A denoising strategy for the improvements of PPGi’s signal-to-noise-ratio

Fubo Deng¹, Jizhao Zhang¹ and Yunfang Jia*¹

¹College of Electronic Information and Optical Engineering, Nankai University, China
*Corresponding author’s e-mail: jiayf@nankai.edu.cn

Abstract. Photoplethysmographic imaging (PPGi) is a burgeoning technology to monitor physiological parameters. Under the background of information technologies’ development, both the PPGi signal’s collecting set-ups and its data processing methods have been widely studied. However, the unsatisfactory signal-to-noise-ratio is still an obstacle to its productization. For this problem, an appropriate denoising strategy would be a feasible solution. Therefore, through the analysis and screening of Butterworth Low Pass filter, Butterworth High Pass filter, Median filter, Wavelet Transform, Hilbert-Huang Transform and Independent Component Correlation Algorithm, three of them are combined to form 3 tactics, their effects in improving signal-to-noise-ratio of PPGi signals are evaluated. It is found, the integration of Butterworth Low Pass filter, Median filter and Wavelet Transform (BMW) can acquire the best signal-to-noise-ratio (31.42dB) in the designed strategies. Furthermore, these denoised PPGi signals by the three tactics are used to calculate the blood pressure (BP) and heart rate (HR). The comparisons with the actually BP and HR data which are measured by a commercial sphygmomanometer also indicate that the close-to-actual BP and HR are obtained from the BMW denoised PPGi signals.

1. Introduction

The pulse signal of human body contains a lot of vital signs, such as heart rate (HR) [1], respiration rate [2], blood pressure (BP) [3], blood oxygen saturation [4], which can reflect the health status and cardiovascular disease. The technologies for acquiring pulse signal are urgently needed in clinical medicine and family health care, in this field the recently developed methods include cuff sphygmomanometer [5], photoplethysmography (PPG) [6] and photoplethysmographic imaging (PPGi) [7]. Among them, the PPGi technique is more attractive than the others, because of its merits of non-contact, low-cost and remote sensing. [8-12] However, it is yet not as popular as the others, because of the unsatisfactory accuracy.

Motivated by the challenges of pushing PPGi technique into the clinical stage and domestic application, lots of efforts have been proposed to acquire high quality PPGi signal, which can be classified into two categories, which are improving the experimental set-up and optimizing the algorithm. For the former one, it refers to the utilization of high-resolution cameras [13] and the optimization of illuminations [14], which can obtain more robust raw video. For the later one, the key issue is to increase the signal-to-noise-ratio (SNR), the recently developed wavelet transform (WT) [15] and adaptive bandpass filter (ABF) [16], methods are evidenced to discern the PPGi signal which is submerged in a large amount of noise. Though lots of algorithms have been applied in this field, their comparative and systematic analysis, which is necessary to have an in-depth understanding about the effectiveness of different methods, is still deficient.
Herein, the study about PPGi denoising strategy is presented based on the exploration of the noises in PPGi signals by using six algorithms, which are Butterworth Low Pass filter (BLP), Butterworth High Pass filter (BHP), Median filter (MF), WT, Hilbert-Huang Transform (HHT) and Independent Component Correlation Algorithm (ICA). Firstly, the noise types are determined by evaluating the waveform and SNRs of the denoised PPGi signals which are acquired by using each of the algorithms alone, because their application scopes are independent with each other [17-22]. It is found, the high frequency noise, baseline noise and complex noise (here is the noise caused by reflection) are the major noises in raw PPGi signals. Accordingly, the three denoising tactics are constructed, which are the combination of BLP, MF and WT (BMW), BLP, MF and HHT (BMH), ICA, MF and WT (IMW), respectively. The BMW should be an applicable tactic for the purpose of making signals as clean as possible, which is demonstrated by comparing the SNRs values of BMW denoised PPGi signals with those of IMW and BMH denoised PPGi signals, respectively. To further evaluate the performances of the denoising strategies in the real application, the denoised signals are used to estimate the HR and BP values, it is found the most close-to-real values are obtained from BMW denoised PPGi signals. In general, it is indicated the proposed denoising method can provide high qualified PPGi data for extracting vital signs and increasing its accuracy, which can pave the way for the commercial applications of PPGi technique.

