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HEART RATE ESTIMATION FROM PHOTOPLETHYSMOGRAM AND ACCLERATION SMARTPHONE DATA BASED ON CONVOLUTIONAL NEURAL NETWORK AND LONG SHORT TIME MEMORY

Abstract
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INTRODUCTION

Reflective light photoplethysmography (PPG) sensor measures the intensity change of skin reflected light and provides PPG signal representing the change of arterial blood volume in the systolic and diastole periods of the heart cycle. This sensor can be installed on a watch or bracelet to measure and monitor instantaneous heart rate (hr), thereby minimizing inconvenience for users, and is therefore of great concern. However, sensors are sensitive to motion artifacts (MAs), which come from the pressure and motion exerted on the wrist worn by the PPG sensor. MAs ultimately lead to inaccurate HR estimation. A few years ago, Zhang et al. shared a dataset for simultaneously measuring acceleration and PPG signals in motion [1], which led to research on using acceleration signals to offset MA in PPG sensors. At present, the most advanced method has reached the accuracy of the average absolute error (aae) of 2—3 bpm in high-intensity exercise [1—13]. Most state-of-the-art methods estimate the two main stages of human resource utilization: MA cancellation and human resource tracking. For MA cancellation, they treat the power spectrum of the simultaneously measured acceleration signal as motion artifacts (MAs) and remove or attenuate the power from the PPG power spectrum. For human resource tracking, they use the assumption that there is no significant change in human resources between two consecutive segments, and predict or correct human resource results. Various signal processing algorithms, such as high-resolution spectrum (including frequency conversion complex demodulation [1—3]), adaptive filters (including Wiener filters [4—8], decomposition (including ensemble empirical mode decomposition, singular value decomposition [9—10]), and nonlinear filters (including Kalman filters (KF) and particle filters [11—13]), have been used for MA cancellation or/and HR tracking.

However, despite the efforts and progress of algorithms, these methods do not always provide accurate results.

One of the most challenging issues is the low signal-to-noise ratio (SNR) of PPG signals. Regardless of the method of using high-resolution spectroscopy for MA cancellation, it is almost impossible to find an accurate HR when the power corresponding to HR in the measured PPG is very low.

This low signal-to-noise ratio mainly occurs when subjects engage in high-intensity physical exercise. HR tracking method can minimize the outlier in the results, but if the low SNR lasts for a long time, it will fail.

To overcome this issue, our group recently proposed a Finite State Machine (FSM) framework that ignores low-quality signal segments or inaccurate estimation results [14—15].

Based on the FSM framework,I can provide very accurate HR results. However, this framework ignores nearly half of the results collected in high-intensity physical exercise. Subsequently,I proposed a multimode particle filter (MPF) method that reduces the dropout rate of the results while maintaining accuracy. However, during high-intensity physical exercise, the abandonment rate of results is higher than 30%. Recently, people have considered a deep learning method. In [17], a deep learning framework named CorNet was proposed, which models the convolutional layer and the short-term memory layer (LSTM), followed by a full connection layer. In the model, bandpass filtered PPG data is used as the input layer.

This article proposes a new deep neural network based on multi class non-uniform multi label classification for HR estimation. In our proposed model,I consider two power spectra from PPG and acceleration signals as input layers. In addition,I use acceleration signal strength in the input layer.I assume that the intensity of the acceleration signal can provide information on recent heart rate changes: high intensity represents vigorous exercise, which may alter heart rate. This model includes two convolutional layers, two LSTM layers, one connectivity layer, and three fully connected layers (including one softmax). In this model, the power spectra of PPG and acceleration signals are fed into two convolutional layers, which provide MA cancellation in the PPG power spectrum. The output is flattened and connected to a fully connected layer, which is then connected to the acceleration signal strength. Then, the output is fed to two LSTM layers, followed by other fully connected layers containing softmax. The LSTM layer tracks HR tracking with the smallest outlier. In this model,I also propose a new approach to evaluate the loss value by modifying the true HR value to a Gaussian distribution. Evaluate the performance of the proposed model by comparing it with the previously reported results [1－17,22].

