# disp2ppg: Pulse Wave Generation to PPG Sensor using Display

## ABSTRACT

Research on wearable devices has been actively conducted, and devices of various shapes and wearing areas have been proposed. Wearable devices are often used to record the user's biometric information, and methods to detect physical abnormalities from the acquired data have been proposed. Among biometric data, pulse data has been used in methods such as emotion estimation. The most common type of pulse sensor is the PPG (Photoplethysmogram), which irradiates a green LED on the skin and measures pulse data from the changes in the light reflected through the blood vessels. PPG sensors have been introduced into commercially available wearable devices such as smartwatches. The PPG sensor requires blood flow for data acquisition due to the characteristics of the mechanism. When a smartwatch is worn on an artificial body such as a prosthetic hand or a wearable robot arm, correct data cannot be acquired because there is no blood flow. In this study, we propose a method to make the PPG sensor measure arbitrary pulse data using a display. If this method is realized, it will be possible to input pulse data measured at the junction of the live body and the prosthetic hand to the display, and have the smartwatch attached to the prosthetic hand read same pulse data. In this paper, we focus on the heart rate, and describe the results of an experiment in which the target heart rate was input and the display was controlled, and whether the target heart rate could be obtained by a smartwatch worn on the display. We implemented a display drawing program and conducted an evaluation experiment using five kinds of smartwatches and four kinds of displays to confirm the effectiveness of the proposed method. As a result, the overall error between the target heart rate entered and the heart rate acquired by the smartwatch was within -3 beats per minute in most cases.

## KEYWORDS

ppg sensor, display, pulse wave, heart rate, smartwatch

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## 1 INTRODUCTION

With the growing awareness of health management, wearable devices that record biometric information have become widely used. The biometric information to be recorded includes a variety of information such as activity, respiratory rate, body temperature, cardiac potential, blood pressure, gaze, etc. The pulse wave and the heart rate are among them. The pulse sensor used to acquire the pulse waves and the heart rate irradiates the skin with LEDs that emit infrared, red light, or light with a green wavelength around 550 nm. The oxidized hemoglobin in the blood of arteries has the property of absorbing these lights. The pulse sensor utilizes the fact that the amount of reflected light decreases as the arterial blood flow increases with the timing of the heartbeat, and uses a phototransistor to acquire changes in the amount of reflected light and measure the pulse wave. The pulse wave data is numerical data of the change of the reflected light, and the heart rate is measured by detecting the peak appearing in the pulse wave data. This types of pulse wave measurement method is called PPG (Photoplethysmogram). Many commercially available wearable devices, such as smartwatches, are equipped with PPG sensor as a pulse sensor.

We consider the possibility of measuring an arbitrary pulse wave by giving a change of light to the PPG sensor and in this paper we propose disp2ppg, a method to let the PPG sensor to acquire pulse data using a display. The proposed method makes a smartwatch to measure an arbitrary heart rate. We assume two objectives for disp2ppg: PPG transfer and fake PPG.

As an application of PPG transfer, artificial bodies, such as prosthetic hands, wearable robot arms, and telepresence robot do not have blood flow. Therefore, it is not possible to measure the biometric data even if a smartwatch is worn on the wrist. Smartwatch functions such as calling, messaging, clocking, and payment, as well as sensors such as accelerometers and GPS, can be used in artificial bodies as in the living body, but pulse data cannot be measured. When a smartwatch is forcibly attached to other body parts where blood flow exists, such as the ankle, in order to measure pulse data, the usability of other functions, such as the messaging, is reduced. With the proposed method, even when a smartwatch is attached to an artificial body, the smartwatch can read the person's pulse data by changing the light of the display under the PPG sensor of the smartwatch according to the pulse data measured at the junction of the living body and the prosthetic hand. It is possible to use the functions provided by a smartwatch since the smartwatch is not modified and only the display is mounted on the artificial body. Users can compare various items such as design, function, and weight of commercial smartwatches and use the model of his/her choice. When applied to a remote robot avatar, the operator's biometric data can be measured on the avatar's body.

As an application of fake PPG, it is possible to let the PPG sensor to measure an arbitrary heart rate by the proposed method and a malicious user could falsify the heart rate and pretend to exercise or continue resting. If a device that realizes the proposed method becomes widely feasible and has a significant social impact, it will be necessary to discuss the use of the current PPG sensor from the viewpoint of the vulnerability of the PPG sensor.

