Robust Wrist-Type Wireless Multiple Photo-Interrupter Pulse Sensor

Toshinori Kagawa, Atsuko Kawamoto, and Nobuo Nakajima

***Abstract*—** Long-term wearable vital sensors, monitoring parameters such as temperature, pulse, and blood pressure, are important for the daily care of patients and the elderly [1][2][3][4][5][6][7]. These monitoring sensors are available for patients who remain in hospital beds; however, for active elderly people who do not stay in bed, long-term continuous measurement is a challenge. The sensor must be attached to the body without increasing stress. Although various types of pulse sensors are available, a wristwatch-type pulse sensor is one of the most common wearable sensors. However, this sensor still does not meet all of the requirements such as being reliable, easy to wear, and stress-free.

In this paper, a novel wristwatch-type pulse sensor is proposed. It employs multiple photo-interrupters. Its structure is very sensitive and robust against movement of the hand. Experiments verified that the proposed sensor met the requirements mentioned above.

In order to use the pulse sensor in daily life, the sensor and the data-collecting server are connected via a ZigBee wireless module.

***Keywords*—** pulse sensor, healthcare, wearable, robust, photo-interrupter, wireless.

I. Introduction

RECENTLY, the proportion of the population made up of elderly people has increased. Maintaining the health of these people has become a very important issue[8][9][10]. Monitoring vital signs such as temperature, pulse, and blood pressure 24 h a day is very useful for this purpose[11][12][13]. For patients who stay in beds in the hospital, these monitoring systems already exist; various vital sign are continuously measured, and if a problem occurs, the system alerts nurses and/or doctors[14][15].

However, for active elderly people who do not remain in bed, long-term measurement is difficult. The sensor must be attached to the body without increasing stress. Detection reliability is required in all situations such as remaining at rest and moving rapidly. For real-time monitoring, the sensor data is sent to the data collection center by wireless transmission. Compactness and low-power consumption are also important.

One of the most typical wearable vital sensors is a pulse sensor. The sensor and/or display are worn on a wristwatch-type terminal. Various types of such sensors are available in the market. However, no sensor meets all requirements simultaneously, namely being robust, easy to wear, and stress-free.

In this paper, a wristwatch-type robust pulse sensor is investigated. It employs multiple photo-interrupters. In section 2, representative existing wearable pulse sensors are listed and compared in terms of their advantages and disadvantages. In section 3, the output signal amplitude distributions of the photo-interrupter are measured for both the palm and the wrist. A multiple photo-interrupter array sensor is employed to improve the robustness of the measurement. Finally, an optimal photo-interrupter array configuration is determined; this configuration meets the requirements of compactness, robustness, and ease of installation.

For application in daily life, ZigBee wireless modules are used to connect the pulse sensor and the data-collecting server via wireless network.

II. Current Wearable Pulse Sensors

Figs. 1–3 show several representative wearable pulse sensors that are/were available in the market. Fig. 1 shows a sensor that is attached to the chest to produce an electrocardiogram. Measured data is wirelessly transmitted to the wristwatch. Although this application can be used for long-term measurement, it is not easy to wear and the user may experience increased stress. Fig. 2 shows a wristwatch-type pulse sensor. The sensor is attached to the finger. Because this structure restricts finger motion, sensors of this type are not suitable for long-term use by people who lead active lives. Fig. 3 shows another wristwatch-type pulse monitor. The sensor is attached to the wrist, and the device's operation is almost the same as that of a regular wristwatch. This type of sensor is both easy to wear and suitable for long-term measurement; however, currently, this device is not available in the market because of its unreliable performance.

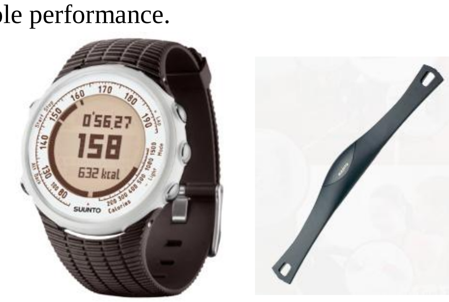

Fig. 1 Pulse Sensor on the Chest

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Fig. 2 Pulse Sensor on the Fingertip

Fig. 3 Pulse Sensor on the Wrist

III. Robust Pulse Detection by the Photo-Interrupter Array

A. Detection Principle

A photo-interrupter, made of an infrared LED and a phototransistor (Fig. 4), can be used to detect a pulse. We use Kodenshi, SG-105 in this study. As shown in Fig. 5, the reflectivity (output voltage from the phototransistor) of the infrared light from the capillary vessel changes according to the heart beat.

