J Med Syst (2016) 40:126
DOI 10.1007/s10916-016-0485-6

MOBILE SYSTEMS

A Pulse Rate Estimation Algorithm Using PPG and Smartphone Camera

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Received: 31 December 2015 / Accepted: 28 March 2016

Abstract The ubiquitous use and advancement in built-in smartphone sensors and the development in big data processing have been beneficial in several fields including healthcare. Among the basic vitals monitoring, pulse rate monitoring is the most important healthcare necessity. A multimedia video stream data acquired by built-in smartphone camera can be used to estimate it. In this paper, an algorithm that uses only smartphone camera as a sensor to estimate pulse rate using PhotoPlethysmograph (PPG) signals is proposed. The results obtained by the proposed algorithm are compared with the actual pulse rate and the maximum error found is 3 beats per minute. The standard deviation in percentage error and percentage accuracy is found to be 0.68 % whereas the average percentage error and percentage accuracy is found to be 1.98 % and 98.02 % respectively.

Keywords Pulse rate · PhotoPlethysmoGraph (PPG) · Smartphone sensor · Mobile health

Introduction

Cardiovascular diseases are very common among the elderly as well as the younger population. This situation creates a need for monitoring the basic vitals such as pulse rate, blood pressure, heart rate variability, blood oxygen levels, blood glucose level, electrocardiogram, hemoglobin, etc. [1–13]. Among the aforementioned vitals, pulse rate is the most important physical parameter that can point towards the abnormality in the cardiovascular system as well as other human body systems [14, 15]. Numerous methods, devices and tools can be used to measure the aforementioned basic vitals. PhotoPlethysmoGraph (PPG) signal can be successfully used for the estimation of pulse rate, blood pressure, blood oxygen levels, hemoglobin and biometric identification etc. [5, 16–18]. A typical PPG waveform is shown in Fig. 1.

The blood flow in the vessels is reflected by a PPG signal [5, 14, 19, 20]. A PPG signal has two components; an AC component and a DC component that reflects the pulsatile and non-pulsatile part of the signal respectively [20–22]. The DC component represents the absorbed light in veins, tissues and also the diastole arterial blood volume whereas the AC component is synchronized with the heart [23].

Pulse oximeters are conventionally used to optically acquire PPG from the fingertip, earlobe or wrist of an individual as shown in Fig. 2 [17, 24]. PPG sensor captures the change in blood volume non-invasively by using an LED and a photodetector [21]. It can work in two modes; transmission mode where the light source and the photodetector are on the opposite sides of each other; and reflection mode where both the photodetector and the LED are on the same side [12, 20, 21, 25].

The ubiquitous use of smartphones and advancement in big data processing make smartphones an excellent tool for regular, cost effective and portable healthcare monitoring. Smartphones these days are very well

This article is part of the Topical Collection on *Mobile Systems*

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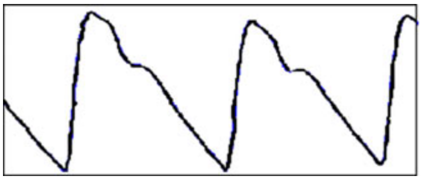

Fig. 1 Typical PPG waveform

equipped with advanced technologies and sensors that can be used for acquiring input data from the users. The data generated by smartphone sensors is diverse in nature and termed as 'Big Data'. A camera and an LED built into the smartphone are a good choice for an inexpensive and portable oximeter for PPG measurement.

PPG signals can be extracted from a video stream of the fingertip. The finger must be placed in a way to cover both the camera and the LED of the smartphone. Some light from the LED is absorbed and some is reflected by the blood and the finger tissues. The amount of the reflected light varies with the varying amount of blood flowing through the finger that is noticeable on video frame intensity. When the heart contracts, it pumps out blood in vessels and the fingertip becomes full of blood so it absorbs more light making the frame darker. On the other hand, less light is absorbed with less amount of blood in the fingertip when the heart takes blood from the vessels that result in the lighter frame [21, 25]. Changes in the intensity of the frames can be used to extract PPG signals from the sequence of frames. Pulse rate can be estimated using the PPG signal periodicity [17].

In this paper, an algorithm is proposed that uses smartphone camera as an input sensor and PPG to estimate pulse rate. The algorithm employs motion detection for reducing the probability of corrupt input data and uses all the three channels (red, blue and green) for PPG extraction. The use of smartphone makes the system portable, affordable, comfortable and convenient [10]. It can also help in providing telemedicine so the patient does not have to visit the hospital frequently, instead a doctor can give advice and consultations

Fig. 2 Earlobe, fingertip and wrist oximeters

from a remote location using communication modules such as 3G/4G, Wi-Fi, etc.

