IRSTI 20.23.27
https://doi.org/10.56132/2791-3368-2026-2-66-162-179

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DEVELOPMENT OF A HARDWARE ARCHITECTURE FOR AN UPPER-LIMB BIONIC PROSTHESIS CONTROL SYSTEM FOR MILITARY AND CIVILIAN REHABILITATION APPLICATIONS

Abstract. This paper presents the development of a hardware architecture for a control system of an upper-limb bionic prosthesis based on surface electromyography (EMG). The proposed system is intended for acquisition, amplification, filtering, and digitization of bioelectrical signals generated by skeletal muscles to provide reliable input data for prosthetic control algorithms. The designed hardware architecture includes an instrumentation amplifier for acquiring low-amplitude EMG signals, an active common-mode interference suppression circuit to reduce external noise, an active band-pass filter with a passband of 60–500 Hz to isolate the informative frequency range of the EMG signal, an adjustable gain stage, and a high-resolution sigma–delta analog-to-digital converter (ADC) for signal digitization.

The relevance of the proposed solution is driven by the increasing need for advanced prosthetic and rehabilitation technologies for civilian patients and military personnel with upper-limb amputations resulting from trauma and combat-related injuries. The developed hardware architecture provides a reliable platform for biosignal acquisition and processing in rehabilitation-oriented prosthetic systems, supporting restoration of motor functions and improvement of functional independence.

To evaluate the performance of the proposed architecture, circuit modeling was performed in the Multisim simulation environment. Real EMG recordings obtained from the PhysioNet biomedical signal database were used as input signals. In addition, synthetic disturbances, including 50 Hz power-line interference and low-frequency respiratory artifacts, were introduced to simulate realistic operating conditions. The simulation results demonstrated effective suppression of undesirable harmonics while preserving informative spectral components of the EMG signal.

A component-level analysis was conducted considering parameters such as input impedance, noise characteristics, power consumption, and physical dimensions. The developed architecture is characterized by modularity, adjustable amplification capability, energy efficiency, and scalability for multi-channel implementations.

The proposed solution can be applied in development of autonomous upper-limb bionic prostheses for medical rehabilitation of civilian patients and military personnel and can serve as a hardware platform for integration of intelligent control algorithms in advanced prosthetic systems.

Keywords: surface electromyography (EMG), bionic prosthesis, hardware architecture, medical rehabilitation, military medicine, rehabilitation technologies, upper-limb prosthetics, interference suppression, sigma–delta analog-to-digital converter.

Introduction.

The restoration of lost upper limb functions remains one of the major challenges in modern biomedical engineering and rehabilitation technology. Bionic prostheses controlled by bioelectrical muscle signals significantly improve the level of social adaptation and quality of life of patients after limb amputation [1-7], [10], [11].

Surface electromyography (EMG), which reflects the bioelectrical activity of muscle fibers, is considered one of the most informative sources of control signals for such systems [7]. The amplitude of EMG signals typically ranges from several to hundreds of microvolts [8], which imposes strict requirements on the hardware design of the signal acquisition system. The main technical challenges include a low signal-to-noise ratio, the presence of industrial power-line interference, baseline drift, and motion artifacts that may significantly distort the recorded signal [9-11].

The aim of this study is to design and experimentally validate the hardware architecture of a control system for an upper-limb bionic prosthesis capable of ensuring stable acquisition and preprocessing of EMG signals for subsequent control of the prosthetic actuator.

This research also contributes to the achievement of the United Nations Sustainable Development Goals (SDGs):

1) SDG 3 — ensuring healthy lives and promoting well-being for people of all ages through the development of accessible and effective rehabilitation technologies.

2) SDG 10 — reducing inequality within and among countries by developing affordable bionic prosthetic solutions that can be implemented in resource-limited environments.

Materials and Methods.

