Heart Rate Estimation Based on PPG signal and Histogram Filter for Mobile Healthcare

Ju-Won Lee, Byeong-Ro Lee, *Member, KIMICS*

Abstract— **The heart rate is the most important vital sign in diagnosing heart status. The simple method to measure the heart rate in the mobile healthcare device is using the PPG signal. In developing the mobile healthcare device using the PPG signal, the most important issue is the inaccuracy of the measured heart rate because the PPG signal is distorted from the user's motions. To improve the problem, this study proposed the new method that is to estimate the heart rate without an additional sensor in real life. The proposed method in this study is using the histogram filter. In order to evaluate the performance of the proposed method, the study compares its results with the moving average method in motion environment. According to the experimental results, the performance of the proposed method was more than 40% better than the performances of the MAF.**

Index Terms— **Mobile healthcare, Histogram filter, photoplethysmograph, Heart rate**

I. INTRODUCTION

THE people want to enhance the quality of the life while they keep their health and pursue happiness. By these needs, the current science and technology at present are focused on developing the mobile healthcare devices that combined the information technology and the biomedical technology [1],[2]. The several companies are servicing the healthcare using the developed healthcare devices. Currently, the developed mobile devices for the healthcare are heart rate monitor, blood pressure meter, thermometer, pulse oximeter, etc. These devices use the non-invasive method for measuring biomedical signal. In these devices, the most important device is the heart rate monitor, and the heart rate monitor for measuring the heart rate use the PPG(photo-plethysmograph) signal that is the pulse wave acquired at a finger or a radial artery by using the LED(wavelength : 660[nm] or 940[nm]) and a photo sensor [3]-[5]. In developing the mobile healthcare device using the PPG signal, the most important issue is the inaccuracy of the measured heart rate because the PPG signal is distorted from the user's motions. To improve the problem, the general method which used the filter such as LPF(low pass filter) and HPF(high pass filter) is difficult to remove the motion noises(motion artifacts) because the frequency band of the PPG signal and motion artifact overlapped [2]-[5]. In the last few years, the several researchers proposed the new methods to solve the problem, and their methods shown the good performance in filtering the motion artifacts. One method developed to remove noise through an adaptive filter by producing a motion artifact model from an accelerometer [2]. The method performed well, but led to additional costs. Another method employed based on the short time-frequency analysis. The method also performed well in heart rate extraction, but the method needs a significant amount of operation memory and processing time. Thus, it is difficult to apply the method to the mobile healthcare device for real time processing. Therefore, this study proposes the new method that is to estimate the heart rate without an additional sensor in real life. The proposed method in the study is to estimate the heart rate using the period histogram of the PPG pulse wave. In addition, the method is similar to the short time-frequency analysis and will be able to do real time processing based on small operation memory. In order to evaluate the performance of the proposed method, the study compares its results with the moving average method and adaptive filter methods in terms of PPG signals generated by resting, finger and wrist movements, and walking.

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II. PPG SIGANL AND MOTION ARTIFACTS

The PPG signal is the biomedical signal to measure oxygen saturation, blood pressure, and cardiac output in a wide range of commercially available medical devices. It is often used non-invasively method for obtaining measurements at the skin surface based on the electro-optic method and Beer-Lambert's law. In other words, the PPG signal $p(t)$ defined as Eq.(1) is acquired by illuminating skin with light $i(t)$ generated from an infrared or red light emitting diode (LED) and then measuring the amount of light either transmitted or reflected to a photodiode.

$$p(t) = i(t)e^{-\Delta d} \tag{1}$$

In Eq. (1), the distance Δd between the light source $i(t)$ and photodiode changes according to the volume of blood in the artery within the skin. The PPG signal obtained from the variance distance Δd is affected by various noises in the user's environment, such as the user's condition, respiration, or movement. The frequency band for these motions overlaps with the frequency band of the PPG signal. For example, the frequency band of respiration is 0.04~1.6[Hz], and the frequency band of motion artifacts caused by the patient's movements is 0.1[Hz] and higher. The frequency band of the PPG signal pulse wave is in the range of 0.5~4.0[Hz] [5]. Because of this, it is difficult to detect the heartbeat using classical filtering methods.