# 2 RELATED WORK

## 2.1 Studies using Smartwatch

Smartwatches have been commercially available for a long time and many researches using a smartwatch have been conducted. Sen et al.[10] proposed a method to record eating behavior, such as whether the user ate with hands, chopsticks, or a spoon, using data obtained from the accelerometer and gyroscope of a smartwatch. Johnston et al.[6] proposed a method for biometric authentication based on gait using data obtained from the accelerometer and gyroscope of the smartwatch. Iakovakis et al.[4] conducted a study that predicts the blood pressure drop caused by postural changes using a smart watch. Mauldin et al.[9] proposed an Android application "SmartFall" that detects falls using acceleration data obtained from a commercially available smartwatch. These methods using inertia sensors such as accelerometers are applicable even with artificial body, however, methods using pulse data are unavailable.

## 2.2 Studies using Pulse Data

There have been proposed several methods and applications using pulse data. Havriushenko et al.[3] proposed a method for estimating respiratory rate from pulse wave data using neural networks. Han et al.[2] proposed a method for detecting premature atrial contraction (PAC) and premature ventricular contraction (PVC) using PPG data acquired from a smartwatch. Goshvarpour et al.[1] proposed a method for classifying emotional responses with the electrocardiogram and finger pulse activity. Kajiwara et al.[7] focused on the fact that many logistics companies adopt a manual order picking system, and that emotions and engagement affect work efficiency and human errors, and proposed a method for predicting emotions and engagement during work with high exercise intensity based on behavior and pulse waves acquired by wearable devices. Lee et al.[8] conducted research on improving the speed of emotion recognition using PPG signal. Pulse data is one of the most important biological information, as it can detect abnormalities in the body and estimate emotions. Most of the pulse sensors in commercially available wearable devices use photoplethysmogram. Therefore, when a wearable device is worn on an artificial body where blood flow does not exist, pulse data cannot be acquired. We propose a method to let a wearable device to measure pulse data similar to that of a living body even on an artificial body.

# 3 PROPOSED METHOD

This section explains the details of the proposed method.

## 3.1 Overview

The flow of the proposed method is shown in **Figure 1**. First, the real and target heart rate of the user is obtained with PPG sensor which is different to the smartwatch. The proposed method changes the brightness of the display connected to a microcomputer according to the target heart rate. Then, the smartwatch worn over the display measures the heart rate which is the same as the target heart rate.

## 3.2 Target Heart Rate Calculation

The target heart rate that the proposed method lets the smartwatch to measure is the wearer's heart rate obtained using another PPG sensor, and that value can be specified in real time. Let $H_{target}$ be the target heart rate. $H_{target}$ can also be given manually if the user want the smartwatch to measure specific heart rate.

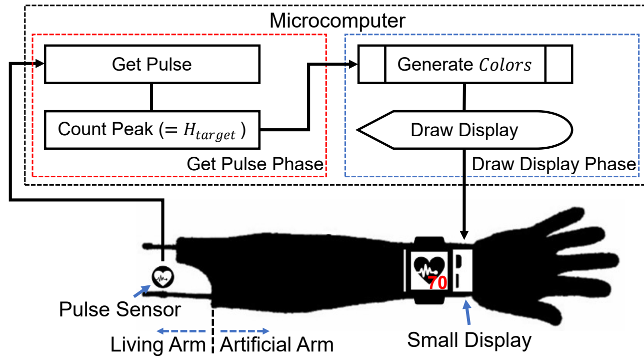


**Figure 1: Process flow of the proposed method.**

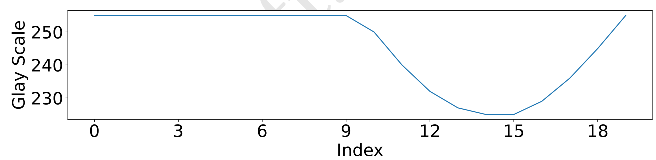


**Figure 2: Time-series brightness of the display that makes a smartwatch detect a single pulse.**

## 3.3 Display Control

The brightness of the display is controlled so that the heart rate measured by the smartwatch becomes $H_{target}$. An array *Colors* that holds the brightness of the display to let the smartwatch to detect a single pulse is prepared in advance. *Colors* is grayscale data. Grayscale is a type of computer color representation that uses 256 levels (0-255) to represent shades of color from black to white. *Colors* whose length is $L$ is generated in the following flow.