The hardware architecture of the control system for an upper-limb bionic prosthesis was developed using a systems engineering approach. Biopotential acquisition was performed using silver–silver chloride electrodes. The recorded signal was applied to an instrumentation amplifier (AD623 or INA114), providing high input impedance and effective common-mode rejection. The amplified signal was then processed by a second-order active band-pass filter with a passband of

60–500 Hz, followed by an adjustable gain stage with a gain range of 2–202×. Signal digitization was carried out using a 24-bit medical-grade sigma–delta analog-to-digital converter (ADC).

Circuit-level modeling and verification were performed in the Multisim simulation environment. AC Sweep and Transient Analysis were used to evaluate the gain characteristics, filter bandwidth, and the effectiveness of interference suppression.

Real EMG signals obtained from the PhysioNet biomedical signal database, including recordings with myopathy characteristics, were used as reference input data. In addition, synthetic disturbances were introduced to simulate realistic operating conditions, including 50 Hz power-line harmonic and low-frequency artifacts in the range of 0.5–3 Hz.

The analysis included the evaluation of the amplitude–frequency response, signal-to-noise ratio, and verification of the stable operation of the LM317 voltage regulator used in the power supply stage. A comparative analysis of the selected electronic components was conducted considering parameters such as input impedance, noise characteristics, power consumption, cost, and physical dimensions.

An analysis of existing commercial prosthetic systems, including bebionic (Ottobock), revealed limitations associated with closed hardware architectures and highlighted the need for the development of a scalable modular platform. The applied methodological approach ensures compliance with international standards for EMG signal acquisition and enables further scaling of the system to multi-channel configurations.

Results.

Modern commercial prosthetic systems, such as bebionic, developed by Ottobock, employ highly integrated electronic modules with a closed hardware architecture. Despite their high functionality, such solutions are characterized by high cost and limited possibilities for modification and customization.

In this regard, an important task is the development of a proprietary hardware architecture for a control system of a bionic prosthesis aimed at:

- stable acquisition of low-amplitude EMG signals;
- effective suppression of common-mode and industrial interference;
- adjustable signal amplification;
- high-precision analog-to-digital conversion;
- energy efficiency and autonomous operation;
- the possibility of multi-channel scalability.

Within the framework of this study, a hardware architecture of a control system for an upper-limb bionic prosthesis based on surface electromyography was developed.

Development of the Functional Diagram.

During the development of the hardware part of the control system for a bionic hand prosthesis, a functional diagram of biosignal processing was designed.

The functional diagram reflects the main stages of signal conversion, filtering, and amplification of signals received from the sensors (Fig. 1).

The functional diagram of the system includes the following groups:

- preamplification stage;
- filtering stage;
- amplification stage;
- protection stage;
- control stage;
- actuation stage;
- power supply stage.

