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Real-time Heart Rate Measurement based on Photoplethysmography using Android Smartphone Camera

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ABSTRACT

With the development of smartphone technologies enable photoplethysmogram (PPG) acquisition by camera and heart rate (HR) measurement. This papers presents improved algorithm to extract HR from PPG signal recorded by smartphone camera and to develop real-time PPG signal processing Android application. 400 video samples recorded by Samsung smartphone camera are imported as input data for further processing and evaluating algorithm on MATLAB. An optimized algorithm is developed and tested on Android platform with different kind of Samsung smartphones. To assess algorithm's performance, medical device Beurer BC08 is used as reference. According to related works, accuracy parameters includes 90% number of samples that has relative errors less than 5%, Person correlation *(r)* more than 0.9, and standard estimated error (*SEE*) less than 5 beats-per-minutes (bpm).

Key words: Photoplethysmogram, Heart Rate, Mobile Devices, MATLAB, Android..

1. INTRODUCTION

Monitoring vital parameters such as heart rate, blood pressure plays a very important role in detection, recognition the dangerous situation and prevent of any health diseases [1]. An approach to monitor HR is through the use of pulse oximeter, which is a small device that uses photoplethysmography (PPG) to capture blood volume changes by illuminating the finger with a light emitting diode (LED) and measure the changes in skin illuminated light by transmitting it through photodiode. Another approach is replacing the photodiode, used in pulse oximeter, by a smartphone camera that enables PPG imaging as shown in Fig. 1 [2]. While it is easy to position on the finger, pulse oximeters are somewhat obtrusive and impractical for intermittent use throughout the day, smartphones are so much more portable and practical.

To program a real-time application on mobile devices, further analysis and optimization are caried on MATLAB for evaluate the robustness, simplicity, and accuracy of algorithms. In this study, the approach of real-time PPG signal processing application on Android smartphone is presented.

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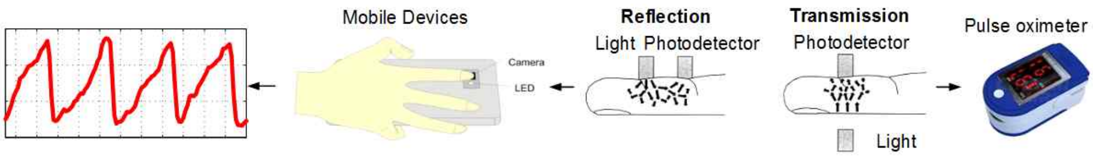

Fig. 1. Methodology of PPG on mobile devices.

Our paper is organized as follows. In section 2, we discuss the related works and in section 3, we explain heart rate measurement methodology in detail. Then, in section 4 we perform experiments and discuss about the experimental results, evaluate the performance of algorithm. Finally, we conclude this paper in section 5.

2. RELATED WORKS

The current generation of smartphones includes video recording capabilities using a photodetector with an accompanying light-emitting diode (LED) light source positioned close to or surrounding the photodetector lens. This is very similar to the PPG imaging technology therefore these smartphones can directly measure some vital characteristics. Nowadays, there are smartphone-based commercial applications such as Instant Heart Rate, Heart Rate Tester, Cardiograph, etc. that allow evaluating HR. However, while they provide a PPG-like waveform in the ideal usage conditions, they often fail when something goes wrong [3]. Pelegris et.al proposed a novel method to detect heart beat rate using a mobile phone, and the authors reported a performance problem of the Android-based smartphone [4]. Jonathan and Leahy used a Nokia E63 smartphone for pulse rate measurement, and they assessed that the green channel provides a stronger PPG signal than the red one [5].

The objective of this paper is to develop an Android application to measure the PPG waveform and calculate the heart rate based on video recorded by a smartphone. Therefore, related works for a smartphone-based PPG acquisition system are evaluated. Later, a new method is proposed on the development of robust algorithm suitable for Samsung smartphone models that address motion artifacts by distant constraints and RGB threshold. The Android application utilizes the original equipment manufacturers video hardware and software. The experimental tests are performed on different Samsung smartphones with a comparison to medical device (Beurer BC08 wrist blood pressure monitors) with given maximum error of 2 beats per minute (bpm).