The main contributions of the current research are:

1. An algorithm is proposed for pulse rate estimation with a reduced probability of corrupt input to the system.
2. PPG waveform obtained from all the three channels (red, green and blue). The three channels have been compared to determine the one that can give pulse rate by using simple calculations only.
3. As shown via extensive experiments, the algorithmic error has been minimized and the processor load has been reduced by using simple yet effective calculations.

The rest of the paper is organized as follows, section 2 discusses the related work, section 3 describes the proposed algorithm, results obtained by the proposed algorithm are explained in section 4 and section 5 concludes the paper.

Related work

Heart rate monitoring using PPG signals has attracted extensive interest from the biomedical researchers in the past few years. Some most recent related works are discussed below.

Zhihao Chen et al. [6] proposed a methodology to estimate systolic blood pressure (SBP), diastolic blood pressure (DBP) and pulse rate using BCG (ballistocardiography) and PPG signals obtained from optical sensors in 2013. Signals are smoothened and filtered before applying the respective peak detection algorithm to determine the peak locations. Pulse rate is estimated from the intervals of PPG peaks. The proposed method has mean and standard deviation of 0.6+/-0.9 beats/minute for pulse rate. Specific hardware SpO2 sensor is attached to the fingertip in order to acquire PPG signal that affects the portability and cost of the system.

Sungjun Kwon et al. [14] proposed to measure heart rate using Electrocardiogram (ECG) data collected by the front camera of an iPhone in 2012. A facial video was recorded and a region of interest (ROI) was selected from each frame. A raw signal was traced using the green channel of the image and an Independent Component Analysis (ICA) was applied. Heart rate was obtained by the frequency analysis of both the raw signal and the ICA applied. The accuracy of the proposed system was determined by comparing the obtained results with the results of a reference Electrocardiogram (ECG). The maximum pulse rate error recorded is 7.33 %. An application named FaceBeat was developed for iOS to extract heart rate from the facial video. Complex computations are done in order to estimate pulse rate that increases the processor load. Complicated processes that uses a lot of energy should be avoided for efficient use of battery. Such applications are used for precautionary and monitoring purposes only, they do not need to perform exact measurements, a close estimations, for example ±4 beats/minute, are sufficient.

In 2015, Zhilin Zhang et al. [17] proposed a novel framework called TROIKA that estimates the heart rate using PPG signals. The PPG signal is recorded from the wrist using an oximeter with a green LED. It is based on three major components; signal decompositIon, sparse signal Re-cOnstructIon (SSR), and spectral peaK tracking. The signal decomposition is achieved by singular spectrum analysis (SSA) that decomposes the time series into noise and oscillatory components; SSA helps to remove the motion artifact frequency components from the PPG signal. The signal is then temporally differentiated to make the heartbeat fundamental, harmonic spectral peaks more prominent and random spectrum fluctuations suppressed. A high resolution spectrum of the PPG signal is calculated by SSR. FOCUSS algorithm is used for SSR in the illustrations of the proposed framework. Heart rate (HR) can be estimated by choosing the highest spectral peak in a PPG spectrum. The correct peak to estimate the HR from the PPG signal spectrum is then found using the spectral peak tracking. Experimental results for 12 subjects showed an average absolute error of 2.34 beats/minute. Specific hardware wrist oximeter is used for PPG signals acquisition that reduces the cost effectiveness of the system.

Also in 2015, Dazhou Li et al. [26] proposed a method to estimate breathing rate and heart rate from the PPG signal obtained by a wearable biosensor. The paper discusses a new method for PPG signals decomposition based on a finite Gaussian basis. Time domain PPG waveform is represented as a sum of progressive and regressive time domain waveforms at a fixed arterial site. The mathematical model proposed by Goshtasby and Schonfeld is used in the derivation of the proposed mathematical model. Gaussian basis is then used to approximate the PPG signal, for n Gaussian bases, $3n$ parameters are present in the approximation. Optimization techniques already proposed are used to minimize the errors between the original and the approximated PPG signals. Second derivative of the PPG signal is obtained and the relationship between the Gaussian bases representation and the second derivative is investigated. Once all Gaussian bases are extracted, Hilbert spectral analysis is used for extraction of instantaneous frequencies. Respiratory rate and the heart rate were estimated from the frequency axis. The heart rate estimated by the proposed system is compared with an ECG monitor; the maximum error recorded is 7 beats/minute. A biosensor is used to obtain PPG signal that reduces the portability and cost effectiveness of the system and the error of 7 beats is very high.

