Application of SWT for Heart Rate Monitoring Using Smartphone Camera

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***Abstract*—Monitoring of heart rate using smartphone is very popular nowadays. There exist some applications for smartphone with usually unknown accuracy. But there is no certified application for this purpose. The article introduces new method for heart rate monitoring which uses smartphone´s built-in camera and LED light. The algorithm is based on extraction of photoplethysmogram and use of stationary wavelet transform. 52 various wavelets were tested in terms of their suitability for heart rate monitoring. The accuracy is compared with heart rate estimated from electrocardiogram. In the range of 55-111 bpm, the heart rate can be estimated with mean error of 0.4093 bpm and maximum error of 0.8458 bpm. The recommended settings of the algorithm is to use green photoplethysmogram (green color channel of the video), provide stationary wavelet transform with 6-level decomposition, rbio2.4 wavelet, and calculate heart rate using PPG peaks' distance. Data of lower and higher heart rate were tested as well.**

***Keywords*—heart rate, pulse rate, HR, wavelet transform, WT, smartphone, camera, Faros, ECG, photoplethysmogram, PPG**

I. Introduction

It is estimated that in 2017 there are 2.32 billions users of smartphone worldwide [1] and this number grows every day. For this reason, the smartphone is a device with big potential in many areas from telecommunication to healthcare. The other reason for it´s wide use is the fact that people usually have the smartphone with them 24/7.

In healthcare area, the smartphone can monitor many health parameters from heart rate (HR) through oxygen saturation to blood pressure [2] without any additional device. HR can be estimated using three different built-in sensors: camera [3], [4], accelerometer [5], [6], and microphone [7], [8]. HR can be measured in a contact (usually from finger) [3] and non-contact (usually from face) [4] way.

There also exist mobile applications for heart rate monitoring using smartphone, which are accessible to the general public. Unfortunately, none of these applications is certified and majority of them does not offer any information about accuracy or used method. It depends on the users, whether or how much they believe the measured values. For nonexperts, moreover without any reference, it is very difficult decision and it can lead to misinterpretation. There also exist articles and conference papers, which usually describe the method in detail but do not offer the application for smartphone.

Physiological range of rest heart rate is between 60 beats per minute (bpm) and 100 bpm [9]. For well-trained people, HR can fall down to 35 bpm. During and after physical activity, HR is normally increasing above 100 bpm. At least 89% of people between age of 12 to 80 and over have resting HR between 56 bpm and 108 bpm [10].

II. Data and Methods

A. Data

For the testing purposes, we sensed the videos using the camera of the smartphone Honor 7 Lite. The camera was focused at infinity, the white balance was set to the tungsten mode and video resolution was set to 1280×720 px. The frame rate (FR) was set automatically on approximately 29.5 Hz (it fluctuates a little bit video to video). Measured subject lightly placed their finger on the rear camera to cover both the camera and the built-in LED. The LED was set on. The signal length is about 20 s. Altogether 10 signals with physiological HR were sensed. Also 4 signals with higher or lower HR were recorded.

As the golden standard for HR estimation is electrocardiogram (ECG), the reference ECG (Fig. 1 d)) was recorded simultaneously with videos. For this purpose, the mobile device for ECG monitoring eMotion Faros 180° was used. The sampling frequency was set to 250 Hz. In the ECG

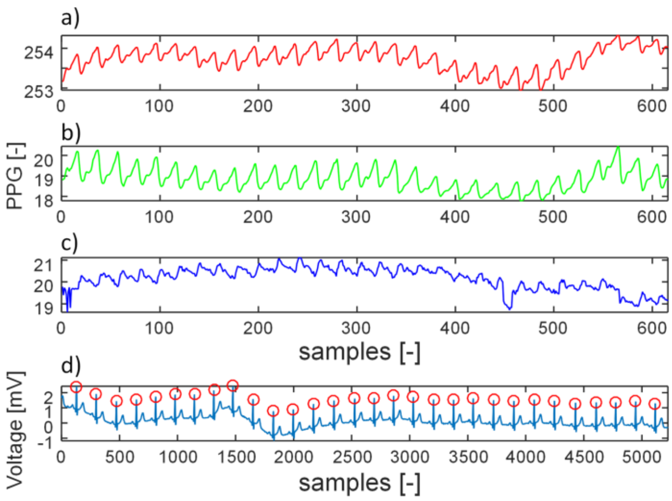

Fig. 1. PPG signals from red, green and blue video channels, and ECG signals with detected R waves (red circles) as a reference for HR.

signal the R waves (Fig. 1 d)) were detected using the QRS detector [11]. For HR estimation, also certified pulse oxymeters can be used. The accuracy of pulse oxymeter Nonin Onyx II 9560 is ±3 bpm.