3. HEART RATE MEASUREMENT METHODOLOGY

This work describes a smartphone-based heart rate estimation technique using PPG signal. In other words, the photodiode and light source, used in pulse oximeter, are replaced by built-in smartphone camera and LED to record video data of fingertips that enables PPG signal acquisition. The HR estimation using smartphone-based PPG system consists of four phases as described in Fig.

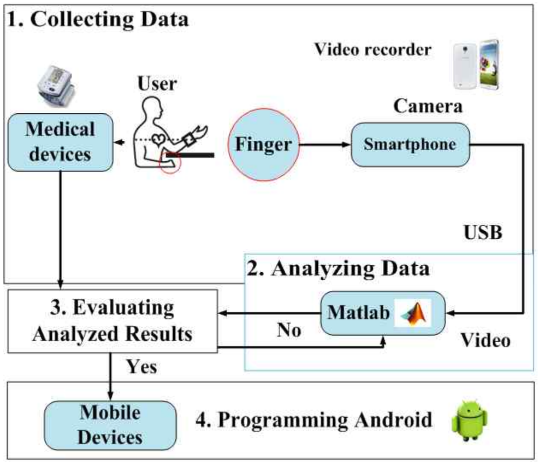

Fig. 2. Smartphone-based system architecture.

2. The first phase is to collect data including the video data of user's fingertip and HR results by medical devices simultaneously. Nextly, the video data is transmitted to computer by USB-port for post-processing by applying the proposed algorithm to measure HR on MATLAB in analyzing data step. Particularly, MATLAB version R2011a is used to post-processing the proposed method. Then, the HR results acquired from MATLAB are evaluated with HR reference by medical devices. If the accuracy requirements are achieved, the algorithm will be programmed in Android platform-Android platform v4.2.1- in the last phase. In details, the application is developed using Android Developer Tools (ADT) software- Android SDK and ADT v22.3. This Android application is supported for devices with flash near camera and run Android OS 4.0 or higher. Note that, the Android applications are tested in several Samsung models from mid-end to high-end smartphones. In the end, the final optimization by adjust the proposed algorithm and video recording settings is to stabilize operation of real-time HR measurement application on Samsung devices.

3.1 Data Collection

400 video samples with duration from 15 to 20 seconds are taken from a group of 20 people between 18 and 50 years old, with an average age of 26.3 years old. Particularly, subjects are asked to wear Beurer BC08 cuff in the left hand and simultaneously hold the smartphone in the right hand and put index finger over smartphone rear-camera len and flash LED. The experiments are conducted in laboratory environment and under supervision to ensure that every configurations is well-setup during the measurement. Moreover, different Samsung smartphones are used to evaluate developed application and device influences.

3.2 Smartphone-based photoplethsmography

The HR measurement system is initially simulated on MATLAB using videos of fingertip captured from the camera as input data. In details, the proposed algorithm for calculating HR based on PPG signal includes four main parts as shown in Fig. 3.

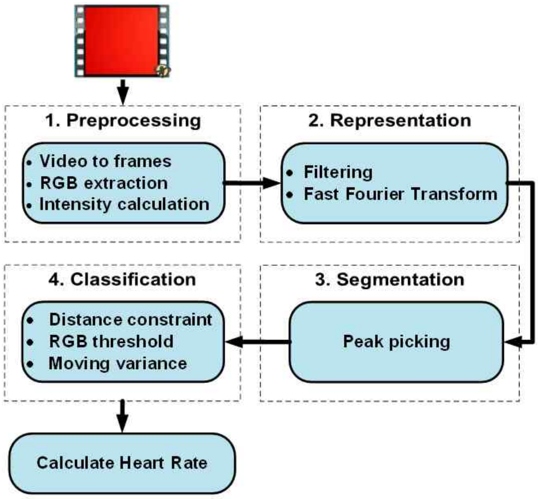

Fig. 3. Block diagram of PPG signal processing.