The aforementioned methods either use specialized external hardware or execute complex algorithms to estimate the pulse rate, which lead to weaknesses. In our work, smartphone camera is used as a sensor that makes the system cost effective, portable and easy to use. Using simple computations save battery time of the smartphone.

Proposed algorithm

To estimate the pulse rate with minimum possible error while keeping the system cost effective, portable and energy efficient, the proposed algorithm uses only PPG signal acquired from a built-in smartphone camera. A video of the index fingertip of the user is recorded using a smartphone camera (1080P, HD video resolution) with the flash on. During the recording phase the fingertip must cover both the flash and the camera as shown in Fig. 3a. A frame difference based motion detection algorithm is used to assure an undisrupted video input [27, 28]. The results are affected if the video is not recorded properly. To avoid such situations, the video is restarted if the predefined level of movement is detected by the algorithm.

The recorded video is processed by a MATLAB application. Red, green and blue channels are extracted from the individual frames of the video as shown in Fig. 3b and c. A threshold is set using Eq. 1 and pixels having intensity greater than the defined threshold are summed up normally for each frame using Eq. 2. The PPG signal is obtained by plotting the calculated sum of each frame as shown in Fig. 3d.

If the threshold is set too low, the output is a horizontal line and not a proper PPG waveform. Threshold higher than a

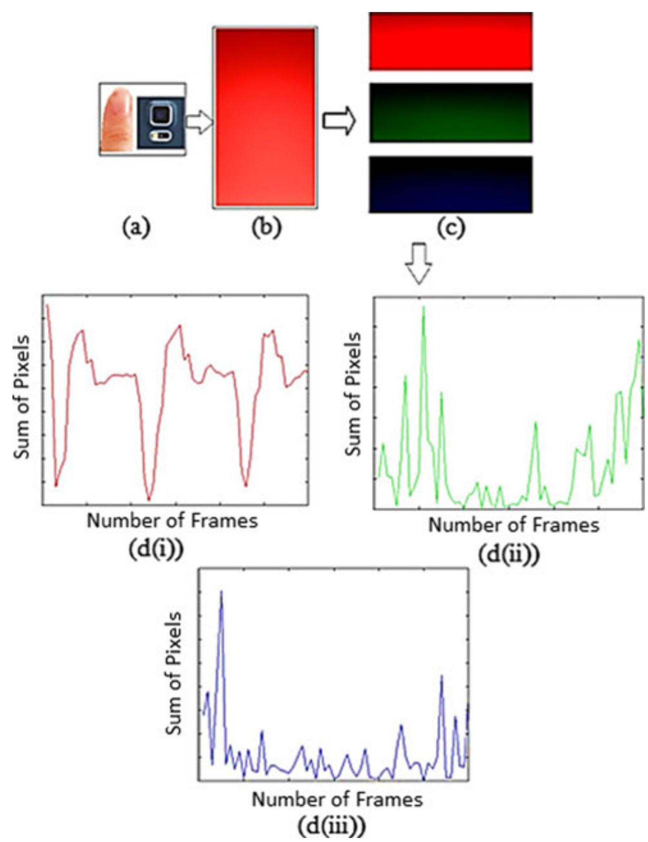

Fig. 3 (**a**) video recording using the smartphone camera, (**b**) a frame extracted from the video, (**c**) red, green and blue components of the frame, (**d**) PPG signals extracted from the red, green and blue components

certain level yields a proper PPG waveform with prominent extremes. Beyond that level, only the magnitude of the extremes is affected by the change in threshold. Without the loss of generality, the empirical value of the threshold in the proposed system is kept to its maximum value i.e. 99 % of the intensity range of the pixels and is calculated for every frame individually. In this paper, the only concern is the number of cycles for pulse rate and not the magnitude.

$$Threshold = 0.99 \times (intensity_{\max} - intensity_{\min}) \tag{1}$$

$$Sum = \sum_{frames=1}^{n} intensity > Threshold \tag{2}$$

To determine the channel that can give pulse rate by simple computations, individual PPG signals for all the three channels (red, green and blue) were extracted as shown in Fig. 3d(i), (ii) and (iii). It is evident from Fig. 3d(i) that the PPG signal acquired from the red channel clearly and without any futher processing shows the blood volume flow during cardiac cycles. It is therefore easy and energy efficient to estimate the number of cardiac cycles per minute from the red channel alone. Cardiac cycles are not clearly visible in the output PPG signal of the green and blue channels as shown in Fig. 3d(ii) and Fig. 3d(iii) respectively. Green and blue channels need further complex processing to extract the required information that increases the processor load and makes the system less energy efficient.

