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Wavelet analysis of remote photoplethysmographic signals for heart rate and variability estimation

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The paper analyzes the heart rate estimation algorithm in real-time using remote photoplethysmography. It is noted method for estimating the plethysmography signal and heart rate variability using the discrete wavelet transform (DWT) can get proper results, which ensures the operation of the remote photoplethysmography approach in real-time. The analysis of the developed method was carried out to processing the photoplethysmography using DWT allows to qualitatively evaluate the net signal and draw conclusions about the heart rate and variability of the human cardiovascular system. The choice of the detector and rPPG method ensures high performance and the ability to scale the system on different platforms. Based on the conducted wavelet transformation, a principle was formed that ensures obtaining a true plethysmogram without interference and noises, for further research and analysis of the human cardiovascular system.

Keywords: photoplethysmography, heart rate variability, filtering, wavelet transform.

Introduction. Heart rate (HR) is an important and perhaps the main indicator of the cardiovascular system, as well as an important indicator of the physiological state of a person. Traditional methods of determining heart rate are based on various electronic and optical sensors that interact with the human skin and body [2]. Such systems are usually expensive or inconvenient to use in everyday life and have many limitations, such as physiological defects in people, burns on the body, various skin injuries, and the absence of limbs, which not only makes it difficult but sometimes impossible to use such sensors and electrical systems correctly. In recent years, research has focused on non-contact methods of measuring HR based on the use of a person's face to generate an informative signal. [2]. The basic principle of contactless methods is directly related to the analysis of RGB images from a camera. However, existing methods have a number of problems, such as noise and interference in images, illumination of the human face, movement in the frame, dependence on the number of frames per second (FPS) of the camera, detector shortcomings, and optimization of existing algorithms.

1. Analysis of Recent Research and Publications

Remote photoplethysmography is a fairly new approach in the study of ECP. Existing approaches are focused on obtaining a true plethysmogram from a finger using a camera, are focused on a short measurement, or are not adaptive to real-time measurements. Such methods have a rather low rate of the truthfulness of the results, high dependence of the results on the characteristics of the camera, and the sampling obtained by this method [5].

2. Presentation of the Main Research Material

2.1. Objective of the Study. Development of a principle and approach for obtaining true remote photoplethysmography in real-time with the ability to filter the results using wavelet transform. Study of the received plethysmogram signal in the time-frequency domain. Determination of the assessment of the truth of the results and determination of the necessary characteristics of plethysmographs for further analysis and drawing conclusions about the variability of the cardiovascular system.

Heart rate is determined by the change in facial skin color caused by natural blood flow, as blood circulation causes changes in facial skin color, these changes can be digitized and used to calculate heart rate. RGB signal analysis has tremendous potential to improve telemedicine, human health, and numerous applications that require real-time physiological knowledge without invasive intervention.

Remote photoplethysmography (RPPG) uses a camera to estimate a person's heart rate (HR) based on an RGB image of the face (Figure 1).

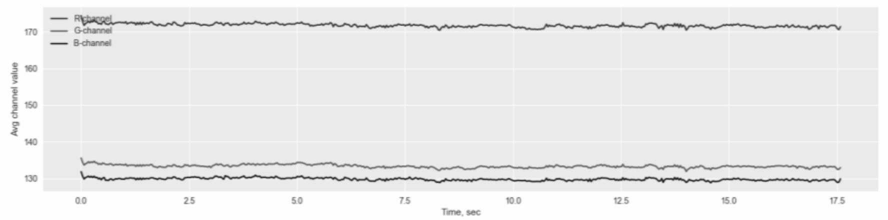

Fig. 1. RGB spectrum of the input signal

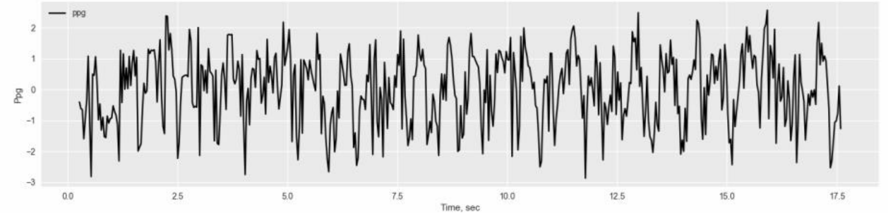

Fig. 2. Remote photoplethysmography (rPPG) signal

Just as heart rate can provide useful information about a person's vital signs, insight into underlying physiological or psychological states can be gained from heart rate variability (HRV). Remote photoplethysmography (rPPG) determines the pulse of blood volume through changes in the color of the skin. An example of a remote photoplethysmography rPPG signal is shown in Figure 2.

