ABSTRACT

of Alexander V. Largin's dissertation work «Development of software and hardware and a method for digital processing and intelligent analysis of electrocardiogram and photoplethysmogram signals for predicting blood pressure levels», submitted for the degree of Doctor of Philosophy (PhD) in specialty 8D06201 – «Radio engineering, electronics and telecommunications»

The relevance of the work

Modern trends in the development of science and technology are largely focused on improving the quality of life of each member of society. Innovations are actively implemented in various spheres of human activity, ranging from interaction with government agencies and commercial structures to medicine and everyday life. Such innovations have a positive impact on the standard of living of the population, both indirectly, by optimizing social processes and logistics, and directly, by improving healthcare technologies.

In particular, in the field of medical technology, the key task is to modernize processes and search for new methods of analyzing biomedical information based on the introduction of modern scientific achievements at each stage of working with data. Such actions can reduce the level of complications after serious diseases and provide early detection of dangerous pathologies, since biomedical signals contain important information about the state of the body. Predicting and monitoring health significantly reduces the level of negative consequences for common diseases, while reducing the burden on medical institutions.

The solution to the problem of deeper and better analysis of biomedical information has become possible due to serious technological growth in the field of microelectronics, computer technology and infocommunication technologies.

The radio-electronic industry has launched the production of new highly integrated systems on chips or systems-on-a-chip (SoC). Modern SoCs can include not only traditional components, such as a processor and memory, but also specialized blocks for processing biomedical information based on modules of high-bit analog-to-digital converters (ADCs). Such ADCs are capable of processing several types of low-amplitude biomedical signals simultaneously and in real time over a wide dynamic range. In addition, modern SoCs have built-in wireless data transmission modules, which significantly increases the ability to integrate equipment into communication networks.

In turn, the improvement of infocommunication technologies has increased the speed of transmission and efficiency of medical data processing, improving the diagnosis and monitoring of patients in real time. The integration of technologies such as telemedicine, artificial intelligence and the Internet of Things provides access to health services for residents of remote areas and helps to solve the problem of shortage of medical specialists.

The progress achieved in these areas opens up opportunities for implementing analysis methods and algorithms for digital signal processing (DSP), which were previously unavailable or were known only in theory and did not find

wide application in practice. It is now possible to study the multi-level structure of biomedical signals by creating multi-stage data processing algorithms.

The main advantages of digitalization in the processing of biomedical information are as follows:

– ability to create multi-level data processing systems based on iterative algorithms;

– compatibility with various hardware platforms, which makes it possible to deploy software on both mobile and stationary devices.

– high economic efficiency, as a result of the possibility of upgrading and replicating these digital systems;

– digital processing ensures high accuracy when working with the signal with maximum stability of characteristics across the entire spectrum;

– the flexibility of digital methods in parameter correction ensures their high functionality, which is especially important in the context of a wide variety of methods used for extracting diagnostic information.

Based on the above, it can be argued that modern achievements in these areas of science and technology significantly increase the efficiency of diagnostic and monitoring automation processes in medical instrumentation. The introduction of new technologies is particularly relevant in the fight against the most dangerous and widespread diseases, providing medical professionals with new tools to support decision-making.

The development of technologies in the field of microelectronics and computer technology, modern DSP algorithms, information and communication technologies, as well as data mining opens up new opportunities for introducing innovations in the field of medical instrumentation. At the same time, modern social challenges determine the relevant area for conducting necessary scientific research. In particular, the problem of monitoring the level of blood pressure (BP) is extremely important, since the prevalence of arterial hypertension (AH) among the population is currently extremely high.