1. $Colors[i] = \sin\left(\frac{2\pi i}{L}\right) \ (i = 0, \ldots, L)$
2. $Colors[i] = Colors[i] + 1$
3. $Colors[i] = 1$ (if $Colors[i] > 1$)
4. $Colors[i] = Colors[i] * SCALE + BASE$

**Figure 2** shows the plot of *Colors* when $L$, $SCALE$, and $BASE$ are set to 30, 19, 225. PPG sensors irradiates infrared, red or green LEDs onto the skin and measures pulse data from the changes in light reflected through the blood vessels. Because blood flow increases with the timing of the pulse, more light is absorbed by the blood vessels, and the reflected light is dimmer. The decreasing values in **Figure 2** represent the timing when the reflected light becomes dark. The smaller the grayscale, the closer it is to black. Since black absorbs more light than white, the more the display is rendered black, the darker the light emitted from the smartwatch worn on the display and reflected through the display.

The drawing interval $T$[s] for each value of *Colors* is set as follows so that *Colors* is played $H_{target}$ times in one minute.

$$T = \frac{60}{L * H_{target}} \tag{1}$$

The proposed method draws the values of $Colors$ on the display $T$[s] one by one for each.

## 3.4 Pulse Data Measurement

In the proposed method, a smartwatch is worn over a blinking display and pulse data is measured. Pulse data measured from a PPG sensor equipped on a smartwatch can be used in various applications. However, the performance of the PPG sensor and the algorithm for measuring the pulse data vary depending on the model of the smartwatch equipped with it, and are not disclosed to the public. Therefore, the target heart rate is set manually in the evaluation experiment. We observe the error between the target heart rate and the heart rate measured by the smartwatch, and discuss the effects of the smartwatch model and display.

# 4 EVALUATION

This section describes the experiments conducted to evaluate the effectiveness of the proposed method. We measured the heart rate acquired by the smartwatch when an arbitrary target heart rate was given.

## 4.1 Display Control Software

A program to change the brightness of the display was implemented using Python and Processing[1]. First, Python receives the target heart rate $H_{target}$. Then, $T$[s] is calculated with Eqn. 1. The Python sends $Colors[i]$ to Processing using Python's `socket` library and waits for the drawing to complete. When Processing receives the data, it uses `background` method to draw the grayscale as the background color of the window on the display. When drawing is completed, Python receives the notification from Processing. If $T$[s] has passed, Python sends $Colors[i+1]$ to Processing. When all the data in $Colors$ has been sent, $H_{target}$ is obtained and the system repeats this flow.

## 4.2 Smartwatch Application

A smartwatch is used to measure the heart rate. Smartwatches have different methods of acquiring heart rate depending on the operating system installed on them. In this section, we describe the methods of obtaining the heart rate for each OS.

*4.2.1 Wear OS by Google.* TicWatch Pro WF12106 and PUMA Smartwatch were used in the evaluation experiment. These are a smartwatch with Wear OS by Google[2] which is an operating system designed for smartwatches based on Google's Android. We implemented the application using Android Studio[3]. The application stores heart rate in the smartwatch storage in csv format. The sensor number 21 is used to acquire the heart rate data. The rate of events "SENSOR_DELAY_UI" is used to set sampling rate suitable for the implementation of the user interface[4].

*4.2.2 watchOS.* Apple Watch Series 3 and Series 5 were used in the experiment. Apple Watch comes standard with an application that

[1]https://processing.org
[2]https://wearos.google.com
[3]https://developer.android.com/studio
[4]https://developer.android.com/reference/android/hardware/SensorManager