For the above reasons, red channel is being used for pulse rate estimation in the proposed algorithm. Although for some cases, other channels might yield better results than the red channel but comparing the results of every channel every single time consumes more energy and processing time so a tradeoff between accuracy and efficiency of the algorithm is needed.

The number of frames taken to complete one cardiac cycle is calculated by taking the difference between the two consecutive minima (frames/cycle). Frame rate is the number of frames/second captured by the smartphone camera. Pulse rate is estimated by calculating number of PPG cycles per minute using Eq. 3.

$$Pulserate = \left(\frac{framerate}{onecycle}\right) \times 60\,\text{beats/minute} \tag{3}$$

The flowchart of the proposed algorithm is shown in Fig. 4.

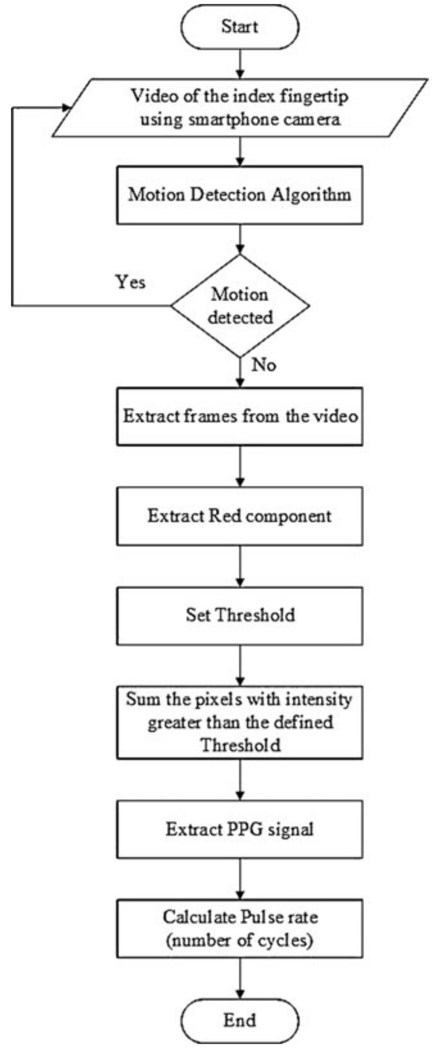

Fig. 4 Flowchart of the proposed algorithm

Evaluation of results

To evaluate the accuracy of the proposed algorithm, pulse rate estimated using red channel PPG is compared to the actual pulse rate of the individuals. The maximum error found was 3beats/minute. The experiment was repeated around 200 times and the standard deviation of the percentage error and percentage accuracy in the results achieved by the proposed algorithm was found to be 0.68 %. The average percentage accuracy and average percentage error were found to be 98.02 % and 1.98 % respectively. Percentage error and percentage accuracy are calculated using Eq. 4 and Eq. 5 respectively.

$$\%error = \frac{|value_{actual} - value_{calculated}|}{value\_actual} \times 100\% \tag{4}$$

$$\%accuracy = 100\% - \%error \tag{5}$$

Results obtained by using the proposed algorithm are plotted in Fig. 5. Every point in the graph represents an estimated pulse rate value with the corresponding actual pulse rate value. The further the points are from the diagonal, the higher is the error and vice versa. The maximum absolute error found was 3 beats/minute but most of the absolute errors lie in the range between 1.5 and 2 beats/minute. Figure 6 shows the