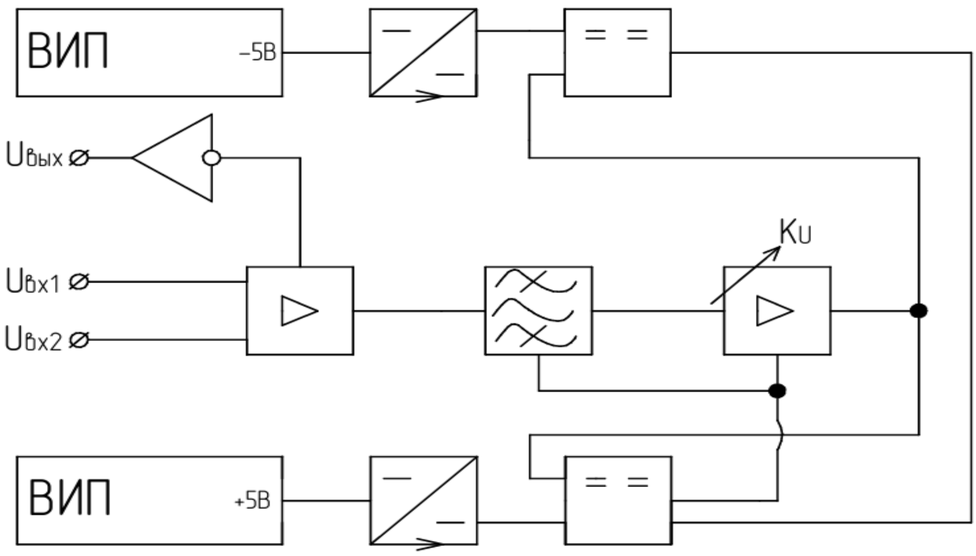

Figure 1 - Functional diagram of the bionic hand prosthesis

Biopotential acquisition is performed using silver–silver chloride electrodes. The signal is applied to an instrumentation amplifier that provides high input impedance and effective common-mode rejection [3-4].

The signal then passes through an active band-pass filter that limits the frequency range to 60–500 Hz [8]. After filtering, additional adjustable amplification is performed. Signal digitization is carried out by a dedicated analog-to-digital converter chip, after which the digital data are transmitted to a microcontroller for processing and for generating a control signal for the actuator (Figure 2) [2].

The system power supply is implemented using linear voltage regulators and an auxiliary inverting converter to generate the negative supply voltage.

Selection of Electronic Components.

The AD623 and INA114 models were considered. The key selection parameters included input impedance, bias current, power consumption, and cost (Table 1) [3], [4].

Table 1 - Characteristics of instrumentation amplifiers

Parameters	AD623ARZ-R7	AD623ARMZ-REEL7	INA114AU
Manufacturer	Analog Devices		Texas Instruments
Package	SOIC-8	MSOP-8	SOIC-16
Input impedance, GΩ	0.1	0.1	10
Input bias current, nA	17	17	2
Input offset voltage, μV	25	200	50
Output current, mA	5	1	30
Quiescent current, mA	0.375	0.375	3
Price, KZT	2610	3200	21300

During the experiments, both microcircuits were used. The instrumentation amplifier provides an initial gain of approximately 10, which prevents saturation of the subsequent stages.

For the implementation of the filter and the final amplification stage, an operational amplifier with a wide bandwidth and low noise level was used. The selection was based on the analysis of frequency response, output current, and operational stability under dual power supply conditions.

Two sigma–delta ADC options were considered: a single-channel and a multi-channel version. Both devices provide a 24-bit resolution [5].

The multi-channel solution ensures system scalability but has greater connection complexity. Both variants were experimentally tested to evaluate their suitability for use in scalable systems.

A stepper motor and a servo drive were considered as actuator mechanisms.

The servo drive was selected due to its compact size, ease of control, and the absence of a need for an external driver. This made it possible to reduce the dimensions of the control board.

Electrical Circuit Calculations.

The gain of the instrumentation amplifier is determined by the following expression:

$$G = 1 + \frac{100\text{k}\Omega}{R_G}. \tag{1}$$

To obtain a gain of 10, a resistor with the corresponding value was selected from the E96 series.

The band-pass filter defines the operating frequency range of 60–500 Hz. The lower cutoff frequency suppresses baseline drift and physiological low-frequency interference, while the upper cutoff frequency limits the influence of high-frequency noise [1], [2], [8], [9].

The cutoff frequencies are determined by the following expression:

$$f = \frac{1}{2\pi RC.} \quad (2)$$

Simulation results showed that the actual passband ranges from 61 to 485 Hz, which corresponds to the calculated design requirements (Figure 2) [2].

