Multifunctional Optical Sensor Module
Integrated Optical Micro Displacement Sensor and Its Application to a Photoplethysmographic Sensor with Measuring Contact Force

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Abstract: Photoplethysmography (PPG) is widely and commonly used, as it produces a wide range of information, such as stress level, heart rate interval, respiration rate, blood vessel hardness, *etc*. It is necessary to control the contact force between a PPG sensor and the measurement location (the skin surface), in order to obtain an accurate PPG signal. We propose new multifunctional sensor modules that can measure both pulse waves and contact force. The sensor module has a micro integrated displacement sensor chip with an optical source, photo diodes, and op-amp circuits, and a gum frame with a mirror. Some incident light penetrates into a finger, and the scattered light, which contains a biological signal (a pulse wave), is detected by one photodiode. The photodiode can also detect reflected light from a mirror, which is displaced by a contact force. In this paper, we fabricate a multifunctional sensor module and attempt to simultaneously measure the pulse wave and contact force.

1 INTRODUCTION

For the purpose of increased safety and security, wireless sensor network systems are being increase-ingly used in applications such as structural health monitoring, human health monitoring, agricultural field monitoring, and animal health monitoring (Spencer et al., 2017). Structural health monitoring can improve the safety and reliability of buildings, bridges, tunnels, and express highways by detecting damage before it reaches a critical state. This damage is sensed by wireless sensor nodes installed on the structure (Yamashita et al., 2016). Human health monitoring detects sleep disorders, Parkinson's disease, *etc*., by logging a person's daily walking movements and posture using Global Positioning System (GPS) devices, triaxial accelerometers, and angular velocity sensors (Olivares et al., 2011). These technologies have also been introduced in agricultural field monitoring, including animal health monitoring (Díaz et al., 2011). It is believed that wireless sensor nodes attached to animals, in conjunction with wireless health-monitoring systems, can achieve early detection and prevention of diseases, and thus reduce economic losses.

In previous studies, a wireless sensor node was attached to a chicken's wing and it measured and transmitted body temperature and activity data (Nishihara et al., 2013). The collected data can be compared with previous epidemic data for chickens and used to monitor the health of an individual bird. In order to build this system, we developed several low-power technologies for the wireless sensor node, including a custom-built LSI for an event-driven system, a bi-metal micro-electro-mechanical (MEMS) temperature switch (Suzuki et al., 2009), a miniaturized 300-MHz band loop antenna (Okada et al., 2009), and polyvinylidene difluoride (PVDF) switches for activity sensors (Nogami et al., 2013). Other studies have developed wearable wireless estrus detection sensors (Anderson et al., 2016) or portable estrus intensity detection sensors (Iwasaki et al., 2015). In this study, we focused on a photoplethysmographic (PPG) sensor.

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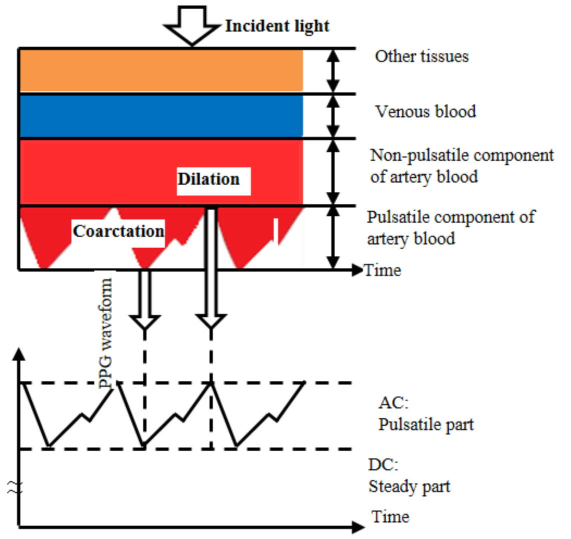

Figure 1: Measurement principle of photoplethysmographic sensor.