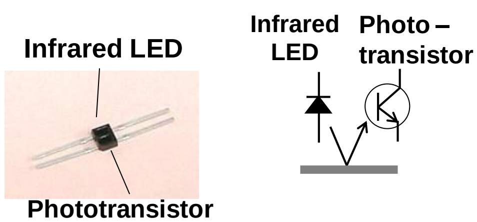


Fig. 4 Photo-Interrupter

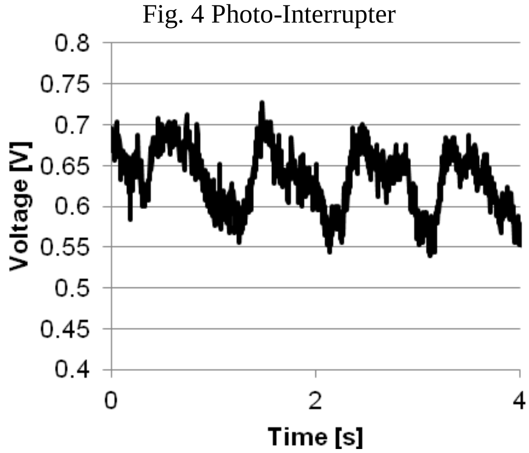


Fig. 5 Output Waveform of the Photo-Interrupter

An electrical circuit used for detecting the pulse is shown in Fig. 6.

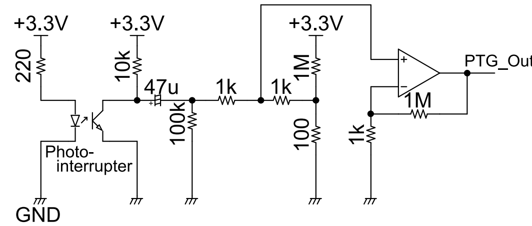


Fig. 6 Photo-Interrupter and Amplifier

The conventional pulse counting procedure is described as follows.

I. The sensor output signal is transmitted to the high-pass filter (cut-off frequency around 0.03 Hz) to eliminate the DC component

II. Then, the signal is fed to the amplifier (LM358: 80dB gain, 33mW power consumption)

III. Then, the signal is transmitted to AD convertor (8bit, 50Hz sampling)

IV. The digitized signal is shaped using the low-pass filter (cut-off frequency around 3 Hz) to reduce high-frequency noise (Fig. 7)

V. Then, DC component of the signal is eliminated by the high-pass filter (cut-off frequency around 0.5 Hz) (Fig. 8)

VI. The number of rising points crossing 0 volt (N) is counted.

VII. N divided by minutes corresponds to the pulse rate.

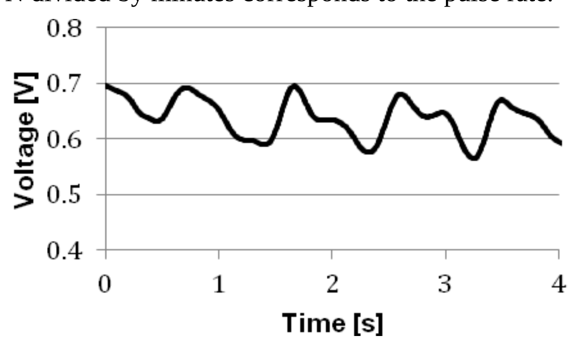


Fig. 7 Waveform after Low-Pass Filtering

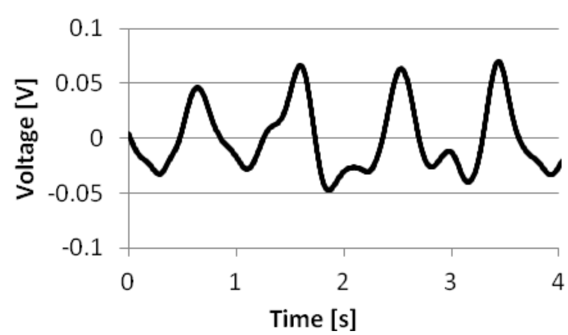


Fig. 8 Waveform after High-Pass Filtering

B. Performance of the Photo-Interrupter Sensor at Various Locations

Generally, a pulse sensor is attached to the fingertip (Fig. 9), where the reflectivity variation can be most clearly observed. At this location, the output signal is strong (Fig. 10(a)). On the contrary, the signal is weaker on other parts of the hand and wrist. Fig. 9 shows the signal strength distribution. The signal is weakest around the wrist. However, at certain locations, a visible signal appears, as shown in Fig. 10(b), although the amplitude is less than 1/10 of that at the fingertip.

In the case of the pulse monitor shown in Fig. 3, the user is required to adjust the sensor so as to find the ideal location (that with the greater amplitude). Because the strong signal area is very limited, it is difficult to place the sensor at the most desirable position. This is the reason why the pulse rate sensor shown in Fig. 3 could not achieve a stable and reliable performance.