A brief description of PPG signal processing is presented as follows. In the pre-processing stage, video goes through video-to-frames and RGB extracting block to obtain sequence of frames with separate Red Green Blue (RBG) channel. In the representation stage, mean brightness of each frame is calculated which Red channel is preferred one to obtain PPG signal. Then, PPG signals are transformed (i.e. moving average filter, or FFT) in order to highlight the peaks. Subsequently, applying peak picking is of purpose to look for candidates peaks in segmentation stages. In classification stage, candidates peaks are reclassified based on distance constraints and RBG threshold to counter motion artifacts (i.e., noise of unstable finger) before calculating HR in the last stage.

In details, video samples which are recorded by smartphone-based PPG system with camera and flashlight share some configuration parameters including resolution, channel, frame rate and number of frames (or recording duration) as shown in Table 1.

Table 1. Video Parameters.

Video Parameters	Formular	Examples
Video data	$V(m,n,c,t)$	
Resolution	$m \times n$ $m = 0..M-1$ $n = 0..N-1$ $t = 0..T-1$	320×240
Channel	$c = 1,2,3$	{Red, Green, Blue}
Number of frames	T	
Frame rate	F	30(*fps*)

The developed smartphone application acquires 320×240 pixels resolution with an effective frame rate of 30 frames per second (fps) sampling rate. Although these configurations are not the current highest available setting, these setting are preferable for our experiments as it reduces the computational cost in Android programming. The number of frames (T) is equal to "recording duration (t) multiple to frame rate (F)". Video is extracted into T frames, and each frames consists of three color channels (c), namely Red Green Blue (RGB) represented as three matrix of pixel separately as shown in Fig. 4.

Each of frames is a matrix of pixels with size $m \times n$, and the corresponding matrix for each channel has elements's value $a_{i,j}$ from 0 to 255 representing brightness of relative pixels ($i=1,2,..,m;\ j=1,2,..,n$). Then, the mean brightness for each channel frames $b(t)$ is calculated as in Eq.(1)

$$b(t) = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} a(i,j,c,t)}{m \times n} \quad (1)$$

where $m \times n$ is video resolution, $a(i,j,c,t)$ is corresponding matrix for each RGB channel with 320×240 resolution, c refers to RGB channel, t is the total frames obtained from recording at 30 fps.

This technique is based on determining only Red channel variation to calculate HR. An alternative techniques is to process data from all channels in RGB mode [6], or as in [5] only green channel intensity is used to obtain pulse wave. In addition, this main target of this paper is to develop Android application with limited resources both in terms of processing power, hardware and memory, it is reasonable to acquire the input data simple as long as the results maintain highly accurate. Experiments on different Samsung smartphone cameras indicate that Red channel provides stably valuable information to extract HR compared to Green and Blue channels due to the effect of natural noise in these channels as described in Fig. 5.

In representation step, this paper presents optimized coefficients of Moving Average Filter (MAF) with window size $k=7$ with coefficients $a_7 = [1, 2, 3, 4, 3, 2, 1]$, and the output of MAF $f(t)$ is calculated as follow

$$f(t) = \frac{1}{W_t}\sum_{k=0}^{W_t - 1} a_k b(t+k) \quad (2)$$

where $b(t)$ is mean red brightness, a_k is moving average filter coefficients, W_t is window size.

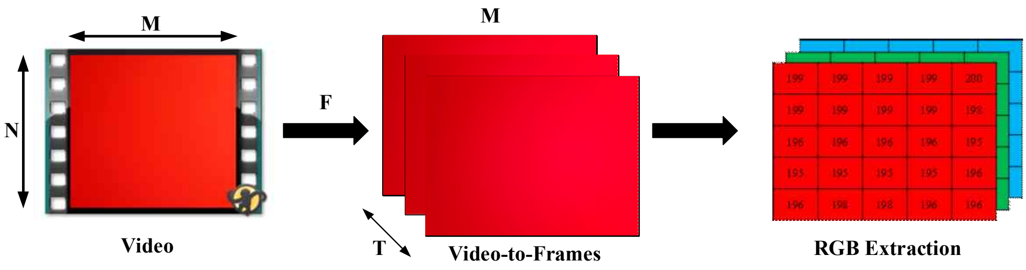

Fig. 4. Detailed pre-processing step.