GENERAL DESCRIPTION OF WORK

Relevance of the subject

The work corresponds to paragraph *6* «*Ensuring the safety of man, society, state*» of the State Program of innovative development of the Republic of Belarus for 2021–2025. The work was carried out in the educational institution Belarusian State University of Informatics and Radioelectronics.

The aim and tasks of the work

The aim of the work isto improve the accuracy of wearable reflective photoelectric volume pulse recording (PPG) sensors that can be integrated into watches or bracelets for measuring heart rate.

To achieve this aim, the following tasks were solved in the dissertation:

1.Collection and preprocessing of PPG and ACC data.

2.Modify the true heart rate value to a Gaussian distribution to evaluate the loss value.

3. Adjust the tracking of heart rate through cascaded acceleration intensity to further optimize.

Personal contribution of the author

A wearable reflective photoelectric volume pulse recording (PPG) sensor can be integrated into a watch or bracelet to provide real-time heart rate (HR) with minimal inconvenience to users. However, sensors are sensitive to motion artifacts (MAs), resulting in inaccurate HR estimation. This paper proposes a new deep neural network based on multi class non-uniform multi label classification, which is composed of two convolution layers, two short-term memory layers, a cascade layer, a connection layer and three full connection layers (including a softmax). For all training and test data sets, the average absolute error of the proposed model is less than 1.5 bpm - the training data set is 1.09 bpm, and the test data set is 1.46 bpm.

Author’s publications

According to the results of the research presented in the dissertation, 3 author’s works was published, including: 3 articles and abstracts in conference proceedings.

Structure and size of the work

The dissertation work consists of introduction, general description of the work, four chapters with conclusions for each chapter, conclusion, bibliography, eight appendixes.

The total amount of the thesis is 78 pages, of which 46 pages of text, 20 figures on 15 pages, 7 tables on 5 pages, a list of used bibliographic sources (15 titles on 3 pages), a list of the author's publications on the subject of the thesis (12 titles on 3 pages), code appendixes on 19 pages, graphic material on 4 pages.

Plagiarism

An examination of the dissertation «Heart Rate Estimation from photoplethysmogram and accleration smartphone data based on Convolutional NeuralNetwork and Long Short Time Memory» by Qiu Gaowei was carried out for the correctness of the use of borrowed materials using the network resource «Antiplagiat» (access address: https://antiplagiat.ru) in the online mode 28.04.2023. As a result of the verification, the correctness of the use of borrowed materials was established (the originality of the thesis is 90.56 %)

SUMMARY OF WORK

The **introduction** addresses the problems of inaccurate measurement of heart rate caused by motion artifacts in portable heart rate detectors.

The **general description of work** shows the connection between the work and the priority areas of scientific research, the aim and tasks of the research, the personal contribution of the applicant for a scientific degree, the approbation of the dissertation results.

In the first chapter the focus is on solving the data processing problem based on PPG and ACC.

In the second chapter mainly introduces the neural networks and feature extraction used in heart rate estimation.

In the third chapter mainly introduces the effectiveness of models and algorithms, evaluates them through comparative experiments, and makes prospects for improvement ideas.

CONCLUSION

This paper propose a deep learning model that utilizes the power spectrum and acceleration intensity of PPG and acceleration signals to estimate HR. The model consists of a two-dimensional convolutional layer, a one-dimensional convolutional layer, and a fully connected layer, which are included in MA elimination. In addition, it also includes a connection layer, two LSTM layers, a fully connected layer, and then a softmax layer, which are merged for HR tracking and estimation. The AAE values of this model on the training and testing datasets are 1.09 bpm and 1.46 bpm, respectively, surpassing the results of currently state-of-the-art methods.

In order to study model optimization,I also considered a bidirectional LSTM layer or two GRU layers instead of two unidirectional LSTM layers. When two unidirectional LSTM layers are replaced by a bidirectional LSTM layer, the ae of the training dataset and the test dataset are 0.99 bpm and 1.61 bpm, respectively.I also confirmed that further stacking of bidirectional LSTM layers did not improve performance. When the LSTM layer is replaced by the GRU layer, the ae of the training dataset and the test dataset are 1.04 bpm and 1.64 bpm, respectively. In addition,I consider regression methods to obtain HR values instead of searching for the dominant frequency bin. Based on the proposed model,I added fully connected layers of different depths and widths using the mean square error cost function, but found that the regression method did not learn the parameters correctly. In the future, it is necessary to conduct in-depth research and comparative research on the network optimization of regression methods.