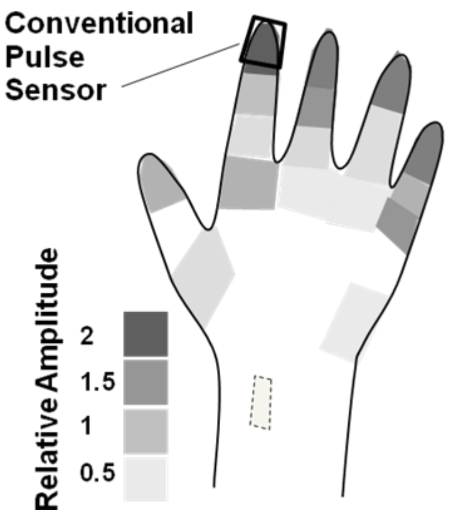
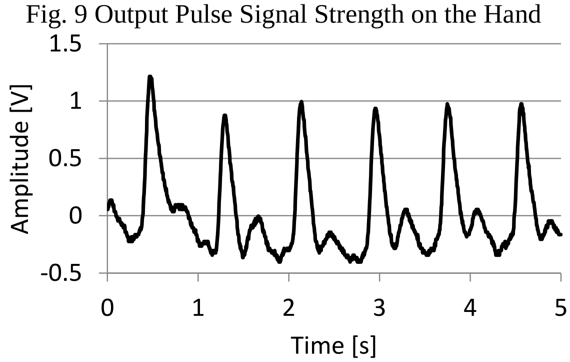
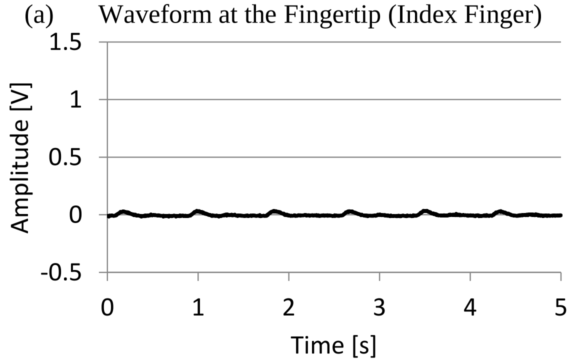


Fig. 9 Output Pulse Signal Strength on the Hand



(a) Waveform at the Fingertip (Index Finger)



(b) Waveform at the Wrist (Ideal Location)
Fig. 10 Output Pulse Waveform

Detailed signal strength distributions around the wrist were measured for two persons A and B. The signal strength was measured at points (spaced every 5 mm) around the wrist. The incremental number is used to identify these points (Fig. 11). Fig. 12 shows the strongest and weakest signal waveforms. Fig. 13 shows the signal strength distribution around the wrist.

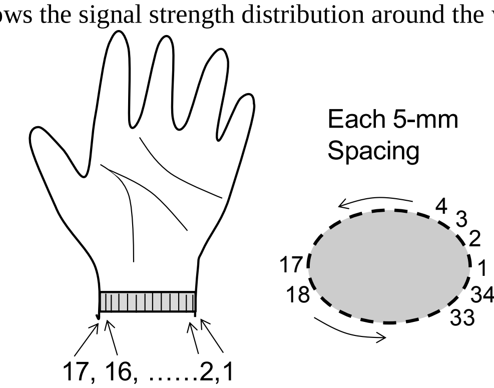
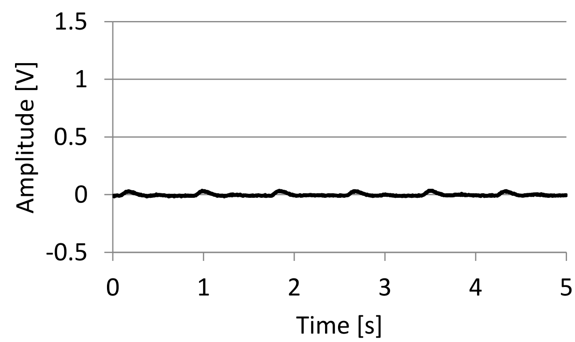
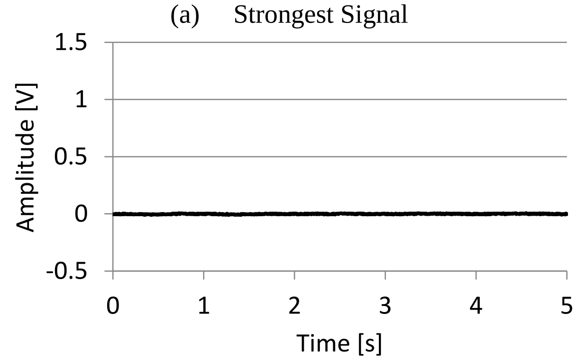