According to the 2021 study, the number of people aged 30 to 79 with hypertension worldwide doubled from 331 million women and 317 million men in 1990 to 626 million women and 652 million men in 2019. A World Health Organization (WHO) report from 2023 shows that hypertension is one of the leading causes of premature death worldwide. 1.28 billion adults aged 30-79 years suffer from hypertension, most of them (two-thirds) live in low-and middle-income countries. An estimated 46% of adults with hypertension are unaware of their condition, and less than half of adults (42%) with hypertension are diagnosed and treated. The same WHO report provides information on the Republic of Kazakhstan, from which it is reported that in 2019, the prevalence of arterial hypertension in the adult population was 42%, and 64% of deaths from cardiovascular diseases (CVD) are associated with high systolic blood pressure.

Currently, sphygmomanometers that provide high measurement accuracy are most widely used to determine blood pressure. These devices consist of a pressure gauge for measuring air pressure; a special cuff worn on the patient's arm, as well

as an air blower equipped with an adjustable release valve. The use of a sphygmomanometer causes some inconvenience to the patient due to the use of a cuff that compresses the artery, in this regard, this method is inconvenient for screening, where maximum simplicity and speed of measurements are required. In addition, sphygmomanometers cannot be used for long-term continuous monitoring of blood pressure, since constant compression of the cuff can affect the tone of the patient's blood vessels and skin.

In common practice, an invasive method is used for long-term and continuous monitoring of blood pressure, in which a catheter is inserted into a blood vessel for direct access to the artery. This method is obviously painful for the patient, has contraindications, requires specialized equipment and constant monitoring.

Due to these circumstances, researchers are currently paying great attention to finding methods for assessing blood pressure that can provide an acceptable level of accuracy, with minimal discomfort for the patient. Much attention is paid to methods of indirect blood pressure assessment based on digital processing and intelligent analysis of photoplethysmogram (PPG) and electrocardiogram (ECG) signals.

Thus, the development of a method for non-invasive assessment of the blood pressure level with acceptable accuracy without using a sphygmomanometer cuff and without requiring individual calibration is timely and relevant.

The aim of the dissertation is to develop a non-invasive non-manget method for predicting the level of blood pressure based on PPG and ECG signals taken synchronously. This makes it possible to create new measuring devices for solving the problem of blood pressure screening and monitoring without prior individual calibration and with acceptable accuracy.

To achieve this goal, the following **tasks were set**:

1. Investigation of existing methods for assessing blood pressure levels at the stages of collecting, processing and analyzing information in order to identify significant problems and features in traditional blood pressure monitoring.

2. Performing analysis of PPG and ECG signals taken synchronously in order to identify the most significant indicators that correlate with the level of blood pressure and can be used to build informative signs.

3. Development and search for effective DSP algorithms for PPG and ECG using theoretical and experimental studies to ensure their compatibility with subsequent stages of information processing in predicting the level of blood pressure.

4. Formation of a representative database of PPG and ECG signals for training machine learning models (ML) of the classifier and regressor.

5. Development and experimental study of intelligent classification and regression algorithms based on extracted informative features from PPG and ECG signals for predicting blood pressure parameters.

6. Synthesis of a software and hardware complex for predicting blood pressure levels based on the developed methods of digital processing and intelligent analysis of PPG and ECG signals taken synchronously.

Research methods

To perform the tasks set in the framework of the dissertation research, DSP radio engineering methods, spectral and wavelet analysis tools, as well as intelligent algorithms for predicting and recognizing patterns were used. In addition, methods of mathematical modeling, linear algebra, and statistical radio engineering were used.

In the process of conducting experimental studies, machine learning (ML) technologies, computer modeling and automation of mathematical calculations were actively used.

The design of circuit solutions for optimized recorders of ion equipment created on the basis of modern radio-electronic components was carried out.

The subject of the research is the technical and methodological justification, as well as the creation of innovative solutions for predicting blood pressure indicators using modern signal processing technologies and ML theory tools.

The object of the research is the processes of extracting, processing and interpreting diagnostic information from ECG and PPG signals.

The scientific novelty of the dissertation consists in the following provisions and results:

1. Efficient algorithms for digital processing of PPG and ECG signals have been developed to ensure their compatibility with subsequent stages of information processing when predicting the level of blood pressure.