2.2. System Architecture. The proposed architecture solves a number of problems of the remote photoplethysmography approach with the help of the following elements:

- Video conversion and frame-by-frame reading element (this element allows processing both recorded video and video stream, regardless of whether it is a physical camera or a stream from the cloud);
- Face and landmark detection (the element of face detection in the frame, face recognition, and landmark control points);
- RGB signal analysis;
- Input signal evaluation (provides control over the incoming video);
- Wavelet transforms and filtering (provides time-frequency analysis of the signal, followed by filtering).

The paper considers the main elements of the remote photoplethysmography algorithm to assess their performance and the noise that can be generated during compression or analysis of the RGB signal. Noise, in turn, degrades the quality of the signal under study. The general architecture of the proposed system is shown in Figure 3.

2.3. Video stream. An important stage of the algorithm is the input signal. In order to scale the system, it is advisable to specify the possibility of providing the input signal in different formats. The main option is a physical video stream from a camera on a PC or a camera on a user's phone. This increases the possibility of using this system both on desktop computers and mobile devices, which increases the convenience of use in everyday conditions [7]. It is worth noting that the video stream from the camera can be used using cloud technologies or so-called virtual cameras without a physical connection using gRPC technology [3].

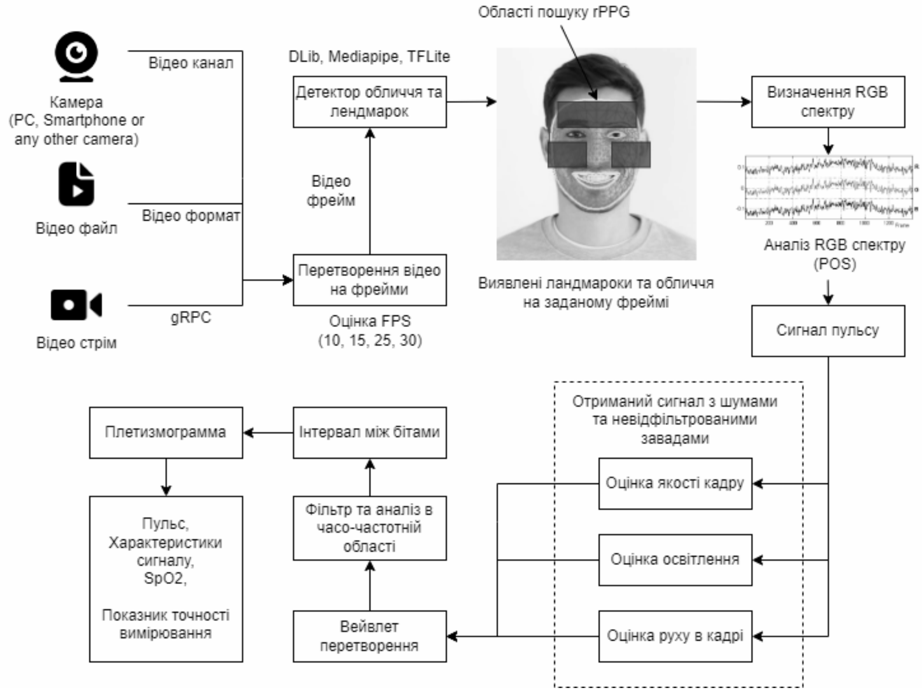

Fig. 3. Architecture for determining the emergency from an input video stream in real-time at 30FPS (30 frames per second)