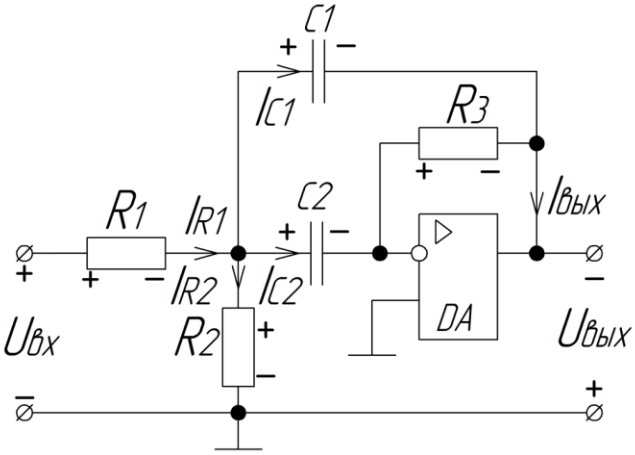

Figure 2 - Band-pass filter circuit diagram

The final amplifier is implemented as a scaling inverting amplifier with an adjustable gain factor (Figure 3).

$$K = 1 + \frac{R_2 + R_{var}}{R_1} \ . \quad (3)$$

The gain range is 2–202, which enables the system to be adapted to the individual characteristics of the user.

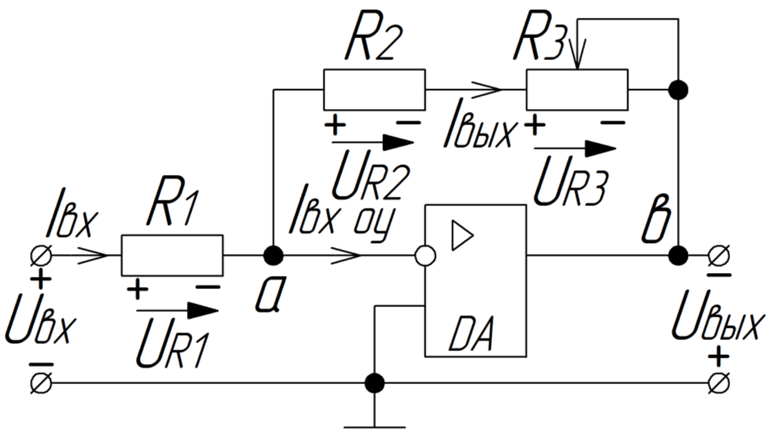

Figure 3 - Final amplifier circuit diagram

To improve noise immunity, an active common-mode interference suppression circuit was implemented (Figure 4). The operating principle is based on the inversion of the common component of the signal and its feedback through the reference electrode, which corresponds to the principle of active common-mode interference suppression [9].

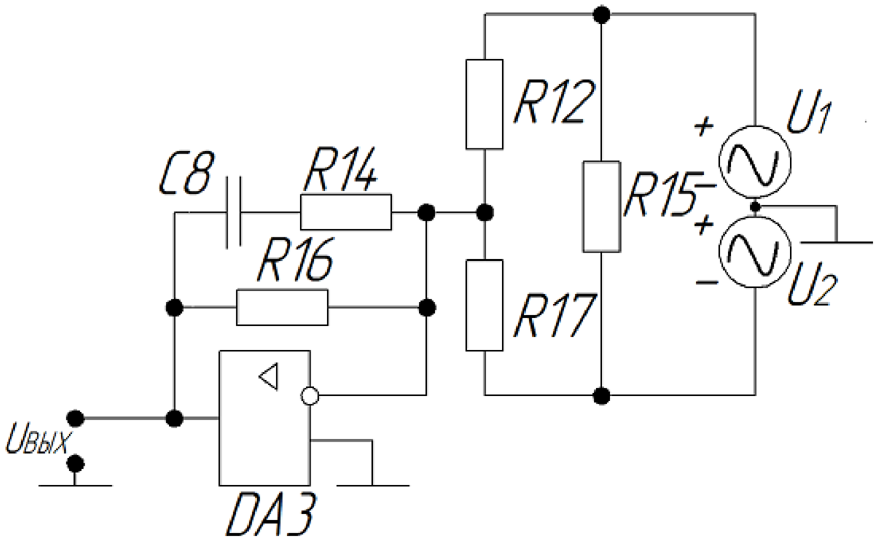

Figure 4 Common-mode interference suppression circuit

To generate a 3.3 V output from a 5 V supply, a linear voltage regulator was used (Figure 5). The resistor values were calculated using the standard formula:

$$V_{out} = 1{,}25\left(1+\frac{R_2}{R_1}\right) \quad . \qquad (4)$$

Simulation confirmed the correctness of the selected component values.