B. *Preprocessing – photoplethysmogram*

The recorded video was divided into frames and each frame was divided in three RGB (red, green, blue) components. For each frame and each RGB component the mean value of the image was calculated. This way, we created three (red, green, blue) photoplethysmograms (PPG). Red, green and blue PPGs are shown in Fig. 1 a), b), c), respectively.

C. *Wavelet Transform*

For the HR estimation, the stationary wavelet transform (SWT) was used. The decomposition level was empirically set to 6. Altogether 52 wavelets from various wavelet families were tested in terms of their suitability for HR estimation. We tested Haar wavelet, Daubechies (db) wavelets, biorthogonal (bior) and reverse biorthogonal (rbio), coiflets (coif), symlets (sym), and Mayer wavelet (dmey).

D. *Heart rate estimation*

After the SWT decomposition, we further used the coefficients of the 4th highest frequency band (Fig. 4, blue) – in case of physiological HR. From the 4th band, HR in range of about 55 bpm to 111 bpm can be estimated. In this band, peaks were found and then HR was calculated in two ways. The first one (HR_1, equation (1)) counts the peaks in the time window and the second one (HR_2, equation (2)) calculates the distance between adjacent peaks.

$$HR_1(bpm) = \frac{NP*FR}{N} * 60, \quad (1)$$

$$HR_2(bpm) = \frac{FR}{\overline{PP}} * 60, \quad (2)$$

where NP is the number of peaks, N is the number of samples of the 4th frequency band, FR is the frame rate, and $\overline{PP}$ is the average distance of adjacent peaks.

In case of HR > 111 or HR < 55, different frequency band should be used to reach as high accuracy as possible. For higher HRs, the 3rd highest frequency band should be used, where HR between 111 bpm and 221 bpm can be estimated. For lower HRs, the 5th frequency band should be used and HR from 28 bpm to 55 bpm can be estimated in this band.

III. Results

A. *Physiological HR (55-111 bpm)*

HR estimated using particular wavelets was compared to the reference and then the percentage quality was calculated. This was performed for all RGB channels, both methods of HR estimation and all 10 signals altogether. The dependence of quality on the used wavelet is shown in Fig. 2. Two levels of tolerance were used for calculation of quality – 0 bpm (zero tolerance, blue color) and 1 bpm (green color). The highest quality was reached using the rbio2.4 wavelet for both levels of tolerance. The other suitable wavelets are from the reverse orthogonal wavelet family rbio2.2, rbio2.6, rbio2.8, rbio4.4, rbio6.8, and from the symlet wavelet family sym6 and sym8.

Then the methods and RGB channels were tested separately, which is pictured in Fig. 3 a) (tolerance 0 bpm) and b) (tolerance 1 bpm). Those 6 combinations (two methods and three colors) are placed on y-axis. The quality is expressed by colormap – the black color means zero quality and the brighter the color is, the better the quality is up to white color, which expresses the quality of 100%. From Fig. 3 a) it is obvious that the best wavelet rbio2.2 enables to reach up to 70% successfulness (with zero tolerance) of HR estimation (for 10 subjects). Fig. 3 b) shows that if the tolerance is set to 1 bpm, the quality reaches 100% for some wavelets. The most suitable wavelets seem to be rbio2.2, rbio2.4, rbio4.4, and rbio6.8, for which the quality is 100% for the second method of HR estimation and R and G channels. In case of B channel, the quality is never 100%.

TABLE I. Results of testing 2 methods of HR estimation and 3 (RGB) PPGs - mean difference between resulting HR and reference in BPM.