2. Materials and methods

2.1. Set-up of PPGi collection
Based on the PPGi principle [23], a set-up of PPGi is constructed, as shown in Figure 1 (a). There are four parts in this set-up, which are: (1) the hand is be used as the object of PPGi; (2) the light source (LED, 6W, 95*161MM) is to generate the illuminations in different colors (red, yellow, orange, green, blue, purple, cyan, white), as shown in Figure 1 (b); (3) the mobile phone (HONOR 9, HUAWEI, China), its camera is used to capture light; (4) the computer (K46C, ASUS, China) to process the obtained data and proposed calculations, which is executed by the software MATLAB (R2014B 8.4.0).

Figure 1. Diagrams for the setup of PPGi collection (a), the different colors of illuminations (b), the experimental procedure (c) and the noise and typical pulse wave in PPGi signals (d). In (a), the experimental setup includes the hand, light source, phone and computer. The hand is be used as the object of PPGi. The light source is used to excite the desired irradiation, eight kinds of light sources are examined in this work which are red, orange, yellow, green, cyan, blue, purple and white (as shown in (b)). The phone is used to capture light and store the of-interest PPGi data. The computer is used to execute the proposed methods. In (c), the experimental procedure is simply summarized as follows: raw PPGi data acquisition, PPGi signals processing, three strategies construction and result analysis. In (d), the noise types and typical pulse wave in raw PPGi signals were showed.

2.2. Experimental procedures
The experimental procedures are shown in Figure 1 (c), and outlined at here: (1) Video collection: the video of whole hand is captured by the camera in mobile phone under different illuminations. (2) Video
interception: the middle 15 seconds are retained, in consideration of weakening the jitter, which mainly happens at the video’s head and tail. (3) Location of the region of interest (ROI): according to the previous work about ROI selection, the first section of the index finger is used as ROI, its position is located by the frame selection function. (4) Extraction of raw PPGi data in ROI: the video data of ROI are fetched frame-by-frame, the average data in each frame are acquired, and these average data in all the frames are used as the raw PPGi signal. (5) Evaluation to each of the denoising algorithms: the raw PPGi signals are denoised by BLP, BHP, MF, WT, HHT and ICA, respectively; their SNR are calculated, according to formula (1). In which, \( p_n \) is raw PPGi signal power and \( p_s \) is denoised PPGi signal power. The evaluation criteria are the close degree of waveform shape and pulse wave, and the big or small of SNR value.

\[
SNR = 10 \log_{10} \frac{p_s}{p_n}
\]  

(6) Construction of denoising strategies: according to the evaluation result in (5), three strategies are proposed, which are the combinations of BLP and MF and WT (BMW), BLP and MF and HHT (BMH), ICA and MF and WT (IMW), respectively. (7) Comparison of denoising effects: the denoising effects of the proposed three tactics are compared and analyzed by computing the SNRs values of PPGi signals which are denoised by using three strategies, respectively. (8) Analysis of denoising strategies in real application: the three strategies are evaluated by comparing the error rate between calculated BP and HR values and measured BP and HR values.

Besides, based on the data from step (4), the influence of different illuminations can be examined, by the rough visual identification of typical pulse wave from the raw PPGi signals.

2.3. Principle of six algorithms

2.3.1. BLP and BHP. The six concerned filtering algorithms have these own characteristic and applicability. For example, the noise with low frequency (< 4Hz in this work) is allowed to pass in BLP [17], in contrary, it is cut off in BHP [22]. Herein, the butter function and the filter function of MATLAB are used to implement BLP and BHP filter.

2.3.2. MF. The MF is a kind of nonlinear signal processing filter, it can eliminate the isolated point and effectively remove baseline noise. According to its calculation, which is replacing each of data points in raw PPGi signal by the median value of its left and right neighbors [18], it is realized by using polyfit and polyval functions in MATLAB.

2.3.3. WT. The procedures of WT [19] are outlined at here: 1) Wavelet decomposition: the raw PPGi signals are decomposed by using sym8 as the basis function and setting the level of decomposition as one and five, respectively. 2) Threshold shrinkage: the decomposed signals in the last step are filtered by the function of wden with the threshold selection rule of Sqtwolog and Heursure, respectively. 3) Wavelet reconstruction: the denoised signals by step (2) are reconstructed by using idwt function in MATLAB.