III. HISTOGRAM FILTER FOR HEART RATE ESTIMATION

This study proposed a simple method based on the quasi-periodic property of heart pulse to estimate the heart rate in the motion artifact environment. The proposed method is focused on estimating heart rate in PPG signal with motion artifacts. The method is consisted of a MAF(moving average filter) for filtering the high frequency noises, an adaptive threshold to detect the peak positions of the PPG signal, and the histogram filter based on the periods between the peak positions as shown in Fig. 1. In Fig.1, the MAF is for filtering the high frequency noises generated from the analog amplifier and the electronic components. The output $y_M(n)$ of the MAF is as follows:

$$y_M(n) = \frac{1}{N}\sum_{i=0}^{N-1} p(n-i) \tag{2}$$

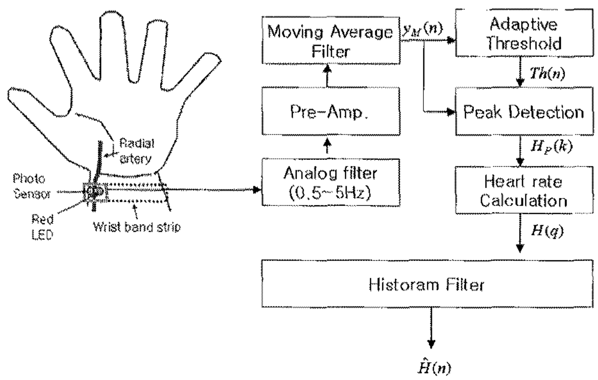

Fig. 1. Structure of the proposed method to estimate the heart rate.

In Eq. (2), N is the filter order, and $p(n)$ is a PPG signal acquired at sample n. The output of the moving average filter inputted to the adaptive threshold processor. The adaptive threshold $Th(n)$ defined as Eq. (3) is to detect the peak position $H_P(n)$ in PPG signal and is similar to moving average. The peaks are used to calculate the heart rate.

$$Th(n) = \frac{1}{N_T}\sum_{i=0}^{N_T-1} y_M(n-i) \tag{3}$$

In Eq. (3), N_T is the order of an adaptive threshold and determined by $N_T=2N$ in this study. The peak point $H_P(k)$ in the PPG signal makes by Eq. (4) and Eq. (5).

$$\mathbf{W_P} = \{y_M(n),\quad y_M(n) > Th(n)\} \tag{4}$$

$$H_P(k) = index_{\max}(\mathbf{W_P}) \tag{5}$$

In Eq. (4) and (5), $\mathbf{W_P}$ is the vector which is set of greater values than the threshold $Th(n)$ at sample n, and the function $Index_{max}(.)$ is to find the position of a maximum value in vector $\mathbf{W_P}$. To calculate the heart rate by the peak points obtained in Eq. (5) is as follows:

$$H(q) = 60 f_s / \{H_P(k) - H_P(k-1)\} \tag{6}$$

where, f_s and q are sampling frequency and index of heart rate. The output $H(q)$ of the heart rate is affected by motion artifact. Thus, we propose the histogram filter to estimate the heart rate in the motion artifacts environment. The processing of the proposed histogram filter to estimate the heart rate is consisted of the heart rate-histogram conversion, the position searching of a maximum value in histogram domain, the effective area extraction based on the maximum value, and the center estimation of the area. The heart rate-histogram conversion is for mapping the heart rate values $\{H(q-i),\ i-0,1,2,...,Q-1\}$ to the histogram domain as Eq. (7). In Eq. (7), P_W is the total number of bins.

$$\underset{i=0,1,...,Q-1,\, j=0,1,...,P_W}{H_t(j)} = \begin{cases} p_k = 0, & initialize \\ p_k = p_k + 1, & if\ H_t(j) = H(q-i) \end{cases} \tag{7}$$

In Eq. (7), P_k is frequency in histogram domain. The position searching of a maximum value is to find the frequent heart rate as Eq. (8).

$$P_H = index_{\max}(\mathbf{H_t}),\ \mathbf{H_t} = [H_t(0), H_t(1), ..., H_t(P_W)] \tag{8}$$