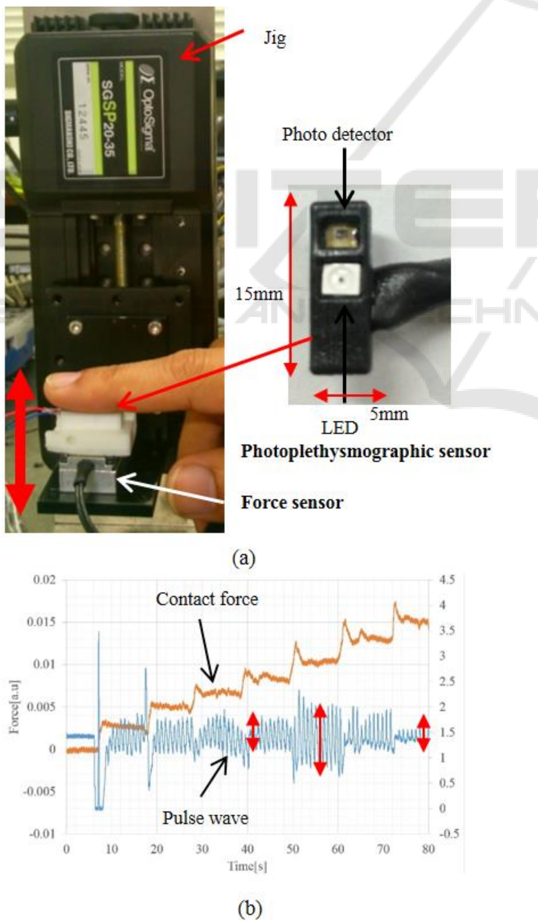

Figure 2: Experimental setup for purpose of evaluating AC signal with measuring contact force (a), and measurement result (b).

Photoplethysmography has been widely and commonly used as a pulse monitor since it was developed by Heraman in the 1930s (Allen et al., 2007). A reflective PPG sensor can be easily attached with low constraint, as it can detect pulse waves from a body's surface. It produces a wide range of information, such as stress level calculated from heart rate interval, respiration rate, heart rate, blood vessel hardness, *etc*. The signal detected by a PPG sensor is composed of an alternating current (AC), caused by the heart cycle, and a direct current (DC) resulting from veins and stationary tissue, as shown in Figure 1 (Asada et al., 2003). The AC signal is necessary for detecting the heart rate interval, blood vessel hardness, and cardiac rate. However, the AC signal is easily varied with the contact force.

Figure 2 shows the experimental setup for evaluating the AC signal while measuring the contact force, and the measurement results. The PPG sensor was fixed on the force sensor (USL06-H5, Tec Gihan Co., Ltd.). Using a low-pass filter circuit, an AC signal (pulse wave) was detected from the output signal of the PPG sensor. When a finger was placed on the PPG sensor, both the AC signal of the PPG sensor and the contact force could be recorded. The AC signal was greatly influenced by the contact force. Thus, a contact force sensor was necessary for measuring a stable pulse wave.

In this paper, we propose new multifunctional sensor modules that can measure both pulse waves and contact force. A sensor chip was designed by applying the principle of an optical micro displacement sensor (Ishikawa et al., 2007). The displacement sensor utilizes light to measure the displacement of an object. By combining the sensor and the structure, it is possible to measure the load and the shear force when the structure is displaced. In this study, the pulse wave was measured using the light that passed through a living body, and the load was measured with other light.

2 SENSOR

In previous work, we developed a micro optical displacement sensor that had a VCSEL and photodiodes in the sensor chip (Iwasaki et al., 2015). However, that sensor required external circuits for each photodiode in order to amplify the output signals, which increased the size the whole sensor system. In this study, CMOS op-amp circuits were integrated in a micro optical displacement sensor chip (Takeshita et al., 2016). Using these sensor chips, we fabricated a multifunctional sensor module that could measure not only pulse waves but also contact force.

2.1 Design

Figure 3 shows a model of an optical displacement sensor (Iwasaki et al., 2015). A VCSEL was centered on the sensor chip and photo diodes were monolithically fabricated around the VCSEL. A mirror was attached to the object. The VCSEL emits beams to the mirror and the PD measures the intensity of the light reflected from the mirror. This sensor can measure the displacement or angle of the object.

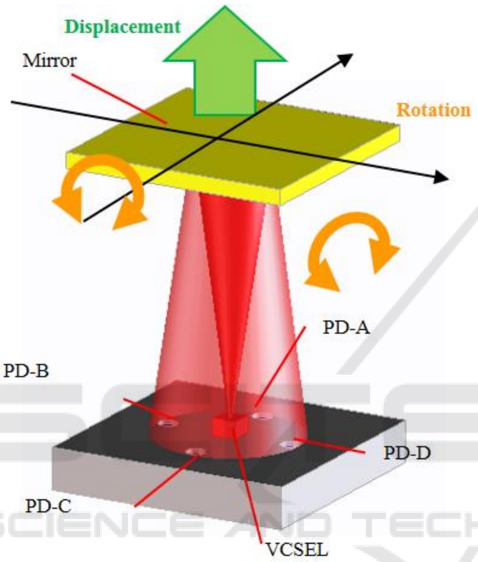

Figure 3: Model of a micro optical displacement sensor.