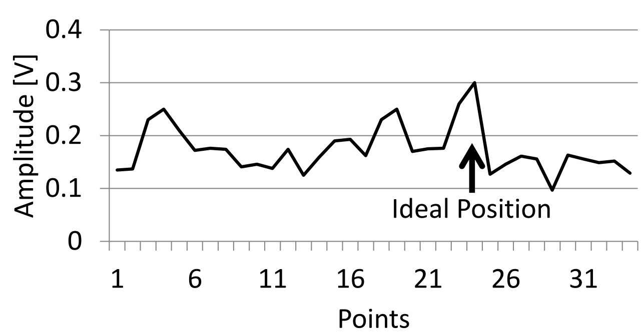
Fig. 11 Tested Points



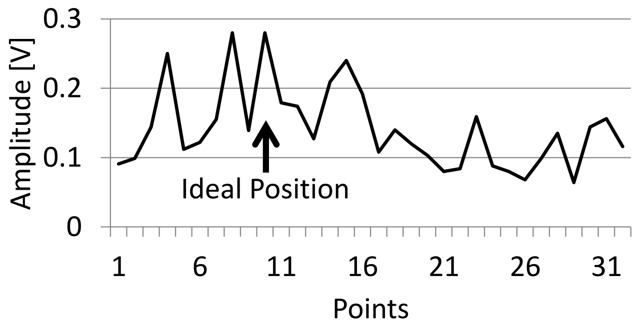
(a) Strongest Signal



(b) Weakest Signal
Fig. 12 Output Waveforms around the Wrist



(a) Person A
Fig. 13 Signal Strength Distribution around the Wrist



(b) Person B

Fig. 13 Signal Strength Distribution around the Wrist

The output signal amplitude varies considerably with position; strong peaks are few and narrow. A half voltage width (the width at which the amplitude is half of the peak amplitude) is around 10 mm. This means that to place the sensor in the optimal location, the tolerance must be less than 5 mm.

Generally, wristwatches are not firmly fixed, but rotate around the wrist to some extent. The deviation of a wristwatch's position from the starting position was measured (Fig. 14). The peak-to-peak deviation was less than approximately 15 mm for the watch shown in Fig. 14. This means that it may be difficult for the wristwatch-type pulse monitor in Fig. 3 to maintain high reliability under variations of position.

Fig. 14 Wrist Watch Position Deviation

C. *Multiple Photo-Interrupter Sensor*

To improve the robustness of the system, a photo-interrupter array is introduced. To avoid missing an ideal point, the spacing of the sensors is set to 5 mm. On the basis of the deviation of the sensor on the wrist, the width of the sensor array was chosen to be 15 mm. From these conditions, it is found that 4 sensors are required. Fig. 15 shows a photograph of the photo-interrupter array. Fig. 16 shows the measured waveforms at the different sensors. In this case, sensor outputs #1, #2, and #3 are weak; however, sensor output #4 is sufficient to allow pulse rate detection.

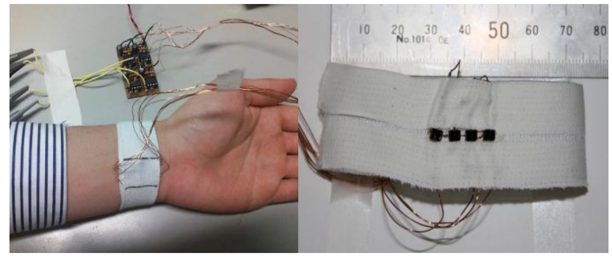
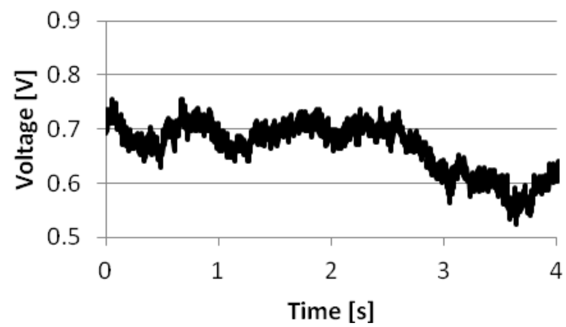
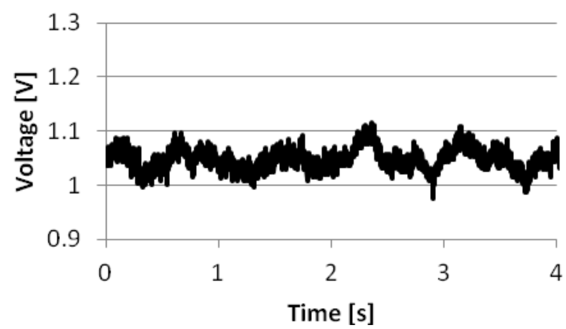