To extract the area of the effective heart rate values in $\mathbf{H_t}$, we used condition defined as Eq. (9).

$$P_s = \left\{ i,\ \underset{i=P_H-1}{\overset{0}{if}}\ H_t(i) = 0, \quad P_e = \left\{ j,\ \underset{j=P_H}{\overset{P_W}{if}}\ H_t(j) = 0 \right.\right. \tag{9}$$

Finally, the positions (P_s:start point, P_e:end point) obtained in Eq. (9) are used to estimate the heart rate by the weighted mean operation as Eq. (10).

$$\hat{H}(n) = \sum_{i=P_s}^{P_e} H_R(i)H(i) / \sum_{i=P_s}^{P_e} H_R(i) \tag{10}$$

IV. EXPERIMENT AND RESULTS

In order to evaluate the performance of the proposed method in this study, we designed the PPG sensor using a red light emitting diode and light-to-voltage optical sensor(TSL250RD). The designed analog filter and the pre-amplifier are a 2^{nd}-order active filter with band frequency 0.5~4[Hz] and a non-inverter amplifier which has 150 times gain. The implemented PPG sensor(Fig.2) was installed on the inside of the wrist strap for measuring the pulsing information of the human's wrist radial artery blood vessel. The method is based on the photo-reflection method. The location of the PPG sensor module is shown in Fig. 3.

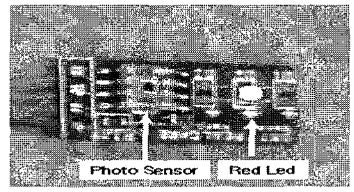

Fig. 2. Implemented PPG Sensor.

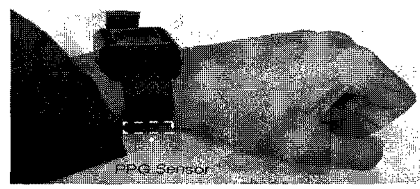

Fig. 3. Location of the PPG sensor.