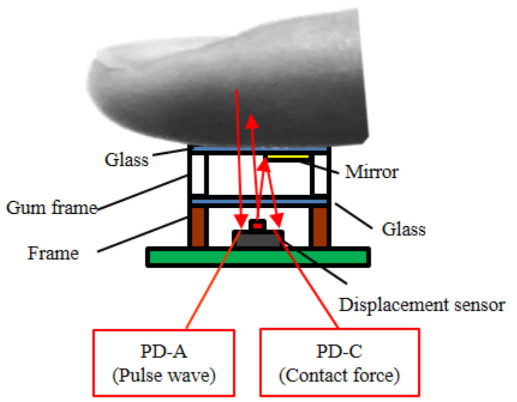

Figure 4: Model of a multifunctional sensor module which could both pulse wave and contact force.

Figure 4 shows a model of a multifunctional sensor module that can measure both pulse waves and contact force. A micro optical displacement sensor was sealed and attached to a gum frame with a mirror. Some incident light penetrates into a finger and the scattered light, which contains a biological signal (a pulse wave), is detected by a photodiode. The photodiode can also detect light reflected from a mirror. The displacement of the mirror varies with the contact force between the sensor module and the finger. In this paper, we fabricated a multifunctional sensor module and measured both pulse waves and contact force.

2.2 Fabrication

Figure 5 shows the sensor chip design. An LED was set at the center, instead of a VCSEL. Four photo diodes were monolithically fabricated around the LED. A CMOS op-amp circuit was located near the photodiode. The op-amp circuit was designed to amplify PD output by around 11 times (Fig. 5(b)).

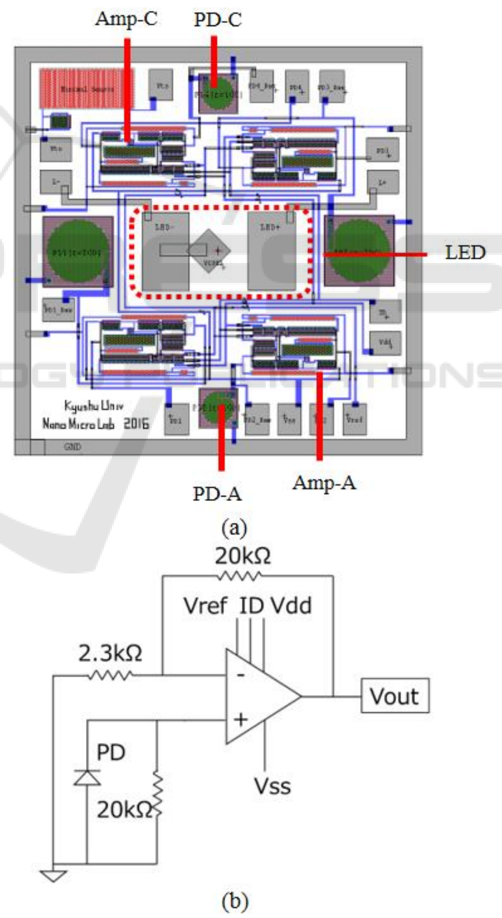

Figure 5: Design of a displacement sensor with a CMOS op-amp circuit(a), and the op-amp circuit (b).

Figure 6 shows a photograph of the integrated displacement sensor chip. The size of this sensor is 3 mm by 3 mm, it is 0.7 mm in thickness, and it is