HR1 - R	HR2 - R	HR1 - G	HR2 - G	HR1 - B	HR2 - B
1.0877	0.6960	0.8103	0.4912	6.7478	6.8755

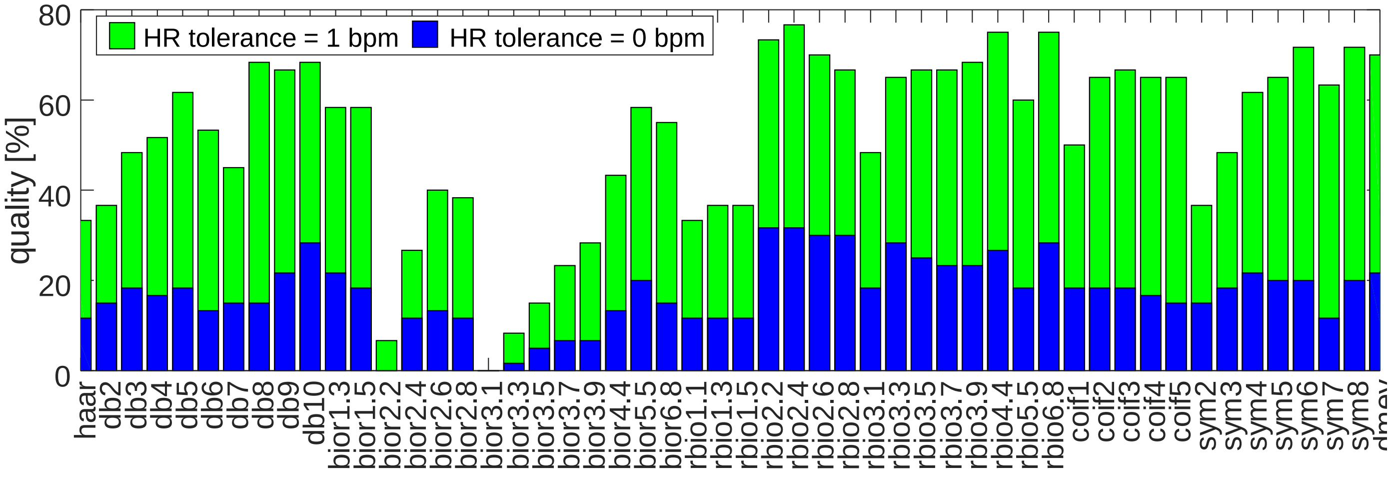

Fig. 2. Comparison of various wavelets in terms of HR estimation (percentage quality).