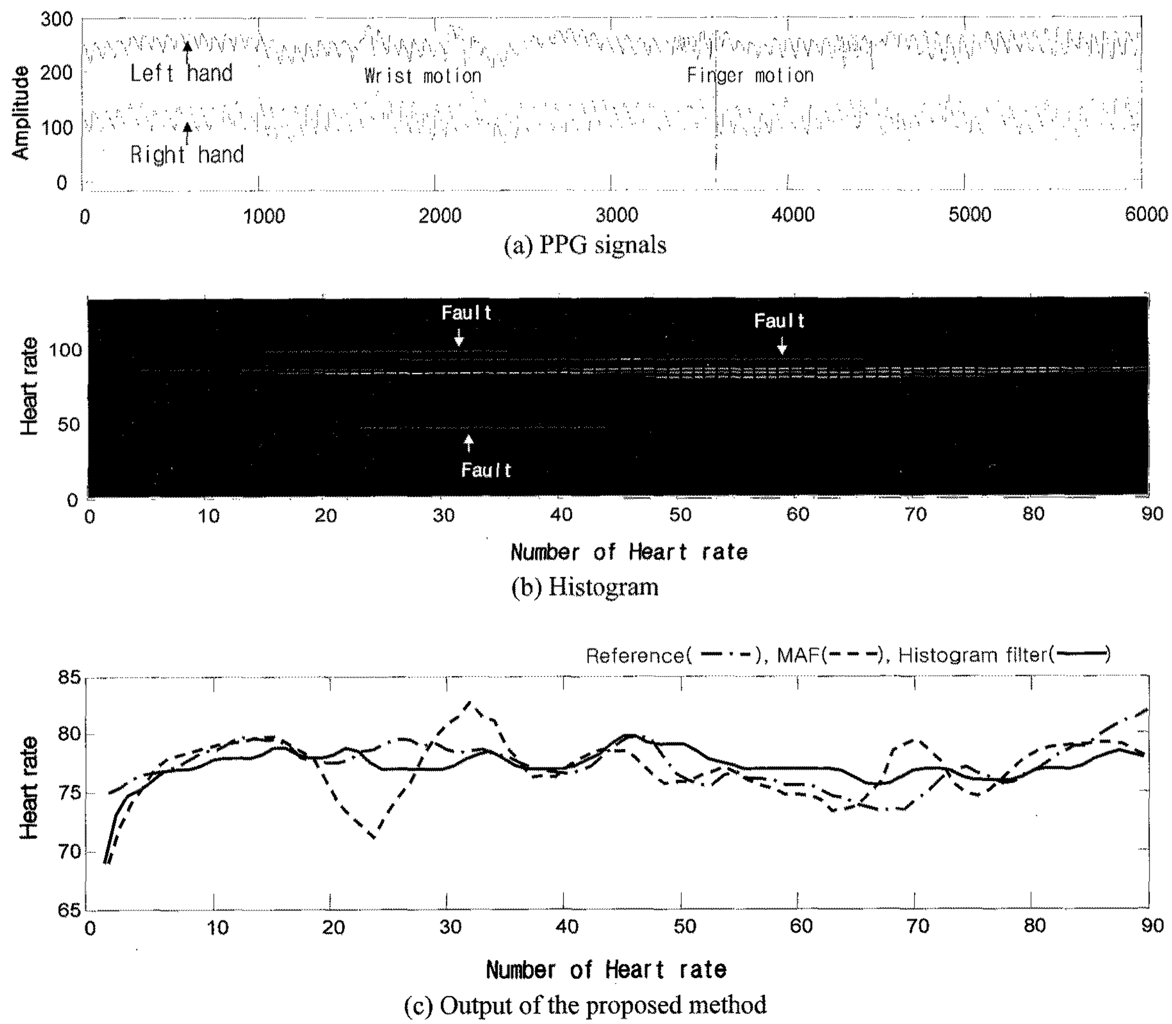

Fig. 4. Results of experimentation.

The experiments were performed for 60s to acquire PPG signals containing motion artifacts from the wrist radial artery of the left hand using the implemented PPG sensor and a reference PPG signal from the finger of the right hand using the PPG amplifier system. The types of motion artifacts tested were free wrist movements and free finger movements. In the experiments, we were set each parameter of the proposed method as follows: sampling frequency = 100[Hz], total bins P_W= 250(50~300[bpm]), N-order of MAF = 20th and window size of the adaptive threshold N_T=2N=500, the total number of heart rates of past and present Q=20. We then compared the proposed method with the MAF to evaluate their respective performances.

TABLE I.
MAXIMUM HEART RATE ERRORS AND MEAN ERROR OF INDIVIDUAL METHODS FROM MOTION ARTIFACTS

Motions	MAF [bpm]	Proposed method [bpm]
Rest	1	2
Wrist	8	2
Finger	6	3
Mean Error (90 heartbeats)	1.64	1.1

The results of the heart rate estimation showed in Fig. 4. In the results shown in Fig. 4, the MAF method showed a large variation when motion artifacts exist in the PPG signal. In contrast, the proposed method performed better than the MAF for several motion artifacts (Table I).

V. CONCLUSIONS

The heart rate is the most important vital sign in diagnosing heart status, stress, etc. The simple method to measure the heart rate in the mobile healthcare device is using the PPG signal. However, it is difficult to obtain precise heart rate when motion artifacts interfere with the PPG signal as noise. Therefore, the study proposed a novel method using histogram filter to estimate heart rate in motion artifacts environments. In order to evaluate the proposed method, the study set various conditions (rest, wrist motion, and finger motion) and compared the proposed method with the MAF method. According to the experimental results, the performance of the proposed method was more than 40% better than the performances of the MAF. Therefore, the proposed method can be applied to mobile healthcare devices to manage user's health in real-time.

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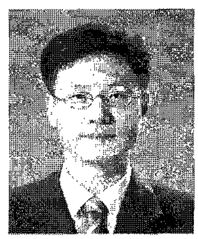

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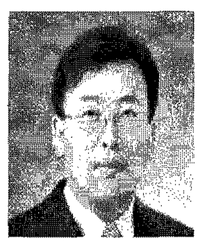

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