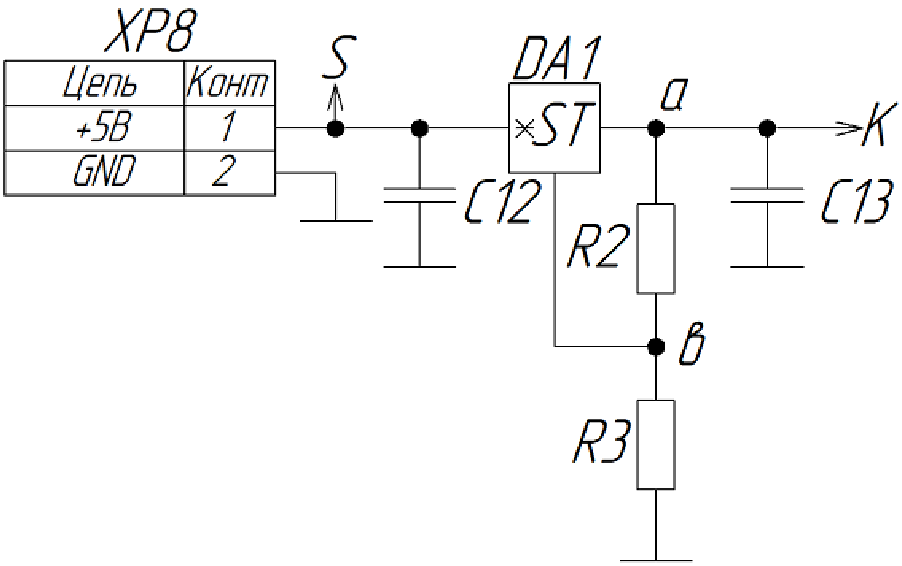

Figure 5 - LM317 voltage regulator circuit diagram

Simulation in the Multisim Environment.

For the experimental verification of the operability of the developed circuit, the Multisim circuit simulation environment was used. The software package has

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an extensive component library, supports various types of analysis (AC Sweep and Transient Analysis), and allows the use of custom signal waveforms.

A digitized electromyogram from the PhysioNet database [6], containing signs of myopathy, was used as a reference biosignal. Myopathy is characterized by reduced muscle strength and changes in the structure of the electromyographic signal, which makes it possible to evaluate the robustness of the developed system when working with real clinical data [7].

One of the main problems in the registration of biopotentials is the influence of industrial power-line interference at a frequency of 50 Hz, the amplitude of which may significantly exceed the amplitude of the useful signal. To reduce the impact of this interference, frequency-selective circuits were integrated into the structure of the electromyographic sensor to suppress unwanted harmonics while allowing the useful signal frequency range to pass [2].

In the electrical circuit calculation section, an active band-pass filter with a designed passband of 60–500 Hz was synthesized. To verify the correctness of the calculations, the amplitude–frequency response (AFR) was simulated using the AC Sweep analysis tool.

The analysis of the ratio of the output signal to the input signal showed that the actual passband ranges from 61 to 485 Hz, which corresponds to the specified design requirements (Figure 6). The lower cutoff frequency suppresses low-frequency baseline drift, while the upper cutoff frequency limits high-frequency noise [1].