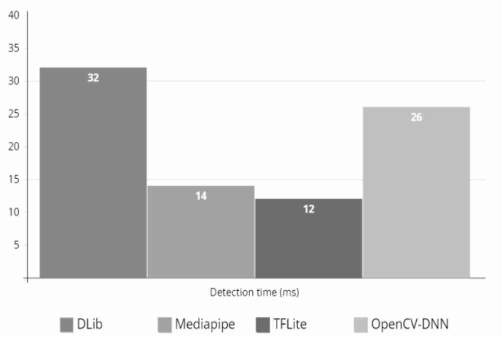

Fig. 4. Comparative characteristics of detectors according to the processing time of one image

3. Face detector

Nowadays, there are many well-known detectors on the market that have high performance and support for many platforms. First of all, these include high-speed detectors that also show high efficiency: DLib, Mediapipe, and TensorFlow Light. The detectors were compared on a physical webcam with HD resolution and 30FPS. As shown in Figure 4, Mediapipe and TensorFlow Light showed the best results. These detectors have sufficient performance to process a large number of input frames, which ensures the efficient operation of all dependent elements of the system.

It is important to note that these detectors also have algorithms for detecting landmarks on a person's face, an example of which is shown in Figure 5. Using these points (landmarks), a region of interest (ROI) is calculated for further processing of the RGB signal. In particular, the TensorFlow Lite detector is a set of tools that provides machine learning on the device, helping developers run their models on mobile, embedded, and peripheral devices. The system under study uses pre-trained models (ML) to detect facial positions and brand marks. TensorFlow Lite (TFLite) is an open-source library developed by Google for deploying machine learning models on edge devices. Examples of edge deployments include mobile (iOS/Android) and embedded devices.

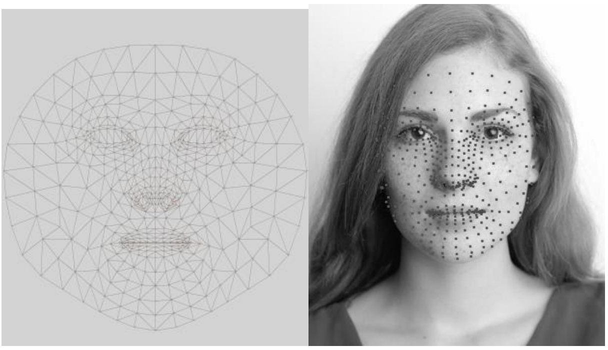

Fig. 5. An example of the TFLite face detector

The TensorFlow Lite package [9] does not use the graph approach implemented in MediaPipe and therefore is not as flexible [10]. However, it is somewhat easier to use and understand, and more accessible for amateur programming and experimentation with pre-trained ML models than the rather complex MediaPipe framework, which is costly to build a complex and multi-platform system [6].

4. Signal Processing Based on the Remote Photoplethysmography Method

Remote photoplethysmography (rPPG) is used to convert an RGB signal into an rPPG signal. All types of rPPG studied in the literature are shown in Table 1. It is important to note that Principal Component Analysis (PCA) and Independent Component Analysis (ICA) are both rPPGs and are based on blind source separation, i.e., without supervision or labeling of the data. In the comparison, all rPPG methods are used exactly as they are implemented in this framework.

A wide range of possible filters was used to improve the rPPG signal. The work shows that it is best to use only a bandpass filter for the estimated rPPG signal. The sixth-order bandpass filter operated in the range from 0.65 to 4 Hz [8], which ensured high-quality analysis and processing of the input signal.

In order to determine the temporal localization of individual signal beats, after receiving the filtered rPPG signal, peak detection, and signal analysis in the time-frequency wavelet domain are performed. Based on the detected beats, the heart rate and heart rate variability are calculated. To do this, the interbeat intervals (IBI) are first extracted from the signal, which are the time intervals between consecutive beats.