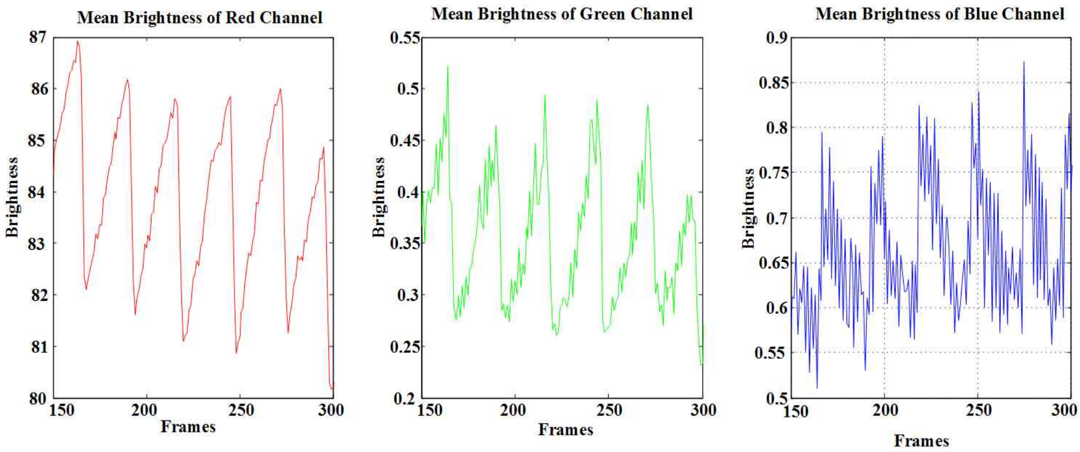

Fig. 5. Diagram of different color channel signal recorded by Samsung smartphones.

Fig. 6. Mean brightness of crude signal and filtered signal.

Fig. 6 illustrate the briefly fluctuation of crude signal due to inteference of natural noise or motion artifacts, and the smoothness of filtered signal. The main purpose of filter is to surpass the noise and highlight the peak of PPG signal to increase accuracy of peak picking algorithm.

In segmentation step, the peak picking algorithm namely Local Maxima/Minimum Detection is applied to count the number of candidate peak as shown in Fig. 7. The peaks are selected if their brightness is higher than 5 adjacent peaks forward and backward as in Eq.(3)

$$p(t) = \begin{cases} f(t) > [f(t-5), f(t-4), f(t-3), f(t-2), f(t-2)] \\ f(t) > [f(t+1), f(t+2), f(t+3), f(t+4), f(t+5)] \end{cases} \quad (3)$$

In classification step candidates peaks are reclassified based on distance constraints to calculate more accurate HR by eliminate false detection peaks, and RGB threshold to counter motion artifacts (e.g., noise of unstable finger). Fig. 8 shows the diagram of PPG signal due to the effect of motion artifacts in different scenarios (i.e., slight movement of finger, remove finger out of camera len) and the normal stable finger as comparison.

As for distance constraints, a minimum $d_{min} = 60 \times F/200$ and maximum $d_{max} = 60 \times F/50$ (F is the frame rate of camera) are used to classify candidates peaks whose distance from one of adjacent peaks are not included in distance range (d_{min}, d_{max}). These distance corresponds to heart rate from 50 to 200 bpm. Then, the peaks whose distances in range (d_{min}, d_{max}) are reclassified again by remove peaks, that distance to one of the adjacent peaks differs from the mean value of the distances for more than max_diff (i,e. 25%) percentage. As for RGB threshold, the mean brightness of red channel threshold is set to 180, that classifies the accepted and invalid frames as illustrated in Fig. 9.