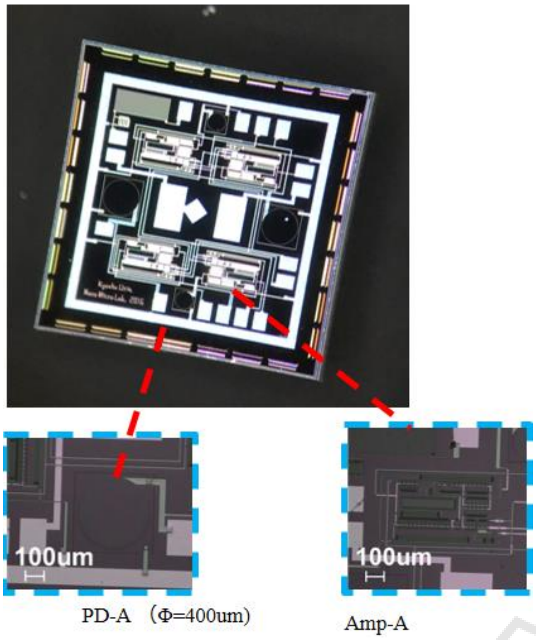

Figure 6: Photograph of a micro optical displacement sensor with a CMOS op-circuit.

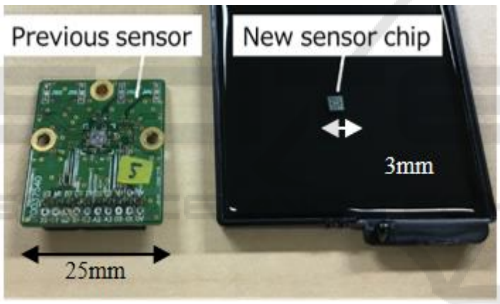

Figure 7: Photograph of a previous displacement sensor including external amplifier circuits and a new sensor chip.

fabricated using MEMS technology. We have successfully downsized the previous displacement sensor that had external amplifier circuits (Fig. 7).

3 EXPERIMENTAL

Figure 8 shows photographs of a fabricated sensor chip and a multifunctional sensor module. A light-emitting diode (LED) was mounted in the center of the sensor chip, instead of a VCSEL. The sensor chip was die-bonded on a printed-circuit board, and wire-bonded on it. After sealing the sensor chip, we attached a gum frame with a mirror to it. Output signals could be measured throughout the printed circuit board.

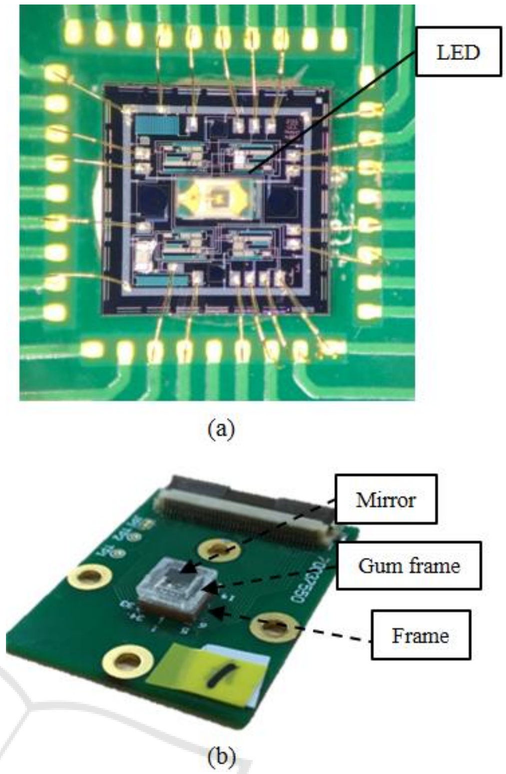

Figure 8: Photographs of a fabricated sensor chip (a) and a multifunctional sensor module (b).

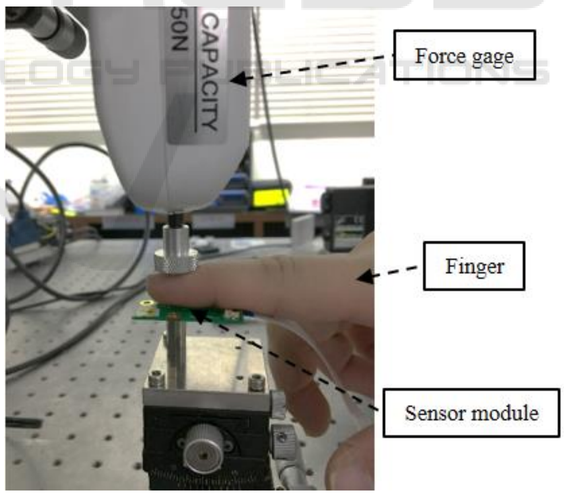

Figure 9: Experimental setup.