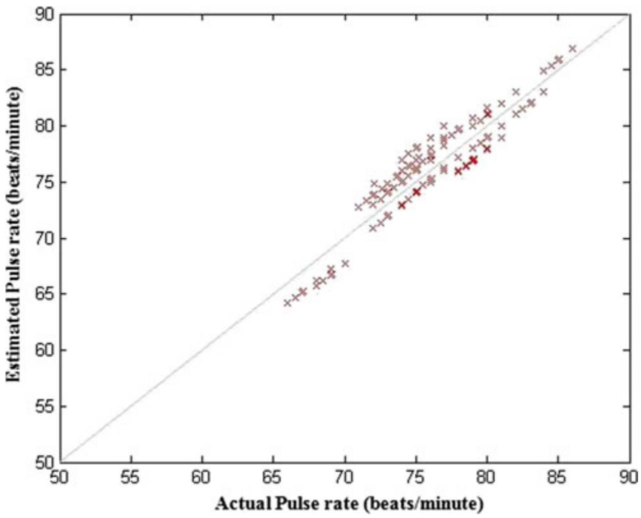

Fig. 5 Results of pulse rate using the proposed algorithm

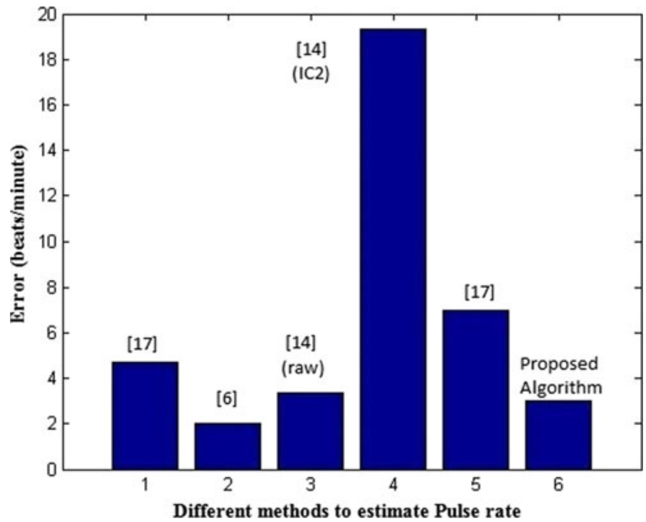

Fig. 7 Comparison between maximum absolute errors in pulse rate estimation using different methods

percentage errors in pulse rate estimation using the proposed algorithm for 20 randomly selected subjects. The percentage errors found are within the range of 1.05 % and 4 %.

The graph in Fig. 7 shows the comparison between maximum absolute error in the pulse rate calculation using the proposed algorithm and methods proposed in [6, 14, 17] and [26]. The maximum estimation error using the proposed algorithm is found to be close to the errors obtained by the methods proposed in [6] and [14]. The method proposed in [6] yields an error of 2 beats/minute which is 1beat/minute lower than the error obtained by the proposed algorithm but a hardware SpO2 sensor has been used to acquire PPG signal which reduces the portability and cost effectiveness of the system. The method proposed in [14] uses a smartphone to acquire PPG signal that makes the system portable and the error yielded is 3.36 beats/minute, but the system uses complex computations like ICA and frequency analysis before calculating the number of beats that reduces its energy efficiency.

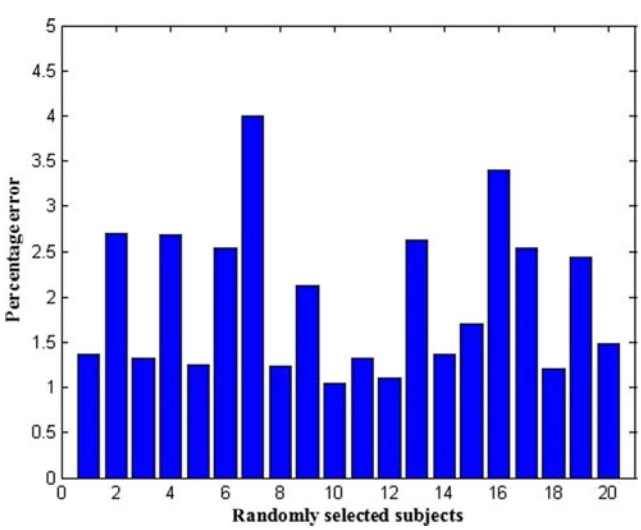

Fig. 6 Percentage error in results using the proposed algorithm

The proposed algorithm was tested using MATLAB so currently the energy consumption could not be measured and compared properly. A mobile phone application is intended to be developed in the future and then we will be able to compare the energy consumption of different pulse rate estimation algorithms.

Conclusion and future work

This paper discusses the algorithm for pulse rate estimation using PPG signals and video stream captured by a smartphone camera. Red channel yields the most prominent cardiac cycles. Only simple PPG processing is needed to get the pulse rate estimate, thus making the system energy efficient. The use of simple calculations as mentioned in Eq. 3 for estimation of pulse rate from the extracted PPG and avoiding complex computations as used in [14] reduces the processor load and processing time. Motion detection algorithm improves the efficiency of the proposed system by keeping it from gathering corrupt data. The proposed system offers an in-expensive, portable and an easy-to-use-solution for pulse rate monitoring. Its accuracy is 98.02 %.

Our future goal is to extend the algorithm to be able to estimate both the blood pressure and the pulse rate with the least possible error and processor load. Complex computations are needed to extract information from the PPG signal to estimate blood pressure with high enough accuracy that increases the processor load and reduces the energy efficiency of the system. The complex computations also increase the processing time. We intend to improve the accuracy while keeping the system energy efficient and responsive.

Acknowledgments This work was supported in part by the National Natural Science Foundation of China under Grant 61572231, 61173079 and 61472163, in part by the Natural Science Foundation of Shandong, China under Grant ZR2013FM004. The corresponding author is Yuan Zhang.

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