Table 1

Definitions and features of remote photoplethysmography methods

rPPG Method	**Definitions and features**
GREEN	Of the three RGB channels, the green channel is the most similar to the PPG signal and can be used as an estimate.
ICA	Independent component analysis (ICA) is applied to the RGB signal to recover the three separate source signals. Typically, a significant rPPG signal is found in the second component (red spectrum).
PCA	Principal component analysis (PCA) is used to distinguish the rPPG signal from the RGB signal.
CHROM	The chrominance-based method (CHROM) generates the rPPG signal by removing noise caused by light reflection using the ratio of normalized color channels.
PBV	PBV computes the rPPG signal with the pulse blood volume fluctuations in the RGB signal to identify pulse-induced color changes from object movement.
POS	To extract the rPPG signal, the plane orthogonal to the skin (POS) method uses a plane orthogonal to the skin tone in the RGB signal.
LGI	Local group invariance (LGI) calculates the rPPG signal using a robust algorithm as a result of local transformations.
OMIT	Orthogonal matrix image transform (OMIT) reconstructs the rPPG signal by creating an orthogonal matrix with linearly uncorrelated components representing the orthonormal components in the RGB signal, based on matrix decomposition.

After the research, a POS algorithm is selected that provides a clean signal with a clear understanding of the RGB signal.

5. Wavelet Transform

The data in the time-frequency domain were analyzed using the wavelet representation of the received signal [3]. In this paper, we propose an approach to identifying characteristic points based on the use of appropriate wavelet filtering to obtain an rPPG signal that corresponds to the true plethysmography signal. To ensure the authenticity of each pulse signal, a discrete wavelet transform (DWT) was applied, calculated to the level of log2N (N is the number of pulse samples) [1]. where Discrete wavelet transform (DWT) is a transform that allows decomposing a given signal into a number of sets, where each set is a time series of coefficients describing the time evolution of the signal in the corresponding frequency band corresponding to the information on the heartbeat. The wavelet transform is used not only to improve the peak signal-to-noise ratio (PSNR) and provide filtering of the present noise but also to estimate other parameters of the vascular filling (Figure 7).
The informative component of DWT can be successfully used to measure other physiological signals, such as ECG, electroencephalogram (EEG), and magnetoencephalography (MEG) [4].

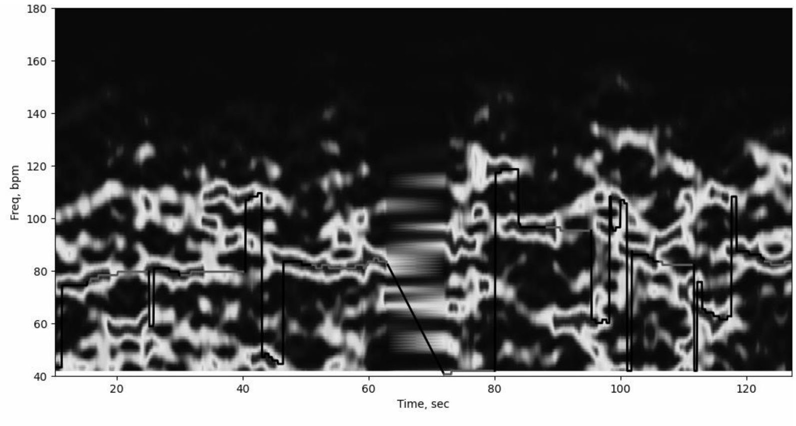

Fig. 6. Spectrogram of the received signal with interference and noise

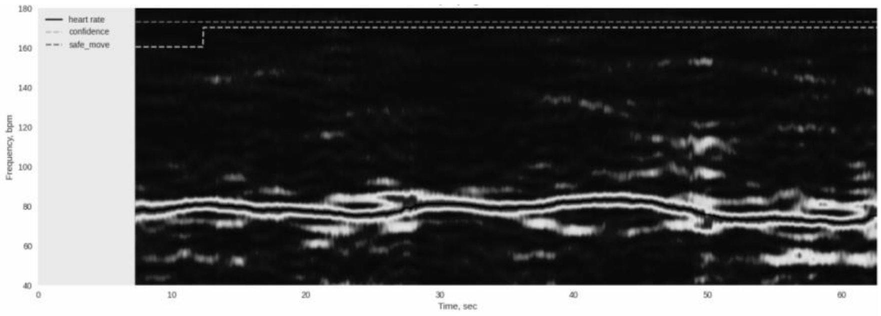

Fig. 7. Spectrogram of the received signal in the time-frequency domain

After evaluating the signal in the time-frequency domain, the data were presented in the spectrogram shown in Figure 8. The resulting spectrogram, using wavelet transform, clearly shows the main signal of heart rate changes over time.It is also worth noting that by analyzing the signal in the time-frequency domain, interference and noise that accumulated during image processing (RGB signal) [10, 11] were filtered out. The wavelet transform also allowed us to evaluate signal duplication, when the main heartbeat signal can be displayed at several frequencies, with different signal intensities.

