PPG System Development for the Organism Physiological Parameters Monitoring with Artificial Intelligence Technologies

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Abstract. Monitoring such health parameters as cardiac rate (CR), respiration rate (RR), blood pressure (BP), degree of oxygen in blood (SpO2), body temperature and other requires careful approach to design and development of medical devices. New non-invasive methods introduced in measuring human physiological parameters based on photoplethysmography (PPG) demonstrated their significant potential in monitoring the state of an organism, but their use in wearable devices is largely hampered by exposure to motion artifacts. This article presents a device for photoplethysmographic studies using various adaptive algorithms for processing the registered signals. The work uses artificial intelligence technologies to monitor the heart rate exposed to external mechanical and electrical interference worsening accuracy characteristics of the system. Besides, system architecture was developed, and a device model was manufactured, which made it possible to measure the optimal algorithm for digital signal processing. When using the PPG system, methods of adaptive signal processing based on Wiener filters, filters on the method of least squares (MLS) and Kalman filtering were used. To ensure heart rate monitoring with the given accuracy, studies were performed with participation of volunteers, and analysis was carried out of the results of various signal processing algorithms operation. In the course of experimental studies, a method was proposed to estimate the heart rate calculation accuracy and to analyze the external noise filtering efficiency by adaptive algorithms. PPG designed and developed system made it possible to monitor the heart rate with the given accuracy, control the organism current state and could be used as a means of cardiovascular disease diagnostics.
1. Introduction

Second half of the twentieth century is characterized by the exceptionally rapid development of technologies and widespread introduction of science-intensive inventions in clinical and laboratory medicine. That is why it is very important to accurately monitor in modern medicine medical and biological indicators of a person condition assisting to timely diagnose any pathology emergence and development [17]. Processing the patient data could take a lot of time for the attending staff; therefore, a system is required to help in making the right decisions in regard to treatment, evaluating its effectiveness, and in many cases preventing the disease onset due to identification of a pathology at the earliest stage of its development [23].

Studying the cardiovascular system is currently relevant, since cardiovascular diseases are one of the main causes of disability and death of the population [1], [21]. It should be noted that anthropogenic impact on the environment leads to violation of the human life safety [17], [23]. As a result, cardiovascular activity of a person is disrupted, and diseases associated with cardiac arrhythmias are often asymptomatic, and clinically nothing indicates the presence of disbalances, while the person is already in the risk group, but does not suspect about being there [2]. Popular research methods include electrocardiography, rheography, sphygmography, Dopplerography and duplex scanning of blood vessels, ultrasound diagnostics, as well as such invasive methods as angiography and thermodilution [22], [18]. Photoplethysmography is used to solve the above problem as the method in screening the cardiovascular system state [3].

Photoplethysmography (PPG) is the non-invasive and affordable optical method for monitoring the blood volume alteration in blood vessels based on studying absorption of light passing through the tissue area under study with the pulsating blood [4], [5]. Due to its simplicity, ease in mobility and predominantly low cost, PPG become a popular means of continuous monitoring such parameters as heart rate, RR, SpO2, and others [6]. PPG system uses photoplethysmographic signals obtained in red and infrared wavelength range using appropriate sensors attached to the patient’s finger, wrist, earlobe, or forehead [20].

It should be noted that PPG signal could be easily distorted, if the sensors are loosely attached to the patient's body, or vice versa, when they are too tight; if there are various kinds of motion artifacts during measurement, changes in lighting, voltage pickups, background noise interference and many other factors significantly affecting the quality of received signals, which leads to erroneous estimate of parameters, especially of the heart rate [7], [8]. Motion artifacts are the most problematic sources of noise, which degrades the registered signal quality and could damage it to such an extent that these signals are becoming unusable [19]. Examples of real-life patient motions are movements during transportation, friction, arm swinging, cramps and kicking with newborns and infants. Consequently, there appears a significant need in effective algorithms to minimize the influence of interference impacts, and to improve thus the accuracy of heart rate evaluation.