2. An approach to identifying significant in formative features from PPG and ECG signals for blood pressure assessment has been developed.

3. Based on the ML tools, an intelligent classifier model has been developed that allows detecting three blood pressure levels based on the data of PPG and ECG signals: low, normal and high.

4. Using algorithms of data mining, regression models have been developed that allow predicting the parameters of systolic, diastolic, and mean blood pressure based on the characteristics of PPG and ECG signals.

5. A software and hardware complex is implemented for real-time prediction of blood pressure parameters based on the PPG signal from the finger and the ECG signal in the first standard lead, taken synchronously.

Practical significance

The practical significance of the work lies in the possibility of using the results obtained in the study to build effective systems for predicting blood pressure both for screening studies and for long-term monitoring.

Thanks to the method proposed in this paper, it becomes possible to create publicly available systems for determining blood pressure that are used in home monitoring and work with acceptable accuracy. This is facilitated by the approach proposed in the paper on the use of self-learning intelligent algorithms for analyzing PPG and ECG signals.

The implemented hardware and software tools for assessing blood pressure levels can be integrated into common wearable electronics devices, such as smartphones, fitness bracelets, or electronic watches, due to their compactness and

integrability. The widespread use of portable and reliable blood pressure assessment systems will provide the following important advantages:

the ability to take timely preventive measures to prevent the development of CVD;

develop personalized treatment and health management plans that take into account each individual's unique characteristics.

reducing the likelihood of serious consequences due to high blood pressure;

the ability to collect data and send it to the attending physician in real time, under various conditions and loads on the body;

improve the quality of life of patients by preventing the progression of diseases and reducing the need for emergency medical care.

Connection with government programs

The development of software and hardware tools and methods for predicting blood pressure parameters contributes to achieving the goals of the strategy «Kazakhstan-2050», aimed at improving the life expectancy and quality of life of Kazakhstanis. Innovative approaches to the diagnosis and monitoring of cardiovascular diseases will ensure early detection of risks and timely intervention, which is an important step in implementing the country's strategic objectives.

This dissertation research corresponds to the priorities of state programs in the field of healthcare of the Republic of Kazakhstan. In particular, the work meets the objectives of the state health development program for 2020-2025 aimed at improving public health and reducing morbidity and mortality from chronic non-communicable diseases, including CVD.

The study makes a significant contribution to the development of medical technologies, including telemedicine and mobile healthcare. Creating a software and hardware complex based on the developed method will allow remote monitoring of patients' condition, which is especially important in conditions of pandemics and limited access to medical institutions.

The socio-economic significance of this study is to reduce the cost of treatment and rehabilitation of patients due to accurate diagnosis and prevention of complications. This helps to reduce the frequency of hospitalizations and reduce the burden on the health care system, which is of great economic importance for the Republic of Kazakhstan.

Provisions of the dissertation submitted for defense

1. A multi-stage algorithm for digital processing of PPG and ECG, which allows extracting significant informative signs from synchronously recorded signals to predict the level of blood pressure.

2. A method of data mining based on the developed classifier model for detecting three levels of blood pressure: low, normal and high.

3. A method of data mining based on developed regression models for predicting the parameters of systolic, diastolic and mean blood pressure.

4. Software and hardware complex for real-time prediction of blood pressure parameters based on the data of the PPG signal from the finger and the ECG signal in the first standard lead, taken synchronously.

Approbation of the work

The main results of the dissertation research were presented and discussed at: International Scientific and Practical Conference «Trends in the development of natural and technical sciences in the modern world» (Kazakhstan, 2022); International Scientific and Practical Conference «Digital transformation of Kazakhstan: goals, objectives and key success factors» (Kazakhstan, 2021); International Scientific and Practical Conference «Youth and Science» (Kazakhstan, 2021).