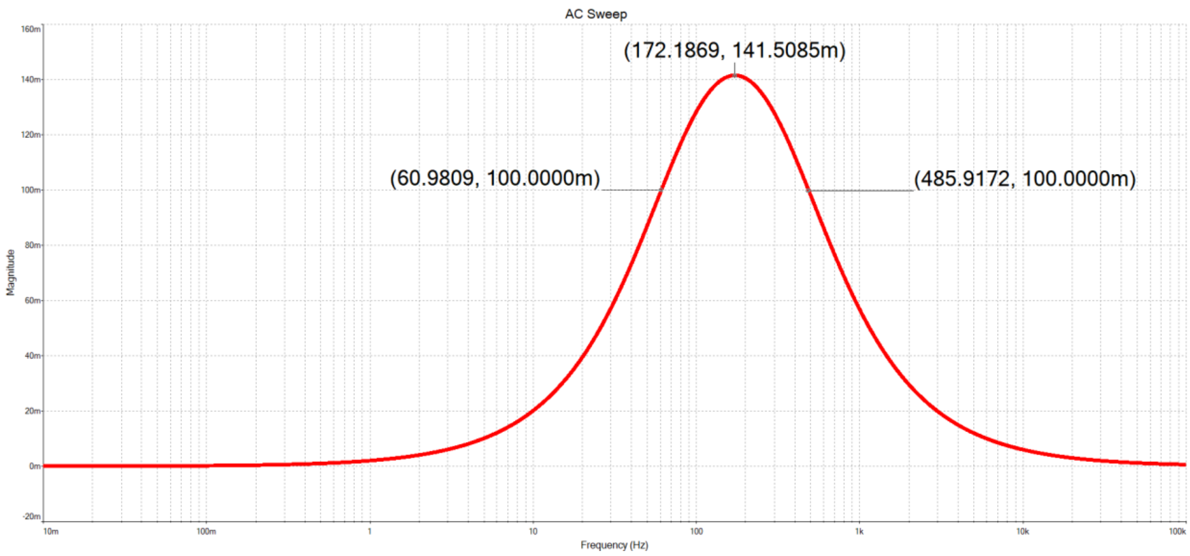

Figure 6 - Amplitude–frequency response of the band-pass filter

To increase the steepness of the amplitude response, a modified circuit with an additional reactive element was implemented, resulting in a second-order filter (Figure7). Simulation showed that the slope increased to −40 dB per decade, which corresponds to the theoretical characteristics of a second-order filter and improves the suppression of power-line interference (Figure 8) [2].