Devices of this type are represented in the medical equipment market mainly by bedside monitors and pulse oximeters. Review of the existing technologies demonstrated that two main approaches are used to remove the motion artifacts. One is a software program analyzing the pulse component using the frequency and time domain analysis methods [9], [10], [11]. Another lies in the hardware approach that removes motion artifacts using information on the body movement obtained from other motion detection sensors [12]. Adaptive filtering methods based on the active noise suppression algorithms are the new approach [13].

The article proposes a method based on using artificial intelligence algorithms and digital adaptive filters, which parameters are automatically adjusted to statistical properties of the processed signal. This made it possible to create a PPG system successfully operating in the presence of noise and interference with previously unknown properties and to solve the problems of noise suppression and signal distortion compensation.
2. System architecture

Operation principle of devices for the pulse curve registration using PPG is based on the effect of tissue absorption coefficient alteration depending on its blood filling. Optical radiation passing through biological tissues is partially absorbed by optically dense media in accordance with the modified Bouguer-Lambert-Beer law:

\[ A_\lambda = \{ \sum \varepsilon_i(\lambda) \cdot C_i \cdot \gamma_i \} \cdot r_{RT} + G, \]

where:
- \( A_\lambda \) is the optical density on the \( \lambda \) wavelength;
- \( \varepsilon_i(\lambda) \) is the absorption (extinction) coefficient of the i-th substance on the \( \lambda \) wavelength;
- \( C_i \) is the i-th substance concentration;
- \( \gamma_i \) is the coefficient characterizing the increase in radiation absorption to the photons’ path lengthening in the medium during their scattering. In general, it could vary with different substances;
- \( r_{RT} \) is the distance between the radiation source and the receiver;
- \( G \) is the coefficient that takes into account the system configuration (distance to the object, surface roughness, etc.).

PPG system presented in this paper is the result of design and development aimed at providing compactness, multifunctionality, versatility and minimal costs in implementing a device distinguished by high measurement accuracy to easily obtain integration with a wearable system. PPG system diagram for monitoring the organism physiological parameters is shown in Figure 1.

![Diagram](image_url)

**Figure 1.** PPG system diagram for monitoring the organism physiological parameters.

Device 3-D model and prototype for heart rate measurement using the photoplethysmometry are presented in Figure 2. PPG sensor is the device main component making it possible to register
alterations in the optical radiation intensity associated with changes in the biological tissue optical density, which, in turn, is associated with dynamics in the concentration of substance absorbing radiation (in the case of blood, main absorbing substances are hemoglobin and its derivatives). Current-voltage converters on operational amplifiers are used further. In order to remove sufficiently constant level of interference from external lighting, external illumination signal compensation circuit is used. Resulting voltage passes through the voltage amplifier and through the analog filter, and after that the signal ready for conversion is transmitted to the ADC input. Digitalized signal from the ADC passes through the digital noise suppressor and is registered in the data register. After that, the signal is transmitted via the I2C interface to the control unit, where the final data message to the PC and the measurement results registration to the database are formed.

MAX30100 integrated sensor module manufactured by the American company Maxim Integrated was used as the sensor. Sensor in the single housing was combined with the current-to-voltage converters, voltage amplifiers and noise filters, and it also included digital interfaces. After registration, signals in digital form were transmitted via the I2C interface to the Raspberry Pi 3 Model B single-board computer.

![Figure 2. PPG 3-D model and device mockup.](image)

Software package was designed and developed for interaction between the single-board computer, sensor module and external devices, as well as for convenience of user interaction with the system, it included modules for receiving, visualizing and processing the received signals. The interface made it possible to work both with a remote workstation (personal computer) via wired and wireless Ethernet connection, and in the stand-alone mode (using a monitor).
3. Materials and methods
To determine the heart rate parameters, and to calculate primarily the CR, PPG signals were registered with healthy volunteers aged from 22 to 52 years. Each of them was exposed to a series of measurements at rest and after exercises lasting for about 25 seconds. Mechanical tonometer was used to register the pulse rate. The sensor module was fixed on the middle finger of the right hand. PPG signals were recorded in the txt files.

Recordings were taken 6 times with a pause of 2 minutes. As a result, 12 PPG signals were received for each person under testing. Examples of registered signals are provided in Figures 3 and 4.