Publications

The main results of the dissertation research were reflected in 5 scientific papers, including 3 articles in scientific journals included in the List of scientific publications recommended for publishing the main results of scientific activity, approved by the authorized body; in 2 articles in international scientific journals with the CiteScore percentile indicator at least 35 in the Scopus database; in 3 papers published in the proceedings of international scientific conferences, as well as in the author's certificate.

Personal contribution of the author

The main experimental, theoretical and practical results obtained during the dissertation research were obtained by the author independently. In published scientific papers as part of a team of co-authors, the applicant has the main contribution to receive, communicate and analyze the results achieved.

Structure of the dissertation

This dissertation consists of an introductory part, the main part, which includes four sections, conclusions, list of used sources and applications. The work is presented on 107 pages of computer text, includes 50 figures, 10 tables and 98 names of bibliographic sources.

In the first section of the dissertation, an analysis of existing methods for indirect assessment of blood pressure that do not require a cuff is carried out using PPG and ECG signals. Mathematical models linking the elasticity of vascular walls, wall thickness, vascular diameter, and blood density with pulse wave parameters for determining blood pressure are presented. The necessity of calibrating existing models to improve the accuracy of forecasting is shown, and suggestions for developing a method that does not require pre-calibration for screening and continuous monitoring of blood pressure are given.

The section also contains international standards for the classification of arterial hypertension (AH). Based on them, tables of blood pressure gradation by systolic and diastolic pressure are presented, which is necessary for standardizing diagnostics and monitoring. The biophysical nature of PPG and ECG signals is reviewed, their morphological characteristics and features related to the cardiovascular system are described. Various types of interference that occur during signal recording are described, including low-frequency (LF) and high-frequency (HF) interference.

The analysis carried out in this section allows us to identify the short comings of existing methods for non-manget determination of blood pressure and justifies the need to develop more accurate and universal models that could be used

for early diagnosis and monitoring of arterial hypertension based on the data of PPG and ECG signals.

In the second section of the dissertation, approaches to the development of the digital signal processing process of PPG and ECG for blood pressure assessment are considered. The structure of the DSP is described, which includes the stages of filtering, normalization, selection of informative features and their preparation for machine learning models (ML).

Algorithms for filtering HF and LF interference are analyzed. Zero-phase Butterworth filters are used to remove HF noise, and wavelet filtering is used for LF interference. Methods of bidirectional filtering and wavelet transform are described to minimize phase distortion in synchronously recorded signals, which improves the accuracy of the analysis.

The stage of selection of morphological components includes automatic detection of peaks and characteristic points, such as the R wave on the ECG, systolic maximum and minimum on the PPG, which is provided by the multiscale peak detection algorithm. A cross-correlation method is proposed for calculating the pulse wave propagation time (PWPT) between ECG and PPG signals. Additional informative features related to vascular stiffness, pulse wave reflection, etc. are introduced, forming a feature space for training models of ML.

The third section of the dissertation presents a method of intellectual analysis of PPG and ECG signals for predicting the level of blood pressure. The expediency of using the selected ML algorithms for solving the set tasks is justified. The process of forming a database of features, including 25 informative parameters, such as PWPT, heart rate, as well as data extracted from the PPG signal, is considered. Outliers were filtered to eliminate artifacts, which improved the quality of forecasting. Methods for classifying the blood pressure level based on random forest, k-nearest neighbors, and extra-random tree models are described. The best quality indicator is the model of the extremely random tree classifier (ERTC), adapted to the class imbalance using the SMOTE algorithm.

A stacking method for regression prediction of blood pressure is also proposed, where the XGBoost-based metamodel combines the advantages of several models, providing more accurate prediction of systolic, diastolic, and mean blood pressure. The achieved model quality indicators meetthe requirements of the British Hypertension Society (BHS) standards and partially ANSI/AAMI SP10, which confirms the applicability of the proposed method for determining blood pressure. The general structure of the method for estimating blood pressure parameters using intelligent analysis of PPG and ECG signals is described.