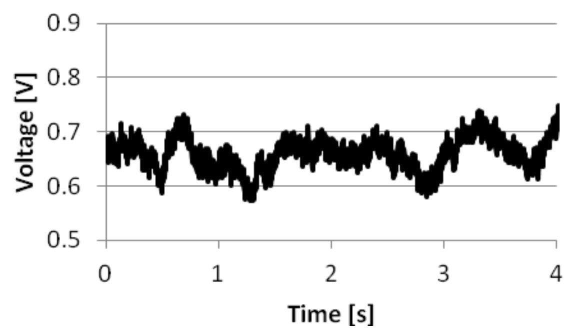
Fig. 15 Photo-Interrupter Array



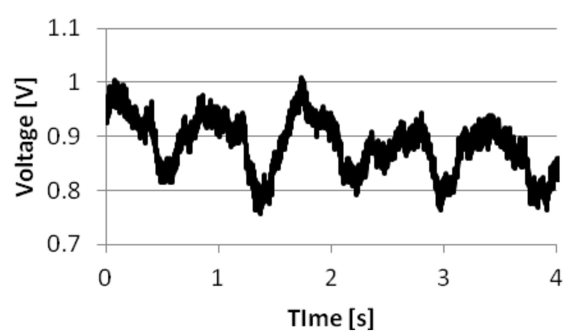
(a) #1 Sensor



(b) # 2 Sensor



(c) #3 Sensor



(d) #4 Sensor

Fig. 16 Output Waveform from 4 Sensors

IV. Algorithm for Selecting the Most Reliable Sensor

In most cases, the human heart pulse rate ranges from 49.5 bpm (beats per minute) to 139.5 bpm, corresponding to 0.83 Hz to 2.33 Hz.

$x(f)$ denotes the frequency spectrum magnitude distribution, where *f* denotes frequency. The maximum spectrum magnitude within $0.83 \leq f \leq 2.33$ is given by $S_{max}(t) = \max x(f)$ at time t.

The average spectrum magnitude $S_{mean}(t)$ within $0.83 \leq f \leq 2.33$ at time *t* is derived using Eq. (1),

$$S_{mean}(t) = \frac{1}{b-a}\sum_{i=a}^{b} x(\frac{i}{n\Delta t}) \qquad \cdot\cdot\cdot (1)$$

where a and b are the start and stop times of the fast fourier transform (FFT), respectively. The order of the FFT is 2048. Pulse waveform sampling time interval $\Delta t = 0.02s$.

If the pulse signal is noisy, $S_{mean}(t)$ increases. Therefore, the measured data $S_{mean}(t)$ that fulfill Eq. (2) are removed, so as to maintain measurement reliability,

$$S_{max}(t) \geq cS_{mean}(t) \qquad \cdot\cdot\cdot (2)$$

where the coefficient $c = 3$.

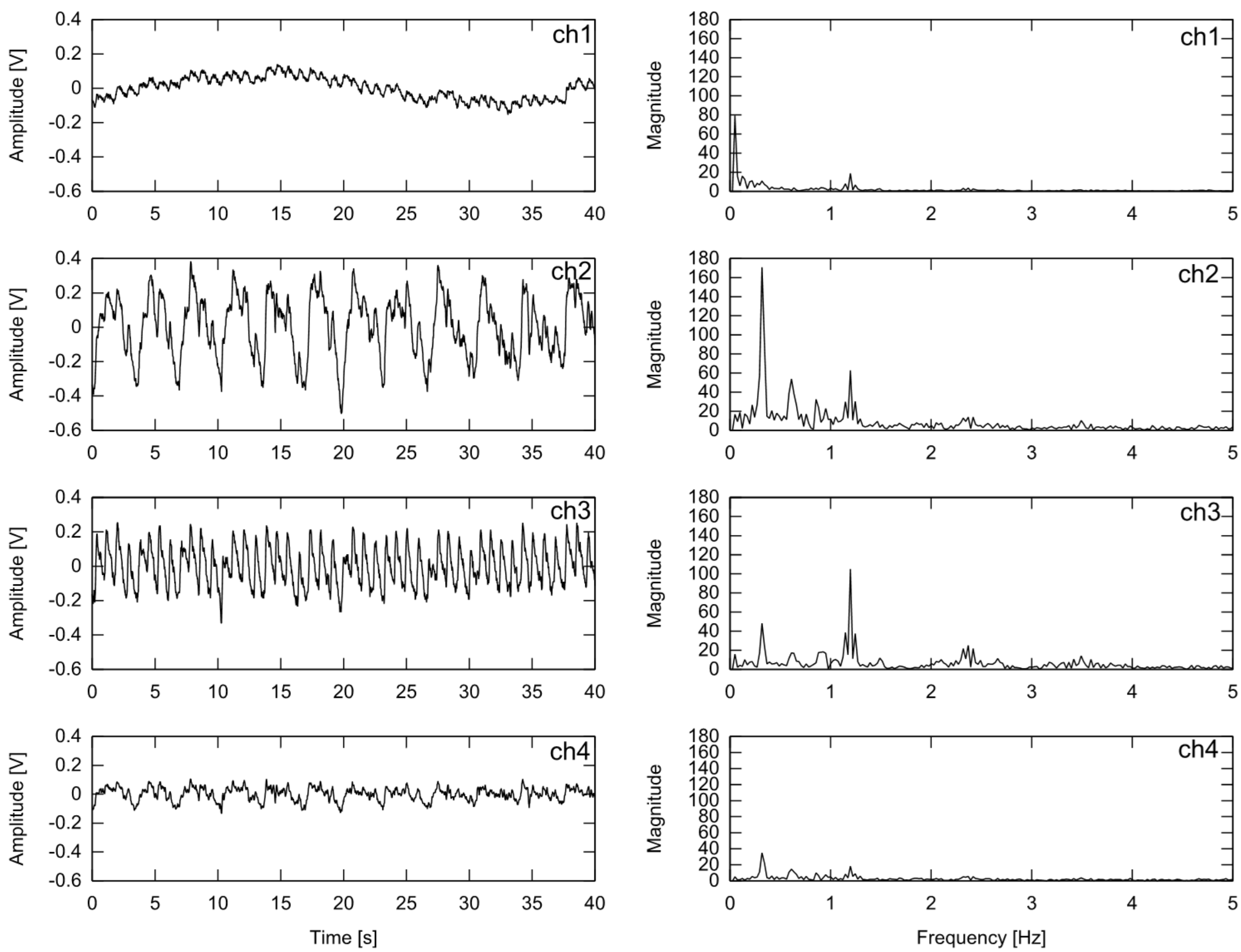
At most, four measured values of $S_{mean}(t)$ are available, because four sensors are employed, after removing the unreliable data. The most reliable data is selected from among the reminders based on majority detection. If it is difficult to select the most reliable data from the majority, the sensor data for which $\frac{S_{max}(t)}{S_{mean}(t)}$ gives the maximum value from among the reminders is selected.