![Figure 3. PPG signal at rest.](image)

![Figure 4. PPG signal after exercises.](image)

Signals obtained using the developed device had the same shape as the shape of the expert photoplethysmogram signals presented in literature [3], [13].

4. Results and discussion
Processing and analysis of the registered signals was carried out in the MathWorks MATLAB integrated development environment. Operation of the program designed for signal processing consisted of the following stages:

- reading raw signals from previously received files;
- determination of the optimal signal filtering algorithm;
- signal filtering using an optimal algorithm;
- detection of P and S peaks in the pulse waves represented on the PPG signal;
- CR calculating for each measurement.

When determining the optimal filtering algorithm, pulse wave signal was processed based on the methods of bandpass frequency filtering and adaptive filtering, which was necessary to ensure correct operation of the algorithm that determined the heart rate parameters.

The readout signals out of the files received from plethysmograph were distorted using the most common types of interference with different intensity and structure, such as white noise, industrial frequency interference of 50 Hz (frequency lumped) and impulse noise (time lumped).

To obtain the best results of the pulse wave noisy signal processing and to improve the signal-to-noise ratio during filtering, various algorithms for determining the adaptive filter coefficients were used, including adaptive filtering methods based on Wiener filters, MLS filters and Kalman filters.
Basic idea of adaptive filtering is that such filter parameters are adjusted to the input signal with previously undefined statistical model during its processing [14].

General design of the adaptive digital filter is presented below in Figure 5. The $x(k)$ discrete input signal is processed by a discrete filter, resulting in the $y(k)$ output signal. This output signal is compared to the $d(k)$ reference (desired, exemplary) signal, and the difference between them forms the $e(k)$ error signal. The adaptive filter purpose is to minimize the error in reproducing the $e(k)$ reference signal. For this purpose, adaptation unit after processing each $x(k)$ input sample analyzes the $e(k)$ error signal and additional data received from the filter using results of this analysis to adjust the filter parameters (coefficients). Filter coefficients are updated at each $k$ iteration.

![Figure 5. Adaptive filter general design.](image)

Filter coefficients adaptive adjustment algorithm has the following general form:

$$H(k + 1) = H(k) + \mu(k)G\left(e(k), X(k), \Phi(k)\right),$$

(2)

where:
- $H(k)$ is the vector of filter coefficient values at the $k$ moment;
- $\mu(k)$ is the parameter (coefficient) that determines the algorithm convergence rate to the filter coefficient optimal values;
- $G(k)$ is the certain nonlinear function (functional);
- $X(k)$ is the filter input signal values at the $k$ moment;
- $e(k)$ is the filter error at the $k$ moment;
- $\Phi(k)$ is the filter state vector containing elements that depend on the input signal, coefficients and filter error in the preceding (previous) time moments.

When searching for the minimum error, the root-mean-square error was used as the objective function, which made it possible to apply computationally simple procedures in calculating the filter coefficient values [15]. Optimization algorithms purpose was to adaptively adjust the filter weight coefficient values to minimize the root-mean-square error of the adaptive noise suppression system output signal [16].

To select the optimal algorithm, results of processing the pulse wave signal using adaptive filtering and results obtained on the basis of bandpass frequency filtering were analyzed. Also, the signal-to-noise ratios were determined at different intensities of three types of interference. Maximum signal-to-noise ratio at the filter output was the optimality criterion for signal filtering.

Bandpass filter parameters were selected based on where the signal maximum spectral density was located. Figure 6 shows signals distorted by different types of interference.
Figure 6. Signals distorted by different types of interference.

Figure 7 presents result of the signal adaptive filtering distorted by white noise in regard to the signal in Figure 5a based on the adaptive filters.
Results of processing noisy signals by various filters are presented in Table 1. As could be seen from Table 1, the Wiener filter is the best in improving the signal-to-noise ratio, since it is impossible to obtain the root-mean-square error value lower than in the Wiener filter in any linear filter.