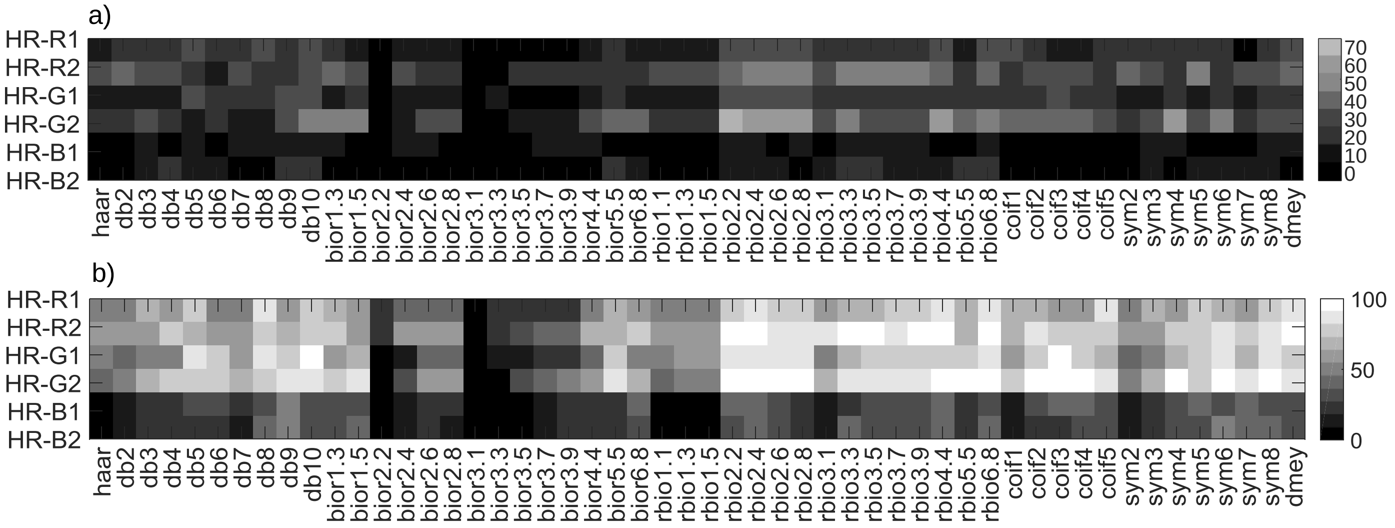

Fig. 3. The results (percentage successfulness of HR estimation) of testing two methods of HR estimation, three (RGB) channels, and 52 wavelets.

The brightest horizontal bands in Fig. 3 mean that these methods – HR-R2 and HR-G2 are more suitable for HR estimation than the other ones. This fact is moreover supported by the Table I (in the test, only the best wavelets, which are mentioned below, were used).

TABLE II. RESULTS OF TESTING 8 BEST WAVELETS – MEAN DIFFERENCE BETWEEN RESULTING HR AND REFERENCE IN BPM.

rbio2.2	rbio2.4	rbio2.6	rbio2.8	rbio4.4	rbio6.8	sym6	sym8
0.4377	0.4093	0.4203	0.4314	0.4908	0.5779	0.5727	0.5898

TABLE III. RESULTS OF TESTING THE BEST SETTINGS ON 10 SIGNALS.

wavelet	mean	median	max	min
rbio2.4	0.4093	0.3667	0.8458	0.0491

Further testing focused only on the best wavelets chosen previously: rbio2.2, rbio2.4, rbio2.6, rbio2.8, rbio4.4, rbio6.8, sym6, and sym8, and the second method of HR estimation from green channel. According to the Table II as well as Fig. 2 and Fig. 3 b), the most suitable wavelet is rbio2.4. For the best wavelet rbio2.4 mean, median, maximum and minimum differences were calculated as is shown in Table III.

B. Higher or lower HR (28-55 bpm and 111-221 bpm)

In case of higher HR, the algorithm is very similar to the one mention above (for physiological HR) except for use of 3rd (Fig. 4, red) frequency band of SWT instead of the 4th band. This variant was tested on 3 signals with mean error of 0.5155 bpm and maximum error of 0.8162 bpm. These results are comparable with the variant for physiological HR.

If HR is lower than 55 bpm, for HR estimation the 5th frequency band would be used, theoretically. It is quite difficult to find person with lower HR, therefore we tested the assumption on one signal with reference HR of 53 bpm, which is very close to the bound (55 bpm). The SWT decomposition is shown in Fig. 4 (black). In this picture we can see that the HR information manifests in the 4th and 5th frequency bands. But it is not clear