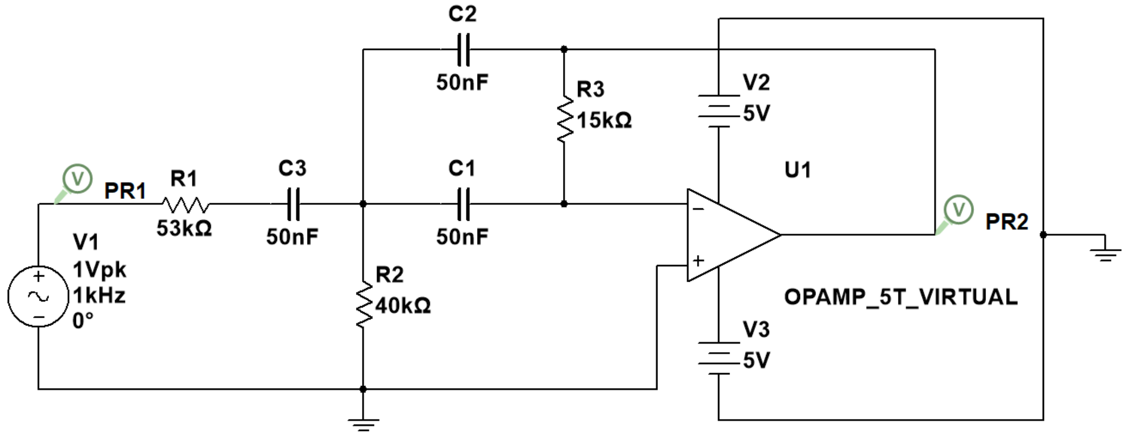

Figure 7 - Second-order band-pass filter

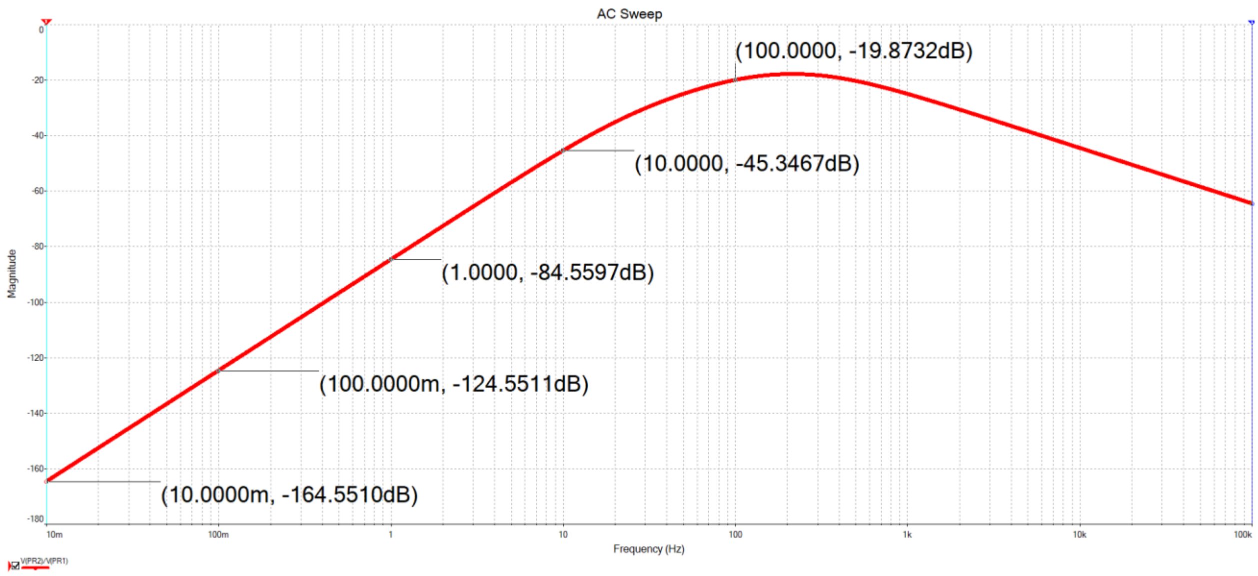

Figure 8 - Amplitude–frequency response of the second-order band-pass filter

To verify the correctness of the calculations, a simulation of a linear voltage regulator based on the LM317 microcircuit was performed (Figure 9). The purpose of the regulator is to convert the input voltage of +5 V into a stabilized output voltage of +3.3 V for powering the digital part of the system.

The simulation results confirmed the formation of an output voltage of 3.3 V, indicating the correctness of the selected resistive divider and the accuracy of the calculated parameters.

The complete circuit of the electromyographic sensor was implemented in the Multisim environment to analyze the signal behavior after each functional stage.