The fourth section describes the development of a software and hardware complex (SHC) for estimating blood pressure parameters based on the developed method of intelligent analysis of PPG and ECG signals. The basis for creating the complex was the principles of energy efficiency, noise immunity, the use of modern systems on a chip (SoC), as well as specialized biosensors.

The hardware of the SHC is based on the ESP32-WROOM-32 chip system and the MAX86150 biosensor, which provides synchronous recording of ECG and PPG signals. Wireless data transmission is implemented via Bluetooth, as well as

via the ESP-NOW protocol to increase the coverage area. The software part that runs on a Windows or Linux PC includes a graphical interface.

The SHC includes integration into infocommunication medical systems with the ability to transfer data on blood pressure parameters to remote servers. The complex was successfully tested as part of an experimental medical assistant robot designed to measure blood pressure in patients in quarantine hospitals.

The conclusion provides findings from the research.

Works published on the topic of the dissertation.

1. Savostin A., Tuleshov A., Koshekov K., Savostina G., Largin A. Devising a method for predicting a blood pressure level based on electrocardiogram and photoplethysmogram signals. Eastern-European Journal of Enterprise Technologies. – 2022. – Vol. 5, No. 2. – P. 62-74. DOI: https://doi.org/10.15587/1729-4061.2022.265066.

2. Seidakhmet A., Tuleshov A., Jamalov N., Koshekov K., Abduraimov A., Largin A., Zhauyt A. Design of a complex of medical service robots and analysis of transmission characteristics of drives. Journal of Applied Engineering Science. – 2022. – Vol. 20, No. 4. – P. 1242-1253. DOI: https://doi.org/10.5937/jaes0-38656.

3. Savostin A.A., Largin A.V., Savostina G.V., Ritter D.V., Koshekov A.K. The method of automatic detection of characteristic points of the pulse wave. Proceedings of Karaganda Technical University named after Abylkas Sagynov. – 2024. – №1 (94). – P. 508-510. DOI 10.52209/1609-1825_2024_1_508.

4. Savostin A.A., Largin A.V., Savostina G.V., Ritter D.V., Koshekov A.K. Development of a measuring device for assessing blood pressure levels based on electrocardiogram and photoplethysmogram signals. Bulletin of KazATC. – 2023. – № 2 (125). – P. 354-362. DOI: https://doi.org/10.52167/1609-1817-2023-125-2-354-362.

5. Savostin A.A., Savostina G.V., Largin A.V. Analysis of methods for suppressing network interference in the tasks of digital processing of electrocardiographic signals. Proceedings of Karaganda Technical University named after Abylkas Sagynov. – 2022. – №1 (92). – P. 291-296. DOI 10.52209/1609-1825_2022_2_291.

6. Abdualiev E.O., Savostin A.A., Largin A.V. The system of two-factor identification of employees of the enterprise. Trends in the development of natural and technical sciences in the modern world: materials of the international scientific and practical conference. – Petropavlovsk: M. Kozybayev NKU, 2022. – P. 502-503.

7. Savostin A.A., Largin A.V., Savostina G.V. Review of the current state and prospects for the development of methods for automatic analysis and classification of electrocardiosignals. Youth and Science - 2021: proceedings of the international scientific and practical conference. – Petropavlovsk: M. Kozybayev NKU, 2021. – P. 380-383.

8. Seydakhmetov B.K., Koshekov K.T., Savostin A.A., Anayatova R.K., Largin A.V. Automatic recognition of the speaker's psychoemotional state using deep learning technology. Digital Transformation 2021: conference proceedings. – Almaty: Academy of Civil Aviation, 2021. – P. 28-31.

9. Certificate of entry of information into the state register of rights to objects protected by copyright. No. 29850 dated October 31, 2022. Koshekov K.T., Fedorov I.O., Savostin A.A., Tuleshov A.K., Largin A.V. A method for predicting blood pressure levels based on electrocardiogram and photoplethysmogram signals.