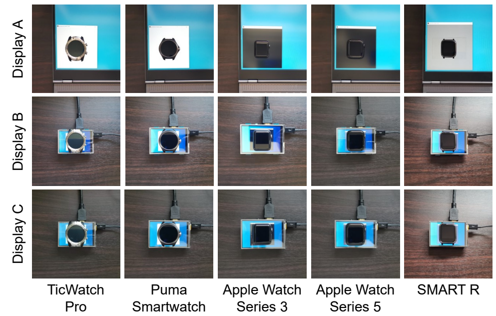


**Figure 3: Smartwatches and displays in the experiment.**

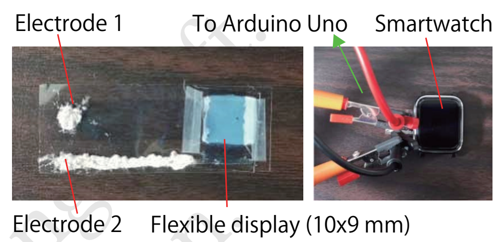


**Figure 4: Appearance of the flexible display.**



measures heart rate[5]. The collected heart rate data can be output as numerical data in XML format using "Health" application of iPhone paired with Apple Watch.[6]

*4.2.3 Original OS.* SMART R F-18 used in the experiment is equipped with a proprietary operating system developed by the manufacturer. By using "WearHealth" application developed for Android and iPhone, heart rate data collected by this smartwatch can be viewed on the application.[7][8]

## 4.3 Evaluation Environment

TicWatch Pro WF12106, PUMA Smartwatch, Apple Watch Series 3 and Series 5, and SMART R F-18 were used for the evaluation experiment. For the display, the laptop display of Legion 7 15IMH05 by Lenovo (Display A), two small 3.5-inch displays designed for Raspberry Pi by OSOYOO and KeDei (Display B and C), and a lightweight flexible display (Display D) were used. The smartwatches and displays A, B, C used in the experiment are shown in **Figure 3**. The size of the lighted part of the flexible display is approximately 1cm square. The appearance of the flexible display is shown in the left side of **Figure 4**. Since the SMART R was the only smartwatch in which the size of the PPG sensor did not exceed the size of the flexible display, the flexible display was tested only with SMART R smartwatch.

HDMI was used to connect Display B or C to the laptop running the display control program. The flexible display blinks by switching the potential direction applied to the terminals. We implemented a

[5]https://support.apple.com/en-us/HT204666
[6]https://support.apple.com/guide/iphone/share-health-and-fitness-data-iph27f6325b2/ios
[7]https://play.google.com/store/apps/details?id=com.zjw.wearhealth
[8]https://apps.apple.com/jp/app/wearhealth/id1265052549

**Table 1: Error of the heart rate obtained by TicWatch Pro, PUMA Smartwatch, Apple Watch Series 3, Apple Watch Series 5, and SMART R.**

| | TicWatch Pro | | | PUMA | | | Series 3 | | | Series 5 | | | SMART R | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $H_{target}$ | A | B | C | A | B | C | A | B | C | A | B | C | A | B | C | D |
| 60 | -1.7 | -1.4 | -1.4 | -1.7 | -1.4 | -1.4 | 0.4 | 1.0 | -0.2 | 58.2 | 0.1 | -0.1 | -1.7 | -1.7 | -1.0 | 1.0 |
| 65 | -1.8 | -1.4 | -1.3 | -1.8 | -1.4 | -1.3 | 0.6 | 0.1 | -0.1 | 16.1 | -0.4 | 0.1 | -1.3 | -1.7 | -1.7 | -1.7 |
| 70 | -1.8 | -2.1 | -1.2 | -1.8 | -2.1 | -1.2 | 0.1 | 2.0 | 0.0 | 1.6 | 2.4 | 0.1 | -1.0 | -1.3 | -1.0 | -1.0 |
| 75 | -2.2 | -1.6 | -1.5 | -2.2 | -1.6 | -1.5 | 0.0 | 2.8 | -0.6 | 0.8 | 0.1 | -0.2 | -2.0 | -2.0 | -1.7 | -0.3 |
| 80 | -2.0 | -1.5 | -1.1 | -2.0 | -1.5 | -1.1 | -0.5 | 1.0 | -0.5 | 1.2 | 0.9 | -0.4 | -1.0 | -2.0 | -2.0 | 0.0 |
| 85 | -1.8 | -1.5 | -1.6 | -1.8 | -1.5 | -1.6 | -5.4 | -0.7 | -0.6 | -0.6 | -1.0 | -0.9 | -1.7 | -1.7 | -2.0 | -0.3 |
| 90 | -2.0 | -1.7 | -1.0 | -2.0 | -1.7 | -1.0 | -0.6 | -1.3 | -0.6 | 4.3 | -1.0 | -0.9 | -2.3 | -2.0 | -2.3 | -1.0 |
| 95 | -2.0 | -1.2 | -1.1 | -2.0 | -1.2 | -1.1 | -1.5 | -0.5 | -1.0 | -0.1 | -0.3 | -1.1 | -1.7 | -1.3 | -2.3 | 0.0 |
| 100 | -1.9 | -1.5 | -1.4 | -1.9 | -1.5 | -1.4 | -0.7 | -1.1 | -0.7 | -0.2 | -7.3 | -0.8 | -3.0 | -3.0 | -2.7 | 0.0 |
| Average | -1.9 | -1.5 | -1.3 | -1.9 | -1.5 | -1.3 | -0.8 | 0.4 | -0.5 | 9.0 | -0.7 | -0.5 | -1.7 | -1.9 | -1.9 | -1.1 |