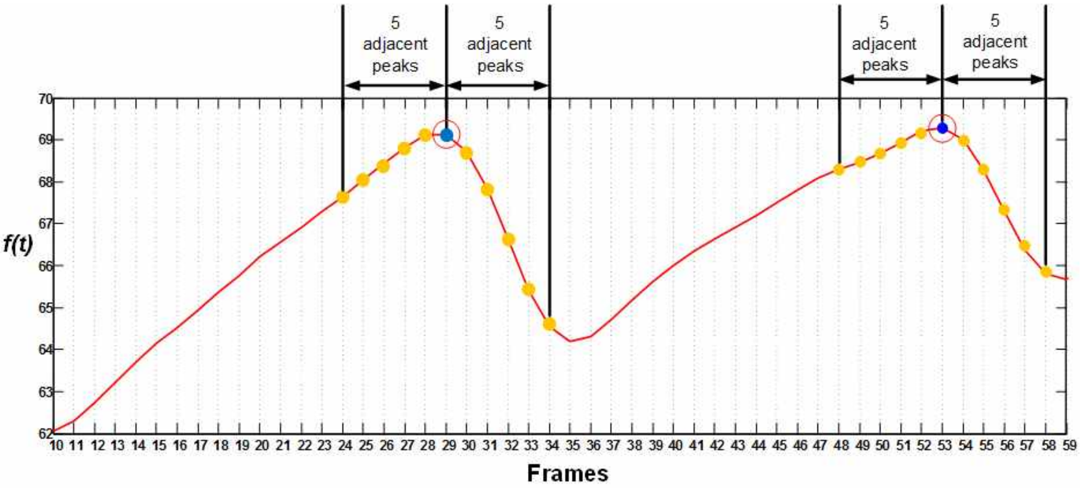

Fig. 7. Diagram of peak-picking algorithm with 11 coefficient adjacent peaks.

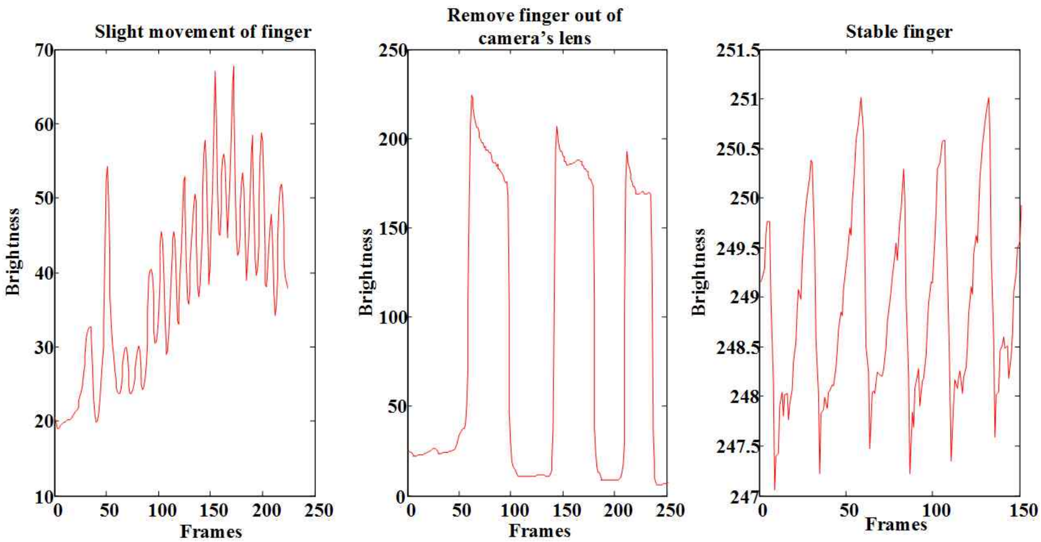

Fig. 8. Effects of motion artifacts to PPG signal as comparison to normal case.

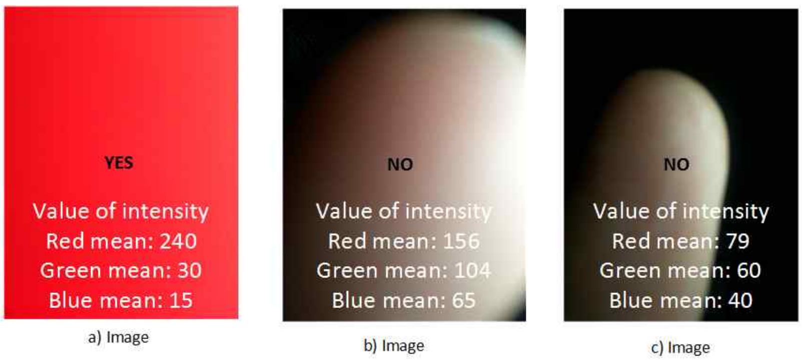

Fig. 9. RGB threshold classifies (a) as accepted frame, (b) and (c) as invalid frames.