Figure 9 shows the experimental setup with a fabricated sensor module. The sensor module was used to make a measurement of a finger as incremental force was applied step-by-step to the finger. The force was controlled with a force gage. The signal of PD-A, the signal of PD-C, and the force were recorded simultaneously.

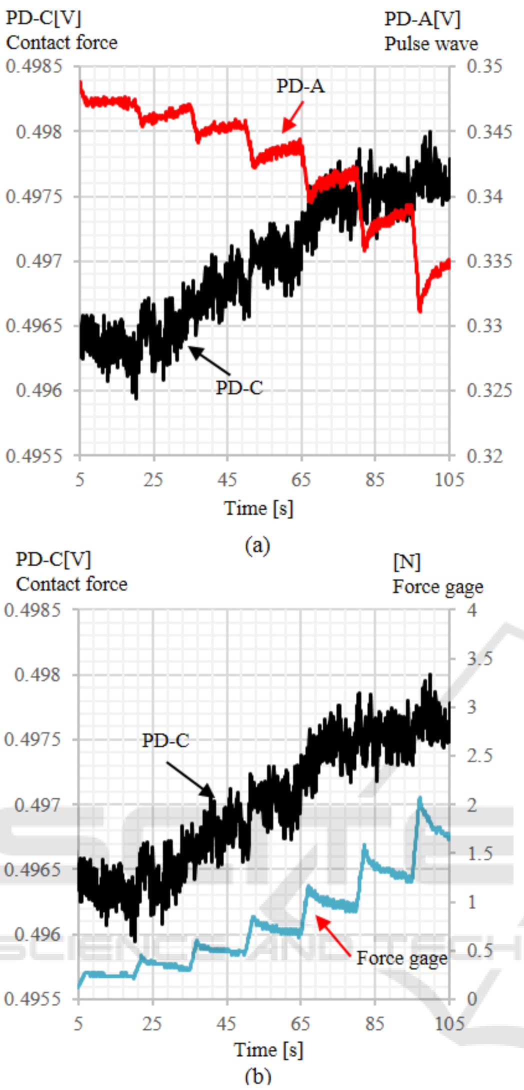

Figure 10: Measurement results of PD-A (pulse wave) and PD-C (Contact force) (a), and PD-C and force gage (b).

4 RESULTS & DISCUSSION

Figure 10 shows the results for (a) PD-A (pulse wave) and PD-C (contact force) and for (b) PD-C and the force gage. The signal of PD-C increased as the force was increased incrementally (Fig. 10(b)). The signal of PD-A decreased as the force was increased incrementally, and the pulse wave could be confirmed. Figure 11 shows the signals of PD-A for different contact forces. The signal of PD-A showed that the pulse wave had the highest amplitude when the force gage was at 2.3 N. These results support the idea that our multifunctional sensor module can simultaneously measure both the pulse wave and the contact force.

On the other hand, the PD-C signals were noisy. The amplitude of the noise was higher than the increase in the signal when the force was increased incrementally. One of the causes is considered to be signals from light reflected from the skin's surface. It is thus necessary to have a structure that detects only the reflected light from the mirror and to improve the signal-to-noise ratio.

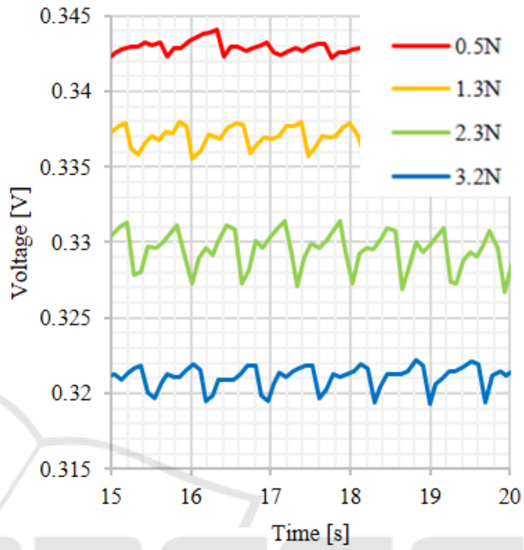

Figure 11: Relationship between PD-A (pulse wave) and contact force.

5 CONCLUSIONS

We succeeded in fabricating an ultra-compact optical displacement sensor chip with integrated LED, PDs, and CMOS amplifiers. By using this sensor chip, our new multifunctional sensor module can measure simultaneously both the pulse wave and contact force between the sensor module and measurement location.

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