V. Experiments

Pulse rate were measured for 5 persons (3 males and 2 females) using 1, 2, 3, and 4 channel photo-interrupters arrays. Measured waveforms were fourier transformed into frequency spectra. The pulse rate obtained is the frequency of the peak spectrum, within the range 0.83 Hz– 2.33 Hz.

Fig. 17(a) and (b) show the pulse waveforms and frequency spectrums of the 4 sensor channels, respectively for person 1. As for frequency spectrum, large amplitude spectrums appear at 1.3 Hz in channel 2 and 3. On the other hand, the pulse spectrum amplitude is very weak and the pulse rate is hard to evaluate.

In section IV, the pulse rate is derived from the most reliable sensor that is decided by the comparison of the amplitude of the



(a) Waveform (b) Frequency spectrum

Fig. 17 Photoplethysmogram and frequency spectrum (4ch person 1) pulse spectrum.

The detected pulse rate at the respective sensor is correct if the measured pulse rate is equal to the actual pulse rate, which was obtained using a conventional pulse rate sensor located at the fingertip (where a strong signal is available). If the measured rate was not equal to the actual rate, the detection is considered to have failed.

Fig. 18 shows whether the detection is considered successful or to have failed when a single or multiple photo-interrupters are applied (1, 2, 3, or 4). The number of the horizontal axis indicates the center position of the sensor array on the wrist. The white squares indicate successful readings and the black squares indicate failed readings. For instance, when two photo-interrupters are used, the detection is successful if at least one of the two sensors detects the pulse correctly (Fig. 18(b)).

Since the detection is successful when at least 1 sensor of the sensor array detects correctly (true), final result (true of false) is derived by logical disjunction (OR) of respective sensor's result (true of false).

This decision procedure is similar to that for the case in which 3 or 4 photo-interrupter arrays are used (Fig. 18(c), (d)).

When 1 photo-interrupter was used (Fig. 18(a)), 44% of the detections failed. When 2 and 3 sensors were used, the failure rate decreased to 18%, respectively. When 4 sensors were used, all of the detections were successful.

Fig. 19 shows that for the five persons, all of the pulse rate detections were successful when 4 photo-interrupter array was used.

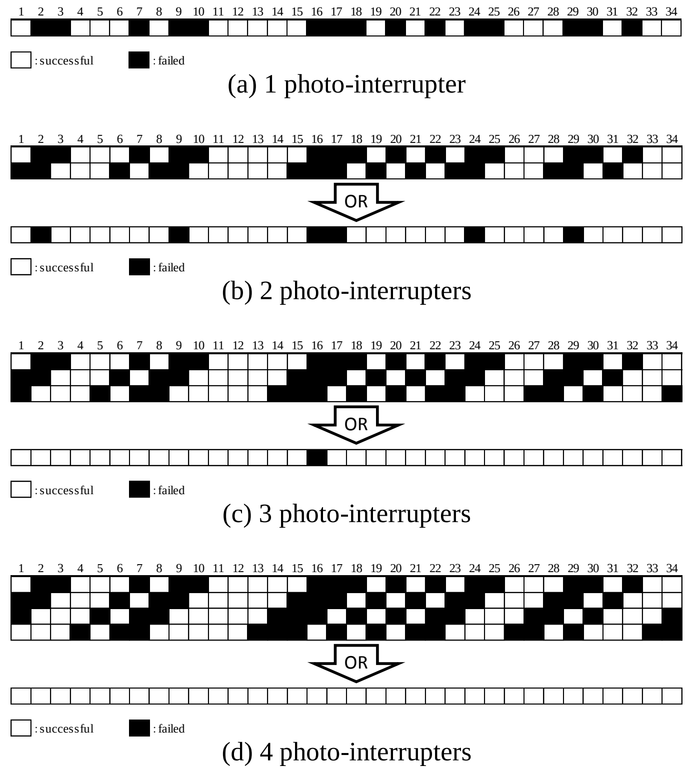


Fig. 18 Pulse wave detection (person 1)