2.3.4. HHT. The procedures of HHT [20] contain three parts: 1) empirical mode decomposition: the intrinsic mode function data (IMFD) is obtained by decomposing the raw PPGi signal, which is realized by using emd function in MATLAB. 2) Hilbert spectrum analysis: the IMFD is converted to frequency domain by the functions of sum, angle and diff in MATLAB. 3) signal reconstruction: the signals after step (2) are reconstructed by using wthresh and sort functions.

2.3.5. ICA. ICA is a typical motion artifact removal algorithm, which is suitable for RGB signal [21]. In this work, the cov, eig and zeros functions in MATLAB are used to implement the ICA filter.
2.4. HR and BP estimation

2.4.1. HR. The Fast Fourier Transform (FFT) is used to estimate the HR by the following steps: (1) data of PPGi is converted from the time domain to the frequency domain by using FFT; (2) the value of HR is obtained by locating the position of the maximum peak value in the frequency domain, then multiplying it by 60.

2.4.2. BP. The BP values are estimated according to the Windkessel model which is a mathematical model of cardiovascular system. In this model, the injection of blood volume during systole of the heart is regarded as an input of the circuit, the BP is seen as the voltage \( P \), blood volume is regarded as the current \( I \), the resistance of the blood vessel is taken as the resistance \( R \), and the capacity of vessel is seen as the capacitance \( C \). Accordingly, the mathematical expressions of the high BP \( (P_s) \) and the low BP \( (P_d) \) can be obtained, respectively[25]:

\[
P_s = P_0 e^{T_s / RC} + \frac{IT_s C R^2}{T_s^2 + C^2 R^2} (1 + e^{T_s / RC})
\]

\[
P_d = P_0 e^{T_d / RC}
\]

In these equations, \( P_0 \) (120 mmHg) is the initial high pressure, \( P_d \) (90 mmHg) is the initial low pressure, \( T_s \) and \( T_d \) are the rising and falling time of single period waveform, respectively, \( R \) is resistance of circuit, and \( C \) is capacitance of circuit.

3. Results and discussion

3.1. Raw PPGi waveforms under different illumination

According to the experimental procedures mentioned in section II B, the extracted raw PPGi waveforms after step (4) are shown in Figure 2. It is found, at the constant power (6W), the colors of illumination have obvious influences on raw PPGi data. Almost no typical pulse waveform (as depicted in Figure 1 (d)) would be acquired under the illuminations of orange, yellow, cyan and purple, as shown in Figure 2 (b), (c), (e) and (g), respectively. While, for the raw data obtained under the illuminations of red (Figure 2 (a)) and white (Figure 2 (h)), it is easy to find the pulse waveform in them. Accordingly, it could be believed the illuminations of white and red may be more suitable than the others.

![Figure 2. Results for the waveforms of raw PPGi signals under the illuminations of red, orange, yellow, green, cyan, blue, purple and white. The vertical axis is the pixel value of the image, and the horizontal axis is the number of acquired image frame. The data of y-axis are calculated average values of each frame data.](image-url)
3.2. Denoised PPGi signal by independent algorithms

Denoised PPGi signal of step (5) are shown in Figure 3, in which Figure 3 (a) is the raw PPGi waveform under the white illumination. Firstly, the effect of BLP can be identified by comparing Figure 3 (b) with (a), most of the burr noise is removed and the smooth waveform is obtained. In contrast, BHP cannot remove the burr noise, as shown in Figure 3 (c). Comprehensive analysis of Figure 3 (b) and (c) suggests the noise in PPGi signal mainly located at the high frequency. Furthermore, as to the baseline offset which is a universal phenomenon in raw PPGi waveform, it can be greatly improved by MF, as shown in Figure 3 (d). Thus far, the messy raw signal can be refined, but there are still residues which are attributed to the complex noise due to the inevitable reflection in the collection environment.

Thirdly, the outcomes of WT in removing the complex noise can be distinguished by the waveforms in Figure 3(e) - (h) which are calculated by the use of different decomposition levels and threshold types. Obviously, the best waveform of pulse wave is in Figure 3 (g), which means it will be a suitable choice by setting the five-level decomposition and the “heursure sln” threshold.

HHT is also a common denoising algorithm like to WT, there is only a little of works about its application in PPGi area [24]. Intrigued by its possible performance in removing PPGi’s noise, the same raw data as being used in Figure 3 (b) to (h) are treated by HHT, it is found the HHT denoised waveform (Figure 3 (i)) is similar to Figure 3(g), but the dicrotic wave (the inset in Figure 3 (g)) is vanished.

