Organism State Identification and Forecast Based on Comprehensive Sensor Measurement Processing with the Adaptive Algorithms

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Abstract. Many medical devices are using photoplethysmography (PPG) signals to estimate cardiac rate (CR), respiratory rate (RR), blood pressure (BP) and blood oxygen (SpO2). Photoplethysmography demonstrated its great potential in non-invasive monitoring of the human organism state [17], but application of this method with wearable devices is extremely difficult due to its vulnerability to motion artifacts. This paper presents implementation of a photoplethysmography device on the Raspberry Pi 3 B+ single-board computer. The work uses adaptive algorithms to study the cardiovascular system state in severe device operating conditions degrading the evaluation accuracy of CR rate and other parameters of the heart rate. Selection of the device component base and component parts was made based on their availability and multi-functionality. The manufactured mockup made it possible to carry out research to determine the most effective algorithms for digital processing of signals received from sensors. Methods of digital signal processing based on adaptive algorithms are proposed: Wiener algorithms, algorithms based on the method of least squares (MLS) and algorithms based on the Kalman filtering. In the course of measurements taken on simulation objects and volunteers invited to participate in the study, analysis of the results of various measurement processing algorithms operation was carried out. A method is proposed for assessing the accuracy of calculating the CR and analyzing effectiveness of the external noise filtering with adaptive filters. Processing the sensor measurements made it possible to monitor the heart rate with the given accuracy, as well as to predict the human body state.
1. Introduction

The number of diseases in the world is growing steadily, and improvement in methods of their treatment does not provide the desired success [17]. Screening and diagnostic devices could be used to identify a disease at an early stage, apply preventive measures, carry out treatment and prevent any critical situation. Therefore, it is important nowadays to ensure accurate monitoring of biomedical indicators of the human body state, which assists in timely diagnostics of pathology emergence and development. It is also important to carry out functional diagnostics of external respiration while monitoring the pathology states [23]. In addition, operation of such devices requires a system assisting to correct decisions regarding the disease treatment and prevention, and to evaluate the treatment effectiveness.

Cardiovascular diseases are one of the main causes of disabilities and deaths with population[1]. Development of cardiovascular diseases is often asymptomatic; nothing indicates clinically the presence of disorders, but the person is already within the risk group knowing nothing about the situation [2].

Occlusive, impedance, electrocardiographic, ultrasound and optical technologies could be distinguished among the existing technologies used in studying the cardiovascular system state [18], [22]. Photoplethysmography method is proposed as a solution to the above problem [3], [23].

Photoplethysmography, mostly known as PPG, appears to be a non-invasive and fairly simple electro-optical technique allowing to measure volumetric blood alterations in the tissues. This technique is based on the study of light absorption passing through the tissue area with pulsating blood under study [4], [5]. Due to its convenience and predominantly low cost, PPG became a popular tool in monitoring such parameters, as CR, RR, SpO2 and others [6].

These parameters are monitored by fixing sensitive elements of the measuring system on the patient's body for a long time. For this purpose, clothespins, suction cups, stickers, rubber straps or cloth tapes with adhesive could be used. At the same time, difficulties arise during long-term monitoring of these parameters in registering reliable signals, and measurement error of the above parameters significantly increases [19], [20]. Untight fixation of the measuring system sensing elements on the patient's body, or, on the contrary, their excessive adherence, various kinds of motion artifacts during measurement, changes in lighting, voltage pickups, background noise interference and many other factors significantly affect the quality of signals received [7], [8].

Devices of this type are mainly represented in the medical instruments market by bedside monitors, stationary photoplethysmographs, finger medical pulse oximeters, various wearable fitness bracelets and smart devices. Review of the existing analogues demonstrated that motion artifacts are the most serious problem; accordingly, many methods to overcome this obstacle were investigated. There are two main approaches: the first is a software approach that analyzes the pulsation component using the analysis methods in frequency and time domains [9], [10], [11]. The second is a hardware approach that removes motion artifacts using information about body movement received from other motion detection sensors [12]. New approach consists of adaptive filtering methods based on the active noise suppression algorithms [13].

Our goal was to develop an extensively approachable measurement method that could be used to monitor physiological parameters not only in medical institutions and laboratories, but also at home, as well as in non-stationary operating conditions (patient transportation in the ambulance mobile ICU, emergency resuscitation assistance, sports medicine).

The designed and developed device uses artificial intelligence technologies, in particular, the digital adaptive filters, which parameters are automatically adjusted to the input signal with previously undefined statistical model during its processing. This made it possible to conduct research in the presence of external noise and interference, and to effectively solve the problem of noise suppression and signal distortion compensation.
2. Solutions

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:

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

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, multi functionality, 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.

![Figure 1. PPG system diagram for monitoring the organism physiological parameters.](image)

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 device 3-D model and 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. Signal processing
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.

4. Experimental 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.

Adaptive filters are used in the following cases:
- interference bandwidth is unknown or is altering over time;
- spectral composition of the useful signal and of the interference are overlapping;
- characteristics of transmission channels, useful signal and interference are non-stationary;
- statistical parameters of transmission channels, signals and interference do not satisfy linearity and normality properties [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:

\[
H(k + 1) = H(k) + \mu(k) G(e(k), X(k), \Phi(k)),
\]

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.](image)

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.

| 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 programmatically 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.

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.

| Signal-to-noise ratio, dB | 10 | 0 | -10 | -20 | -30 |
|-------------------------|----|---|-----|-----|-----|
| Measured heart rate, beats/min | 79 | 79 | 79 | 80 | 108 |
| Photoplethysmography calculated heart rate on the IR channel, beats/min | 78 | 78 | 78 | 78 | 93 |
| 82 | 82 | 82 | 82 | 82 | 111 |
| 124 | 124 | 124 | 125 | 141 |
| 132 | 132 | 132 | 133 | 151 |
| 126 | 126 | 126 | 127 | 147 |
| 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 state 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
This article presented a method for identifying and forecasting body state based on the photoplethysmogram signal processing. Proposed method uses digital adaptive filtering of the received signals and makes it possible to register the human organism CR with a given accuracy, and also provides the ability to analyze the current body state. This method could also be applied to many devices. During the research, the most optimal signal processing algorithms and measurement techniques were identified. In addition, methodology for evaluating the algorithm effectiveness is presented, and algorithm quality criteria for processing the registered signals are formulated. Experimental results confirmed the possibility of monitoring heart rate using the developed device. By virtue of intelligent decision-making support system in regard to disease treatment and prevention, the developed device could be used for screening and diagnostic studies. As further work, possibility of going forward in improving the accuracy would be investigated before a wearable device is designed and developed.

6. References
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