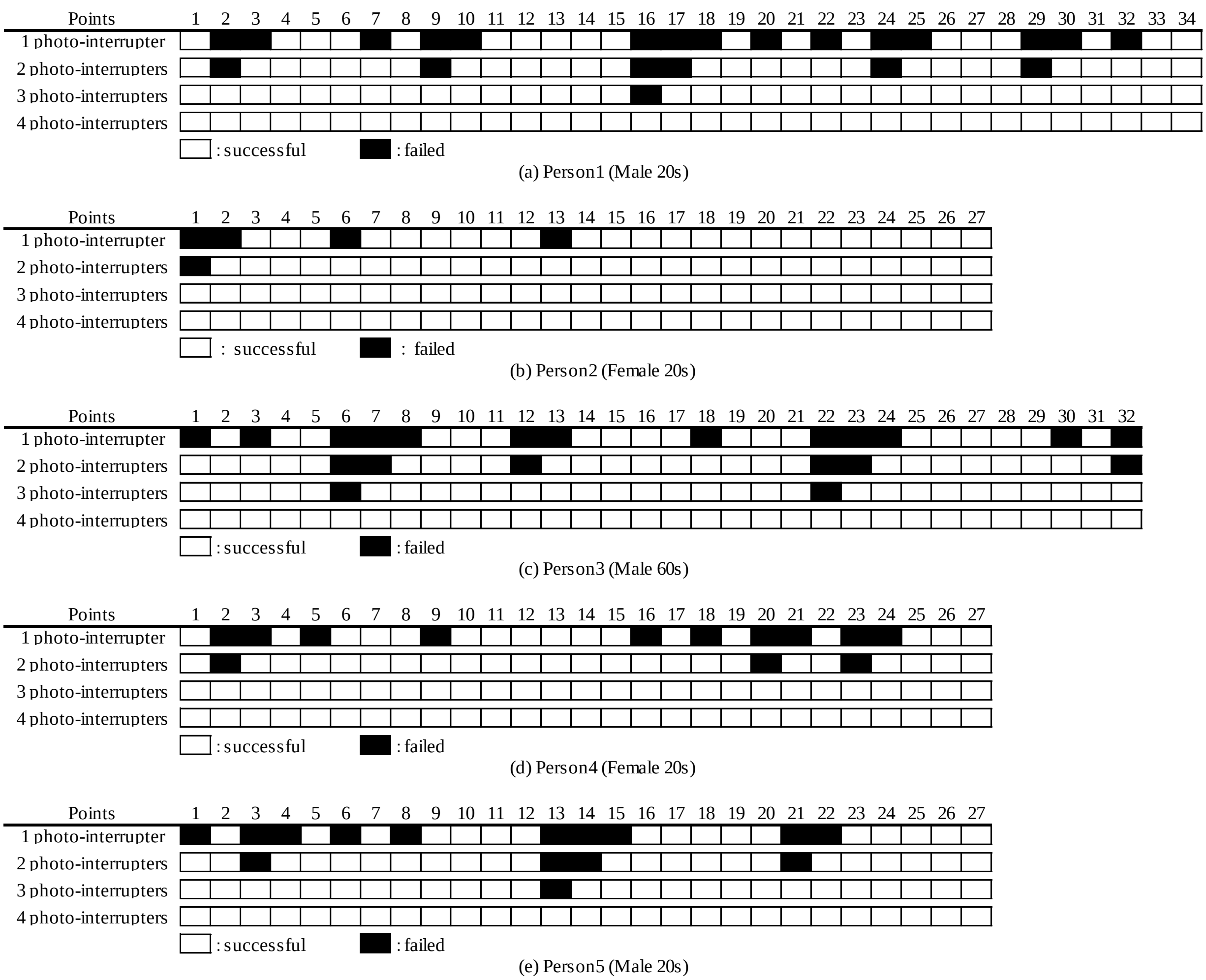


Fig. 19 Pulse wave detection (5 persons)

VI. Wireless Transmission

For daily life application, the pulse sensor and the data-collecting server must be separated and connected via wireless network. A ZigBee module (XBee) is used in our experiment to provide the wireless communication.

Fig. 20 and Fig. 21 show the system structure of the wireless pulse sensor with a photo-interrupter array. The detected pulse waveforms are converted into a digital format by a PSoC microprocessor and transmitted via the XBee wireless module. The received signals are analyzed by the PC and the pulse rate is displayed on a monitor screen. Table 1 lists the specifications of the wireless module and the microprocessor.

