | 1.2V | 1.5V and 1.2V (Digital), 3.3V (LED) |
| Current consumption (w/o LED) | 20.6μA | 143μA | 35.78μA |
| Current consumption (w/ LED) | 21.9μA | 178.8μA | 155.8μA |

Fig. 11. Total current consumption and performance comparison.

consumption by implementing it as an integrated circuit.

The weak point of this paper is that only one subject examined the accuracy. In a future work, we will increase the number of subjects in a wide range of age groups. Another issue is the power consumption of the signal processing. It is implemented by software in this work, and the power of the MCU is dominant with respect to the power consumption of the whole system. It will be implemented in a dedicated hardware to achieve sub-μW PPG sensor.

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