**Table 1. Results of the adaptive filter analysis.**

| Impact       | Signal-to-noise ratio increase, times |
|--------------|--------------------------------------|
|              | Noise | 50 Hz interference | Impulse noise |
| Bandpass filter | 3.3132 | 3.1592 | 0.4092 |
| MLS filter    | 208.5825 | 39.3731 | 1.8468 |
| Kalman filter | 11.4066 | 4.0874 | 0.6077 |
| Wiener filter | 519.0711 | 45.1212 | 9.7218 |

After finding the optimal filtering algorithm, Wiener filter was used for each measurement, which, in comparison with other filters, makes it possible to operate with further algorithms in determining the CR at higher signal-to-noise ratio values.
To calculate the pulse value using the photoplethysmogram signal, the number of local peaks and the signal duration were programatically determined, after that the number of heart beats per minute was calculated for each measurement with each subject. Figure 8 shows the algorithm operation result in detecting the PPG signal peaks.

![Figure 8. Detection of the PPG signal local maxima and minima.](image)

The optimal filtering and CR determination algorithm created in this way was displayed on the screen, registered in a separate file and compared with obtained results of measurements by a mechanical tonometer to indicate accuracy of the proposed method. Table 2 demonstrates dependence of the result of calculating the heart rate on the signal-to-noise ratio for one of the subjects.

**Table 2. Heart rate accuracy calculation comparative analysis depending on the signal-to-noise ratio.**

| Signal-to-noise ratio, dB | 10 | 0   | -10  | -20  | -30  |
|--------------------------|----|-----|------|------|------|
| Measured heart rate, beats/min | 79 | 79  | 79   | 80   | 108  |
|               | 78 | 78  | 78   | 78   | 93   |
|               | 82 | 82  | 82   | 82   | 111  |
|               | 124 | 124 | 124  | 125  | 141  |
|               | 132 | 132 | 132  | 133  | 151  |
|               | 126 | 126 | 126  | 127  | 147  |

| Measured heart rate, beats/min | 79 | 79  | 79   | 81   | 113  |
|               | 78 | 78  | 78   | 78   | 103  |
|               | 82 | 82  | 82   | 83   | 111  |
|               | 124 | 124 | 124  | 126  | 143  |
|               | 132 | 132 | 132  | 132  | 144  |
|               | 126 | 126 | 126  | 127  | 135  |
It is planned in further experiments to determine characteristics of the cardiovascular system state based on comprehensive processing of measurements from the photoplethysmogram contact sensors, as well as from sensors of three-axis gyroscope, three-axis accelerometer and three-axis magnetometer (magnet resistive compass). Using machine learning based on data registered in the form of curves from sensors, it is possible to obtain a complete picture of the human organism state. To do this, let us consider a convolutional neural network for processing signals from sensors, which identifies peaks and intervals in these signals and marks them. Convolution networks appear to be a multilayer perceptron designed to identify two-dimensional surfaces with high invariance to alterations in these surfaces. It is planned to use convolutional neural network as the basis, and its learning would be carried out by a teacher.

The authors put forward the following proposals for further study of the neural network implementation in diagnostics of diseases:
- neural network processes one-dimensional arrays that are time series;
- respectively, photoplethysmogram and motion sensors synchronized readings are provided to the neural network inputs;
- fully connected neural classifier is added at the neural network output, and it acts as the CVS classifier according to the resulting intermediate graph.

Thus, introduction of neural networks to monitor and assess the current state of human organism is an urgent task to be solved by the authors.

5. Conclusion
In this article, we presented a system for monitoring heart rate based on an efficient method of processing the photoplethysmogram signals. The designed and developed PPG system, as well as the presented device mockup made it possible to register physiological parameters of the human organism with a given accuracy, and also provided possibility to analyze the organism current state. Results of experimental studies aimed at determining the optimal signal processing algorithms and the measurement techniques are presented. Artificial intelligence algorithms based on the received signal digital adaptive filtering methods and on the machine learning methods were considered. Technique for efficiency evaluating is presented, and quality criteria for the registered signal processing algorithms are formulated. Heart rate monitoring and current organism state capabilities provided by the proposed by PPG system could be successfully introduced in research as a tool making it possible to decide in regard to disease treatment and prevention. Future studies would investigate the neural network-based algorithms efficiency in CR assessment under various scenarios of system implementation to extend the proposed method to wearable devices.

6. References
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