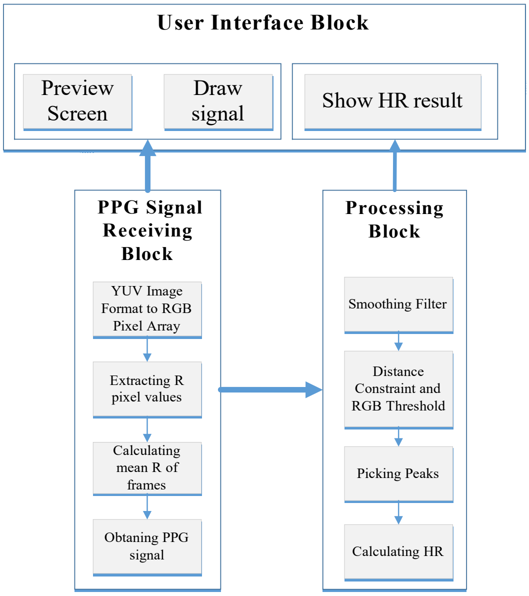

Fig. 10. Block diagram of HR measurement application.

between two adjacent peaks in the set of p peaks.

3.3 Android developed application

The main blocks of the developed Android application that acquire PPG signal from processing frame-to-frame image camera and process to calculate HR are shown in Fig. 10.

Firstly, smartphone application acquires frame image in YUV420sp format with NV21 encoding. Then, a Java script is executed for converting the Android YUV buffer to RGB pixel array following the equation in Eq.(4).

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.144 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.1 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{4}$$

Secondly, the Red component of pixel array is extracted and averaged to obtain PPG waveform. Then, the improved algorithm for PPG signal classification and heart rate estimation are programmed following signal processing procedure on MATLAB as presented in part 3.2. To evaluate smartphone application signal processing, three modes are programmed including fast measurement about 5 or 10 seconds, free mode with unlimited time duration, and noise mode that allows users with some movement artifacts of fingertips. Finally, the optimized version of heart rate application are tested on real-time to provide experimental results. Fig. 11 presents GUI of developed Android application while idle, working with PPG diagram display and obtain final result of HR.

4. EXPERIMENTAL RESULTS

In this section, the performance of the proposed

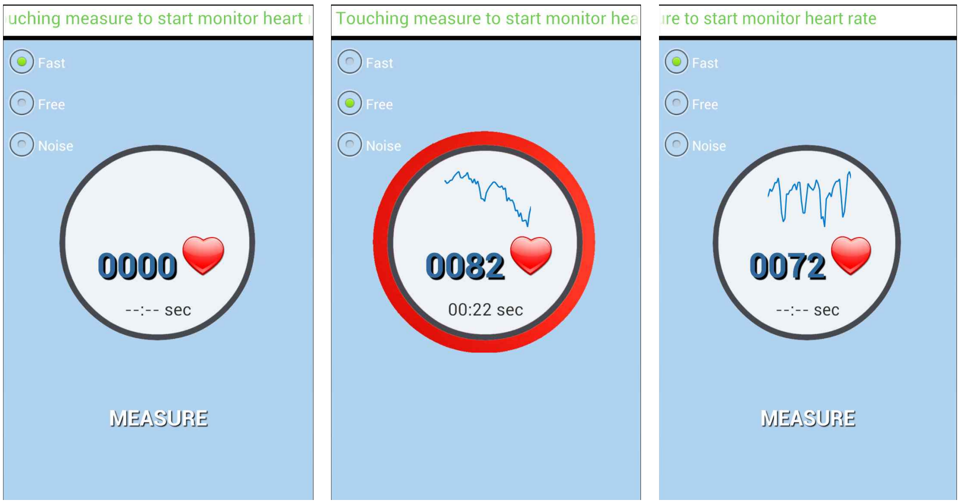

Fig. 11. GUI of developed Android application.