Last but not least, ICA is a common method to eliminate the noise caused by motion artifacts [21]. Nevertheless, in this work, we do not find its obvious impact in polishing the raw PPGi signal, as shown in Figure 3 (j). For the reason, it may be related to the procedures which is mentioned in the section II B. Because in the experiments of this work, the head and tail of the PPGi video are deleted by the second step “Video interception” and the motion artifacts generated noises mainly exist in these periods. In consequence, ICA does not have a remarkable influence in this work.

The SNRs of the denoised PPGi signals by different algorithms and under different illuminations are also calculated and presented in Figure 4. It indicates the higher SNR regions (SNR>20) are located at the positions in Figure 4 where illuminations are red, orange, green, and white, no matter what kinds of algorithms are used. Moreover, at the same illumination, the higher SNRs are gained by using WT, BLP and HHT, respectively. By evaluating the SNR and waveform of the denoised PPGi signal, the major types of noises in PPGi signals can be determined, which are high frequency noise, baseline noise and complex noise.
3.3. Improvement by algorithm synthesis

According to the determined three main noise types in PPGi signals as mentioned above, it is anticipated, the BMW strategy which is the combination of BLP, MF and WT, may be a suitable strategy to remove most of noise and improve the value of SNR in PPGi signals. To verify this estimation, the other two schemes (named as BMH and IMW) are designed by replacing WT with HHT and BLP with ICA, respectively. The SNRs of the denoised PPGi signals by the three tactics are calculated and presented in Figure 5. It suggests the highest SNRs (the blue columns) are acquired by the BMW strategy, while the lowest ones (the grey columns) are from IMW. It demonstrates that BLP is a key part in the process of eliminating the main noise in PPGi signals. Additionally, it is found SNR of BMH (the orange columns) is close to that of BMW, but the dicrotic wave is vanished in HHT treated PPGi signal (Figure 3 (i)), so it is not appropriate for PPGi data process.

To increase the accuracy of the experimental results, the values of HR and BP are calculated by using PPGi signals which are denoised by the above-mentioned three denoising tactics, respectively.
Furthermore, the calculated values of HR and BP are compared with the measured HR and BP which are obtained by the commercial sphygmomanometer. As shown in Figure 6 (a) (b), it can be observed that the lower error rates come from BMW. According to the above results, the BMW is a better solution to improve PPGi signal.

Figure 5. Results for the SNRs of three strategies which are BMW, IMW and BMH. The data of x-axis are the three individual experiments (first, second and third), and the data of y-axis are the values of SNRs.

Figure 6. The deviation between calculated HR and BP values and measured data are evaluated by using the error rates of HR (a) and BP (b). The data of x-axis are the three strategies, and the data of y-axis are the values of HR and BP.

4. Conclusion
The major improvement in this study is that the suitable denoising strategy of PPGi signals is presented based on the exploration of the noises in PPGi data by using six algorithms, which are BLP, BHP, MF, WT, HHT and ICA. Firstly, the noise types in PPGi signals are determined based on the results of each algorithms used separately, in which the high frequency noise, baseline noise and complex noise are three major noises of raw PPGi signals. Secondly, according to the above results, the three denoising strategies are constructed, which are the combination of BLP, MF and WT (BMW), BLP, MF and HHT (BMH), ICA, MF and WT (IMW), respectively. It is found, the higher SNR values come from BMW denoising tactic. Next, to further evaluate the performances of the proposed denoising strategies in the real application, the denoised signals which are acquired using three strategies alone are used to estimate the values of HR and BP, in which the most close-to-real values are obtained from BMW denoised PPGi signals. In a word, the BMW is an applicable tactic for the purpose of making PPGi signals as clean as possible.
Acknowledgment
This work was supported by the National Natural Science Foundation of China (Grant no. 61771260).