It is important to note that the main goal is to reproduce the PPG waveform and preserve the ratio of IBI (Inter Beat Intervals) peaks. Thanks to this, you can estimate the heartbeat signal using HRV, Respiratory Rate (Wave), as well as the amplitude values for the Systolic and Diastolic peaks. This can be done using the wavelet deconstruction-reconstruction method (Figure 8).

This method involves calculating the coefficients for the input signal (deconstruction), followed by using various threshold filters or discarding coefficients with low frequencies (potential interference and motion in the frame).

Table 2

Wavelet decomposition results

Wavelet mother function	Ground Truth of HRV mean (seconds)	DWT of HRV mean (seconds)	Confidence
haar	0.983s	0.913s	92.878 %
dmey	0.983s	0.931s	94.710 %
sym5	0.983s	0.938s	95.422 %
db18	0.983s	0.946s	96.236 %
coif2	0.983s	0.938s	95.422 %
bior2.2	0.983s	0.980s	99.694 %
rbio3.1	0.983s	0.953s	96.948 %

The informative component of DWT can be successfully used to measure other physiological signals, such as ECG, electroencephalogram (EEG), and magnetoencephalography (MEG) [4]. After evaluating the signal in the time-frequency domain, the data were presented in the spectrogram shown in Figure 8.

After the coefficients are cleaned, they can be reassembled into a signal (reconstruction). Such a signal will be considered filtered. Table 2 shows the main mother wavelets that best reconstruct the PPG signal based on the noisy rPPG.

The study was conducted on various datasets, including PHYS, COHFACE, and custom ones, which collected video with H.264, H.265/HEVC, VP8, VP9, AV1, VC1, MPEG1, MPEG2, MPEG-4 codecs. The influence of face lighting in the frame was also studied, which showed a relative dependence of the results on lighting, the better the lighting (no glare, darkening, sharp changes in lighting intensity), the clearer the signal can be obtained.

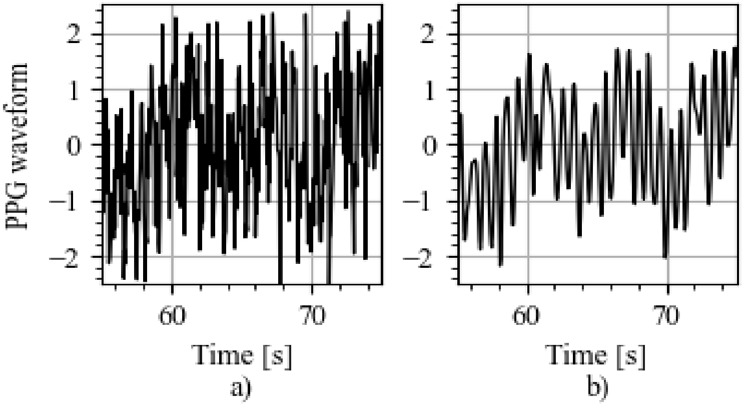

Fig. 8. a) Part of origin rPPG signal. b) Filtered rPPG using the DWT reconstruction method

Confidence in Table 2 refers to the correlation between two signals, the higher the Confidence, the better the resulting rPPG corresponds to the ground truth. Data recorded from real medical devices is believed to be Ground Truth.

Conclusion. A method for estimating the plethysmography signal and heart rate variability using the discrete wavelet transform (DWT) has been developed, which ensures the operation of the remote photoplethysmography approach in real-time. The input resources can be various types of video stream transmission, with subsequent conversion to individual frames and their further analysis. The choice of the detector and rPPG method ensures high performance and the ability to scale the system on different platforms. In addition, DWT-based wavelet transform allows filtering and reducing noise on the main signal, as a result, the system can analyze the true plethysmography in detail and calculate not only heart rate, but also blood oxygen content (SpO2), or respiratory system activity, etc. The developed method eliminates up to 73% of the interference present in the input signal. The true signal can be used to assess the severity of the disease in newborns. Many doctors use the plethysmography of a pulse oximeter as an early sign of cyclical changes in physiology. If the variability increases, it indicates a change in the intrathoracic and volumetric blood flow ratio. Therefore, the developed method of processing the photoplethysmography using DWT allows us to qualitatively evaluate the net signal and draw conclusions about the heart rate and variability of the human cardiovascular system. The proposed approaches result in more than 95% reliability of the data obtained.