Regarding acceleration intensity information,I have shown that acceleration intensity reduces AAE by approximately 15%. However, in real life, the intensity of acceleration may not be related to the intensity of exercise. For example, when a person rides a bicycle, the acceleration intensity is not related to the increase in heart rate. However, in our results from the BAMI-II (test dataset), even with an increase in HR, HR can be accurately estimated at low acceleration intensity. Figure 6 shows the HR estimation results during the pole running phase. During the exercise phase, the acceleration intensity is low, but the increase in HR is correctly estimated. This indicates that acceleration intensity is only one of the many factors in HR estimation.

The lower acceleration intensity indicates that the PPG signal is less affected by motion artifacts and the obtained power spectrum is more accurate. This indicates that without considering the acceleration intensity information, only the accurate power spectrum of the PPG signal can be used to estimate the accurate hr. However, in future work,I need to study real-life scenarios, especially when the intensity of acceleration is not related to the intensity of exercise.

There is an incorrect power spectrum at the same time, without information on acceleration intensity and HR mutation, resulting in inaccurate estimation results. During the first 15 seconds, the dominant frequency is approximately 90 or 180 bpm, while the actual HR is approximately 120 bpm. In addition, the acceleration intensity is also relatively low; Therefore, information on acceleration intensity cannot be used for HR estimation. The growth rate of human resources is relatively high.

In BAMI-II, subject 22 also observed this inaccurate HR estimation result at the beginning. In future work,I will study this issue to minimize inaccurate human resource estimation results.

Most importantly, the most important aspect of future research will involve energy-saving execution when implementing the proposed model in real-time on wearable devices. Deep learning is undoubtedly aimed at providing good performance, but due to limited computing power, its implementation on wearable devices faces many challenges as they require low-power specification algorithms. Our proposed model includes 3275402 weights/biases, requiring approximately 17 million multiplication and addition operations for a single HR estimate. Therefore, achieving real-time implementation of deep learning models on wearable computing platforms is not easy. Referring to [27], offloading deep learning workloads to the cloud is one of the feasible solutions. However, the offloading method results in a minimum delay of up to a few seconds, which may not be available during real-time performance. Recently, ARM announced a computing library (ACL), which is a comprehensive collection of low-level neural network functions optimized for ARM Cortex CPU processors. According to reports, compared to Tensorflow on Zuluko [27], ACL processing time has been reduced by 25%, indicating that using libraries optimized for deep neural networks will support the implementation of our method on wearable devices. In addition,I can reduce the complexity of the model by reducing the size of the input data. In our proposed model, the input data consists of 222 power spectra based on frequency bin, with a frequency resolution of 0.0122 Hz (0.73 bpm). Even ifI halve the resolution to 111 frequency boxes, the frequency resolution is still 1.46 bpm, which is enough to provide accurate HR. In addition,I can also consider using traditional signal processing methods to estimate HR when the wrist movement is not significant; Only when wrist movement is detected and the PPG signal is distorted by MAs can I use this model to estimate HR.I would like to report further investigations and issues related to the implementation of the proposed method in wearable devices.

LIST OF AUTHOR'S PUBLICATIONS

A-1 Qiu Gaowei. Heart Rate Estimation from photoplethysmogram and accleration smartphone data based on Convolutional Neural Network and Long Short Time Memory / Qiu Gaowei // BIG DATA and Advanced Analytics,Девятая международная научно-практическая конференция, Минск, 17-18 мая 2023 г. – Minsk : BSUIR, 2023. – С. 365-368.

A-2 Qiu Gaowei. Heart Rate Estimation from photoplethysmogram and accleration smartphone data based on Convolutional NeuralNetwork and Long Short Time Memory / Qiu Gaowei // Технологии передачи и обработки информации (Technologies of information transmission and processing): материалы Международного научно-технического семинара, Минск, март – апрель 2023 г. – Minsk : BSUIR, 2023. – С. 62–69