References
[1] Yu, Y.P., Raveendran, P., Lim, C.L., Kwan, B.H. (2015) Dynamic heart rate estimation using principal component analysis. Biomedical Optics Express, 6(11):4610–4618.
[2] Karlen, W. (2014) Respiratory rate assessment from photoplethysmographic imaging. Conf Proc IEEE Eng Med Biol Soc, 5397–5400.
[3] Matsumura, K. (2018) Cuffless blood pressure estimation using only a smartphone. Scientific reports, 8:7298.
[4] Liu, H. (2015) A novel method based on two cameras for accurate estimation of arterial oxygen saturation. BioMed Eng OnLine, 6(2):41-45.
[5] Mustafa, R. (2018) Efficacy of Modified Pressure Cuff for Thrombolysis of Lower Limb Deep Vein Thrombus in Comparison with Traditional Sphygmomanometer Pressure Cuff. Science Letters, 6(2):52–68.
[6] Alian, A.A. (2014) Photoplethysmography. Baillière's Best Practice and Research in Clinical Anaesthesiology, 28(4): 395–406.
[7] Mcduff, D.J. (2015) A survey of remote optical photoplethysmographic imaging methods. Engineering in Medicine & Biology Society Conf Proc IEEE Eng Med Biol Soc.
[8] Liu, H. (2012) A review of non-contact, low-cost physiological information measurement based on photoplethysmographic imaging. Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society, 2088-2091.
[9] Liu, H. (2013) FPGA-based remote pulse rate detection using photoplethysmographic imaging. Body Sensor Networks (BSN), 2013 IEEE International Conference on IEEE.
[10] Mcduff, D. (2014) Improvements in remote cardiopulmonary measurement using a five band digital camera. IEEE Transactions on Biomedical Engineering, vol. 61, 10:2593–2601.
[11] Matsumura, K. (2014) Iphone 4s photoplethysmography: which light color yields the most accurate heart rate and normalized pulse volume using the iPhysiometer application in the presence of motion artifact?. PLOS ONE, 9(3).
[12] McDuff, D.J. (2014) Remote detection of photoplethysmographic systolic and diastolic peaks using a digital camera. IEEE Trans. Bio-Med. Electron, 61(12):2948–2954.
[13] Sun, Y. (2012) Use of ambient light in remote photoplethysmographic systems: comparison between a high-performance camera and a low-cost webcam. Journal of Biomedical Optics, 17(3): 037005.
[14] Moço, A. V. (2018) New insights into the origin of remote PPG signals in visible light and infrared. Scientific Reports, 8:8501.
[15] Aydemir, B. (2018) Remote assessment of heart rate and its fluctuations by smartphone camera. 2018 Electric Electronics, Computer Science, Biomedical Engineerings' Meeting (EBBT).
[16] Blöcher, T. (2018) An Adaptive Bandpass Filter based on Temporal Spectrogram Analysis for Photoplethysmography Imaging. 2018 IEEE 20th International Workshop on Multimedia Signal Processing (MMSp), 29–31.
[17] Roberts, J. (1978) Use of the butterworth low-pass filter for oceanographic data. Journal of Geophysical Research, 83(C11):5510.
[18] Chen, T, Ma, K K, Chen, L H. (1999) Tri-state median filter for image denoising. IEEE Transactions on Image Processing, 8(12):1834-1838.
[19] Boujelbenn, F. (2013) Continuous wavelet filtering on webcam photoplethysmographic signals to remotely assess the instantaneous heart rate. Biomedical Signal Processing and Control, 8(6):568-574.
[20] Huang, N. E. (1998) The empirical mode decomposition and the hilbert spectrum for nonlinear and non-stationary time series analysis. Proceedings A, 454: 903-995.
[21] Christinaki, E., Giannakakis, G., Chiarugi, F., Pediaditis, M. and Iatraki, G. (2014) Comparison of Blind Source Separation Algorithms for Optical Heart Rate Monitoring. in Proceedings of the 4th Mobihealth, Athens, Greece. 339–342.

[22] Ngo, N. Q. (1994) Novel realization of monotonic butterworth-type lowpass, highpass, and bandpass optical filters using phase-modulated fiber-optic interferometers and ring resonators. Journal of Lightwave Technology, 12(5):827–841.

[23] Allen, J. (2007) Photoplethysmography and its application in clinical physiological measurement. Physiological Measurement, 28: R1-R39.

[24] Raghuram, M, Madhav, K V, Krishna, E H et al. (2012) HHT based signal decomposition for reduction of motion artifacts in photoplethysmographic signals. IMTC. IEEE.

[25] Choudhury, Banerjee, R., Sinha, A., and Kundu, S. (2014) Estimating blood pressure using windkessel model on photoplethysmogram. Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Germany.