system to realize the proposed method described in Section 3 using a microcomputer, Arduino Uno R3. This microcontroller can control the output voltage by pulse width modulation (PWM). The Arduino receives the target heart rate from Python running on a computer connected to it, and changes the voltage to the display. The color of the display becomes darker when higher voltage is applied to the electrode 1, and lighter when higher voltage is applied to the electrode 2. The voltage of each electrode was switched between LOW and HIGH every $30/H_{target}$ seconds to let the smartwatch measures the target heart rate.

To obtain the correct heart rate, a 2-mm acrylic plate was placed between the display and a smartwatch in some combinations of the display and smartwatch. The smartwatches were placed on the display and the target heart rate was set to the display drawing program. The target heart rate was tested from 60 to 100 beats per minute (bpm) in increments of 5, which is the rage of the average heart rate for adults[5]. For wearOS and watchOS smartwatches, heart rate was recorded for 60 seconds and averaged measurement was used for the evaluation. For the originalOS smartwatch, heart rate was recorded once after 30 seconds due to logging software limitation. Heart rate measurement were conducted three times for each condition.

## 4.4 Results and Discussion

The error of the measured heart rate is calculated by subtracting the measurement from the target. The results of the evaluation experiment using TicWatch Pro, PUMA Smartwatch, Apple Watch Series 3, Apple Watch Series 5, and SMART R are shown in **Table 1**. This result is the average of three sets. Zero means that the heart rate is same as the target heart rate, and minus means that the heart rate is smaller. Also, the average of the errors is shown for each display.

*4.4.1 WearOS Smartwatch.* The results showed that the heart rate could be input into the smartwatch within an error of less than -3 bpm. In both wearOS smartwatch results, the average error is smaller for Display A, B, and C in that order. This suggests that differences in performance, such as display brightness and refresh rate, may affect the generated heart rate. In the future, we need to conduct evaluation experiments using more displays to find displays with smaller errors.

*4.4.2 WatchOS Smartwatch.* The results showed that Using Display C, the heart rate could be input into the Apple Watch within an error of 0.1 to -1.1 bpm. On the other hand, when using Display A and B, it was not possible to obtain the correct heart rate under some conditions. In particular, when the target heart rate was set to 60 with the combination of Apple Watch Series 5 and Display A, the correct heart rate was not obtained even once. However, there are many cases where the heart rate is obtained correctly. In the future, it is necessary to clarify the conditions under which the heart rate cannot be obtained correctly.

*4.4.3 Original OS Smartwatch.* The results showed that the heart rate could be input into the smartwatch within an error of less than -3 bpm. Especially for the flexible display, the heart rate could be input into the smartwatch within an error of less than -2 bpm.

# 5 CONCLUSION

In this paper, we proposed a method to let the PPG sensor measure an arbitrary heart rate using a display. We implemented a display drawing program and conducted an evaluation experiment using five kinds of smartwatches and four kinds of displays to confirm the effectiveness of the proposed method. As a result, the overall error between the target heart rate entered and the heart rate acquired by the smartwatch was within -3 beats per minute in most cases.

In the future, we will improve the reproducibility of PPG data for use in a real environment, and implement a mechanism that allows the wearable device worn on the display to measure the same PPG data by inputting PPG data obtained from a live body part. To achieve this, the system needs to continue to automatically determine the colors to be drawn on the display. Therefore, we will build a generative model that can output the color to be drawn on the display by inputting PPG data.

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