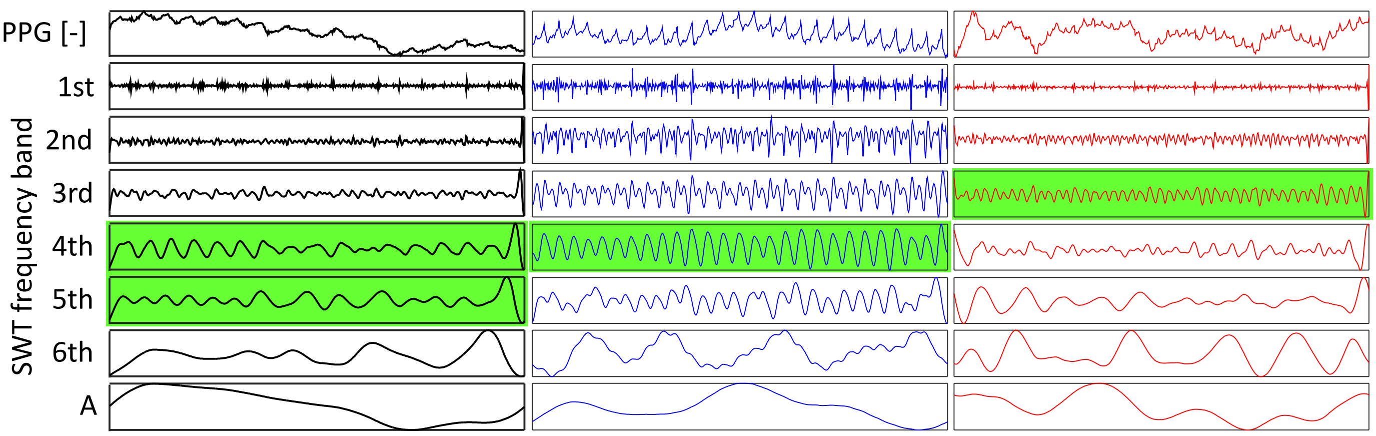

Fig. 4. Green PPG and SWT frequency bands for physiological HR (blue), lower HR (black), and higher HR (red). Frequency bands from which the HR is estimated is highlighted by green color.

whether to use the 4th or the 5th band for HR estimation. In both the 4th and the 5th frequency bands, the HR was calculated and the results are 58.4159 bpm and 43.3811 bpm, respectively.

C. Comparison with other methods

In this part, we compare our algorithm (for physiological range of HR) with other methods. The best method of HR estimation from [12] is based on green PPG filtration and detection of peaks. For HR estimation, equation (2) is used. This method reaches mean rounded error of 0 bpm and maximum rounded error of 2 bpm. If we round our results of HR, the mean error is 0 bpm and maximum error is 1 bpm. Microphone-based HR monitoring has mean error of 0.92 bpm [8]. The method of HR estimation using accelerometer has mean error of 0.17 bpm [6]. Both these methods used as a reference pulse oxymeter, which can be less accurate than HR estimation from ECG. The accuracy of method which estimates HR from camera [3] is 98.02%. The accuracy of our method calculated according to the equation published in [3] is 99.4253%. Our method´s accuracy also exceeds the accuracy of methods of HR estimation from user face, which are 98.92% and 98.53% [4].

IV. Discussion

The previous facts result in requirement to decide from which frequency band the HR will be estimated. For this purpose and to automatize the whole process of HR estimation we need some rule that precede the SWT. This rule can be based on some simple method for HR estimation, such as those mentioned in [12] and briefly described above. The easier variant of rule can be based on users' decision whether they are well-trained athletes, in normal condition, or after some physical performance (e.g. sport or stairs). One more variant may be possible: to directly quantify the suitability of each SWT frequency band for HR estimation.

The advantage of the method based on SWT is: robustness (it can estimate HR from signals of worse quality more accurately than simpler algorithms), easier setting of peak detection (due to the character of signal in relevant frequency band), and accuracy (at least in physiological range of HR excluding bound values of HR). Also the use of built-in camera has advantages: the measurement can be provided in any environment (it is not necessary to measure in quiet place as in case of use of microphone [8]), and in any position of person (the person does not have to lie as is recommended in method, which uses accelerometer [6]). The disadvantage is higher computational demand due to use of SWT. Another disadvantage seems to be lower accuracy in small segments around the borders (HR information is divided into two frequency bands).

V. Conclusion

HR was estimated using smartphone built-in camera and LED. For this purpose, extraction of RGB PPGs was done and the PPGs were decomposed using the SWT. Application of SWT on this problem is the innovation of this work. The level of decomposition was empirically set to 6. Altogether 52 wavelets were tested in terms of their suitability for HR estimation using two methods and three (RGB) PPGs. Each setting was tested on 10 signals with physiological value of HR. The error of the methods was calculated as the difference between the resultant HR and the reference HR estimated from ECG. The most suitable wavelet is rbio2.4 applied on the green PPG with the second method of HR estimation (using peak distance). In this case, mean error of HR is 0.4093 bpm and maximum error is 0.8458 bpm. The accuracy in physiological range of HR seems to be better than accuracy of pulse oxymeter. The physiological range of HR is sufficient for healthy teenagers and adults to measure their resting HR.

In case of higher (> 111 bpm) and lower (< 55) frequencies, the algorithm should be adjusted in terms of use of the suitable SWT frequency band. Estimation of higher HR has similar accuracy as for physiological HR. The accuracy of HR estimation in the border area is low, because the HR information is present in two SWT frequency bands. This should be adjusted as well in the future.

The results of application of SWT for HR monitoring using smartphone built-in camera are encouraging and the method has a great potential. Nevertheless, several issues should be solved to reach maximal accuracy.

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