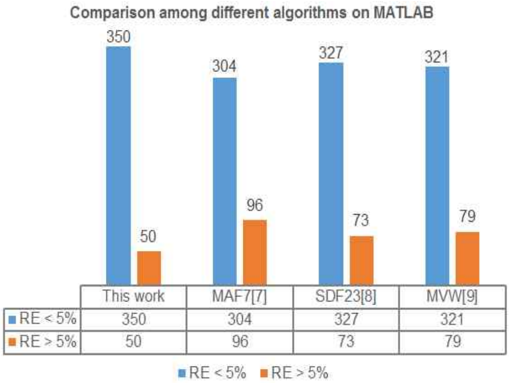

Fig. 12. Evaluation of proposed algorithm on MATLAB based on relative errors.

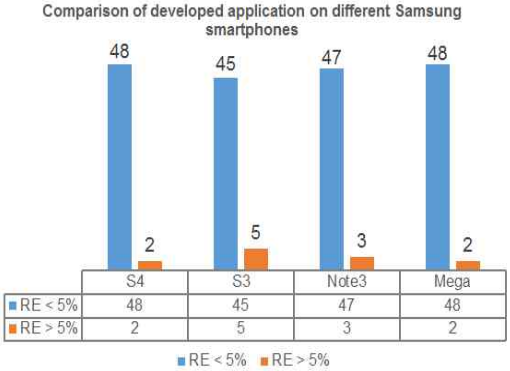

Fig. 13. Evaluation of developed Android application.

algorithm is compared to three PPG signal processing algorithm [7-9] and a commercial medical device Beurer BC08 with a given maximum error of 2 beats per minute (bpm). The algorithm described in [7] proposed to filter signal with a moving average filter [MAF], which split the filtered signal into windows of fixed length and calculated the HR by determining the number of peaks and multiplying the peak count with ratio of 60 to the window length. In [8] authors proposed smooth differentiation filter (SDF) which normalized the signal to calculate HR by multiplying the number of peaks of the normalized signal with the ratio of 60 and dividing by the length of the signal. The main idea of algorithm in [9] was to calculate the mean distance between adjacent peaks as input of moving variance window (MVW), which the HR was calculated by multiplying frame rate of video recorder by 60 and divided the mean distance. Since there was not given any information about filter parameters and peak detection in [7-9], parameters are chosen to achieve the least number of errors. The relative error was used in [7-9] to evaluate performance of HR algorithms, and according to [10], the HR tested were considered to be valid if the Pearson correlation (r) between the recorded heart rate and the corresponding pulse oximeter was more than 0.9 and with a standard error of estimate less than 5 beats per minutes (bpm). This proposed algorithm achieves higher accuracy than related works with the highest number of cases (350 over 400) which has relative errors less than 5%, the Pearson correlation (r) and

Table 2. The performance for proposed algorithm and conventional algorithms on MATLAB with Pearson correlation and SEE.

Accuracy Parameters	HR results on MATLAB			
	This work	MAF7[7]	SDF23[8]	MVW[9]
r	0.9525	0.8390	0.9486	0.9380
SEE	2.4480	4.3738	2.5428	2.786

Table 3. The performance for proposed algorithm on Android with Pearson correlation and SEE.

Accuracy Parameters	HR results on Android Application			
	S3	S4	Note3	Mega
r	0.9064	0.9675	0.9221	0.8453
SEE	2.4268	1.8071	1.6666	1.6567

the standard error of estimate as 0.9525 and 2.4480 respectively as in Fig. 12 and Table 2.

Four different Samsung smartphone models including S3, S4, Note3 and Mega are used to experimental tests with 50 samples to evaluate the performance of developed application as in Fig. 13 and Table 3. This developed application is evaluated to work stably and accurately on different kind of Samsung smartphones.

5. CONCLUSION

In this paper, a review of existing algorithms for heart rate measuring using mobile phones is evaluated. The objective of this proposed algorithm is to develop Android application to measure HR in real time with duration about 10 seconds that optimizes for Samsung smartphones. Thus this method proposes a simple moving average filter with only 7 coefficients to reduce complexity when developing on Android platform but achieves affordable accuracy with classification stage with distant constraints and RGB threshold that outperformed some previous works with the same 400 video samples as input data and works stably on different Samsung mobile devices with 50 sample tests.

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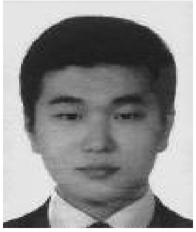

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