References

[1] Nakonechnyi A.Y., Lagun I.I., Veres Z.E., Nakonechnyi R.A., Fedak V.I. Theory and practice of signal processing in the low-wave (wavelet) region: edited by Nakonechnyi A.Y. – Rastr-7, Lviv, 2020;978-617-7864-75-1.

[2] Popadyn R., Nakonechnyy R. “Implementation and Benchmarking of Respiration Monitoring Algorithms Based on Camera-Based Remote PPG” Proceedings of the Forth International Conference

on Automatic Control and Information Technology ICACIT' 17, December 14-16, 2017 Cracow, Poland.

[3] G. Bradski. The OpenCV Library. Dr. Dobb's Journal of Software Tools, 2000.

[4] D. McDuff, S. Gontarek, and R. W. Picard. Remote detection of photoplethysmographic systolic and diastolic peaks using a digital camera. IEEE Transactions on Biomedical Engineering, 61(12):2948–2954, 2014.

[5] I. Starr, A. Rawson, H. Schroeder, and N. Joseph. Studies on the estimation of cardiac output in man, and of abnormalities in cardiac function, from the heart's recoil and the blood's impacts; the ballistocardiogram. American Journal of Physiology-Legacy Content, 127(1):1–28, 1939.

[6] Z. Zhang, P. Luo, C. C. Loy, and X. Tang. Facial landmark detection by deep multi-task learning. In European conference on computer vision, pages 94–108. Springer, 2014.

[7] H. Demirezen and C. E. Erdem. Remote photoplethysmography using nonlinear mode decomposition. In 2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pages 1060–1064. IEEE, 2018.

[8] Macwan, R.; Bobbia, S.; Benezeth, Y.; Dubois, J.; Mansouri, A. Periodic variance maximization using generalized eigenvalue decomposition applied to remote photoplethysmography estimation. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops, Salt Lake City, UT, USA, 18–22 June 2018; pp. 1332–1340.

[9] Boccignone G., Conte D., Cuculo V., D'Amelio A., Grossi G., Lanzarotti R. An Open Framework for Remote-PPG Methods and Their Assessment. IEEE Access. 2020;8:216083–216103. doi: 10.1109/ACCESS.2020.3040936.

[10] Elgendi M. PPG Signal Analysis. Taylor & Francis (CRC Press); Boca Raton, FL, USA: 2020.

[11] Wang W., den Brinker A.C., Stuijk S., de Haan G. Algorithmic principles of remote ppg. IEEE Trans. Biomed. Eng. 2016;64:1479–1491. doi: 10.1109/TBME.2016.2609282.

Вейвлет-аналіз дистанційних фотоплетизмографічних сигналів для оцінки частоти та варіабельності серцевого ритму

Адріан Наконечний, Ігор Бережний

У статті проаналізовано алгоритм оцінювання частоти серцевих скорочень у реальному часі за допомогою дистанційної фотоплетизмографії. Зазначено, що метод оцінки плетизмографічного сигналу та варіабельності серцевого ритму з використанням дискретного вейвлет-перетворення (DWT) дозволяє отримати адекватні результати, що забезпечує роботу методу дистанційної фотоплетизмографії в режимі реального часу. Проведено аналіз розробленого методу обробки фотоплетизмограми з використанням DWT, що дозволяє якісно оцінити чистий сигнал та зробити висновки про частоту серцевих скорочень та варіабельність серцево-судинної системи людини. Вибір детектора та методу rPPG забезпечує високу продуктивність та можливість масштабування системи на різних платформах. На основі проведеного вейвлет-перетворення було сформовано принцип, який забезпечує отримання істинної плетизмограми без перешкод та шумів, для подальших досліджень та аналізу серцево-судинної системи людини.

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