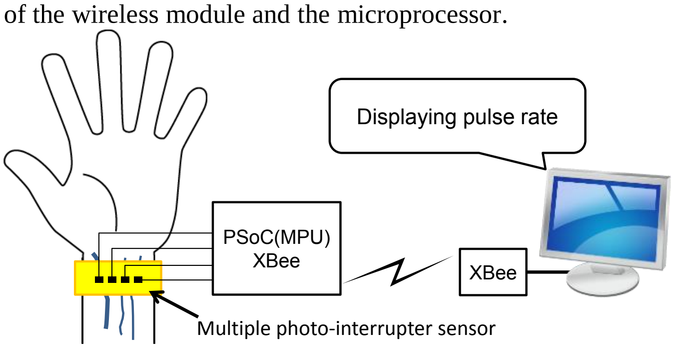
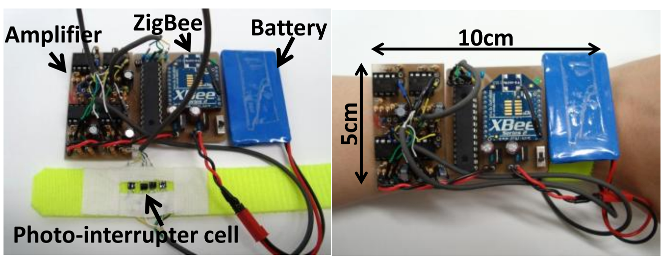


Fig. 20 Configuration of wireless pulse sensor



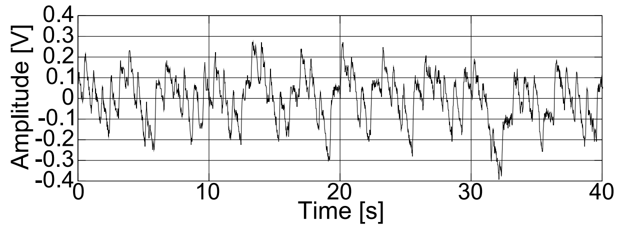
(a) Component (b) Mounting

Fig. 21Wireless pulse sensor

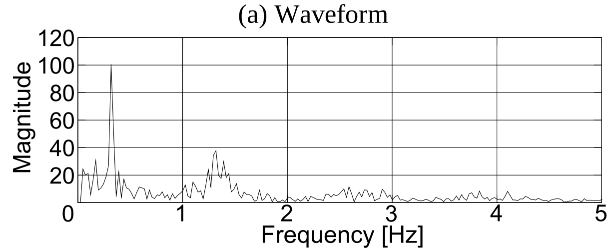
Table 1 Specification of wireless pulse sensor

MPU	PSoC CY8C29466 (Cypress)
ZigBee module	XBee XB24-ACI-001(Digi)
Battery	Lithium-ion 3.7 V 1050 mAh
Current consumption	~50 mA
Frequency	2.405 GHz
Transmit power	1 mW
Bit Rate	250 kbps
Width	~10 cm
Depth	~5 cm
Height	~1.5 cm

Fig. 22 (a) shows an example of the received pulse waveforms in the case that the transmitter and the receiver are separated 5m. Fig. 22(b) shows the fourier transformed spectrum. The pulse spectrum appears at 1.31 Hz which corresponds to 79 bpm. The capacity and quality of the ZigBee wireless transmission is sufficient to allow the device to send all four pulse waveforms simultaneously.



(a) Waveform



(b) Frequency spectrum

Fig. 22 waveform and frequency spectrum based on data from wireless pulse sensor

VII. Conclusion

In this study, a robust wristwatch-type pulse sensor is proposed.

The pulse sensing was very difficult on the wrist by the conventional photo-interrupter sensor due to the very weak signal amplitude[16]. Whereas, the proposed pulse sensor employing 4 photo-interrupters array achieved very stable measurement at any position on the wrist.

The proposed pulse sensor is useful for patients and elderly people who are active (that is, who do not stay in bed), but who also require continuous vital sign monitoring for maintaining good health. Because the proposed sensor has almost the same structure as that of a conventional wristwatch, it is easy to wear throughout the day.

There are two methods for using this device. One is to log the pulse rate data over a long term. The other is real-time pulse monitoring, which is the same as that used in hospitals, healthcare houses, and homes in which an elderly person lives alone.

For real-time monitoring applications, wireless transmission was adopted for data transmission between the sensor and the data-collecting server (PC). A ZigBee module, which transmits a 250 kbps signal, is applied. Because the ZigBee has an ad-hoc networking function, sensor data can easily be transmitted throughout a wide area such as the whole floor of the building. The measured data is transmitted to the data-collecting server whenever (and wherever) the user is in the building.

The proposed sensor and the low-power ZigBee wireless module create a real-time, reliable, easy to wear, and long battery life pulse sensor. This will contribute to the future healthcare for a large number of elderly people.

In Fig. 17(b) and Fig. 22(b), we found a 0.32 Hz spectrum peak and a 1.31 Hz spectrum peak. The former frequency corresponds to breathing. Therefore, the photo-interrupter may also be applicable as a breath rate sensor[17][18]. Thus, a wrist watch-type pulse and breath rate wearable sensor is the next target of our research.

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