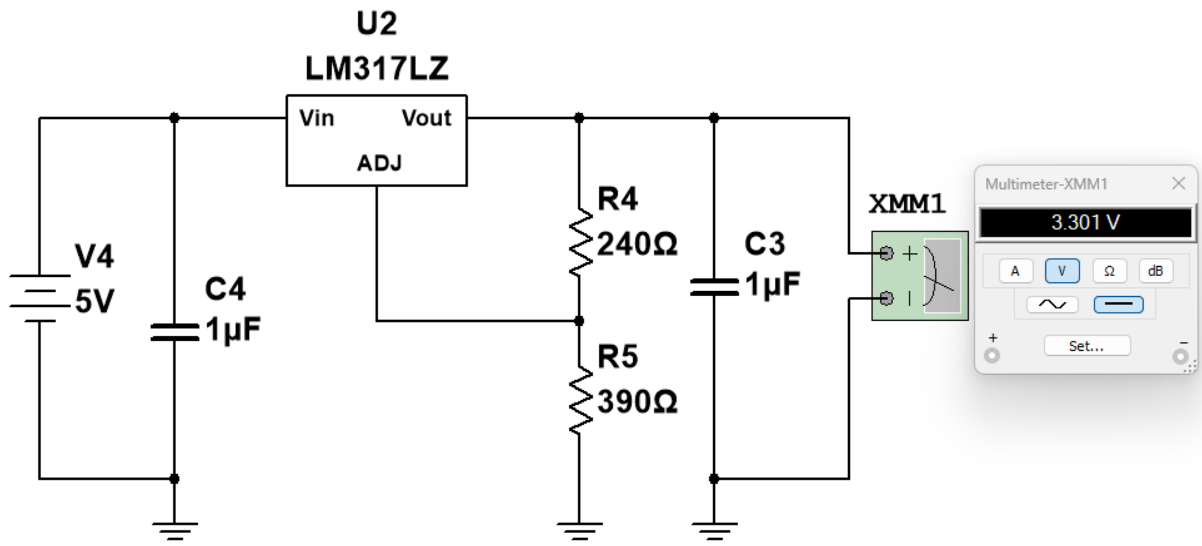

Figure 9 - Simulation of the voltage regulator in the Multisim environment.

A reference electromyographic signal loaded from the PhysioNet database was used as the input stimulus (Figure 10) [6].

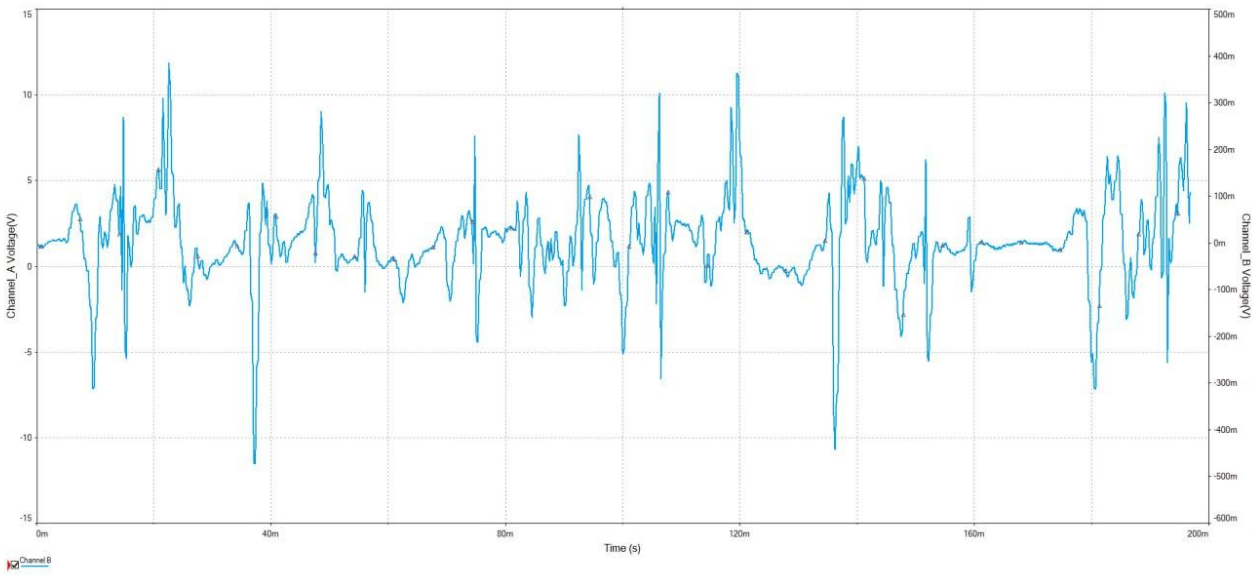

Figure 10 - Electromyographic signal from the PhysioNet database

To approximate the model to real signal acquisition conditions, two main interference components were added to the signal:

– a sinusoidal harmonic of the industrial power frequency of 50 Hz with an amplitude of 2 V, simulating power-line interference (Figure 11);

– a low-frequency signal in the range of 0.5–3 Hz, simulating respiratory and physiological interference that causes baseline drift (Figure 12).

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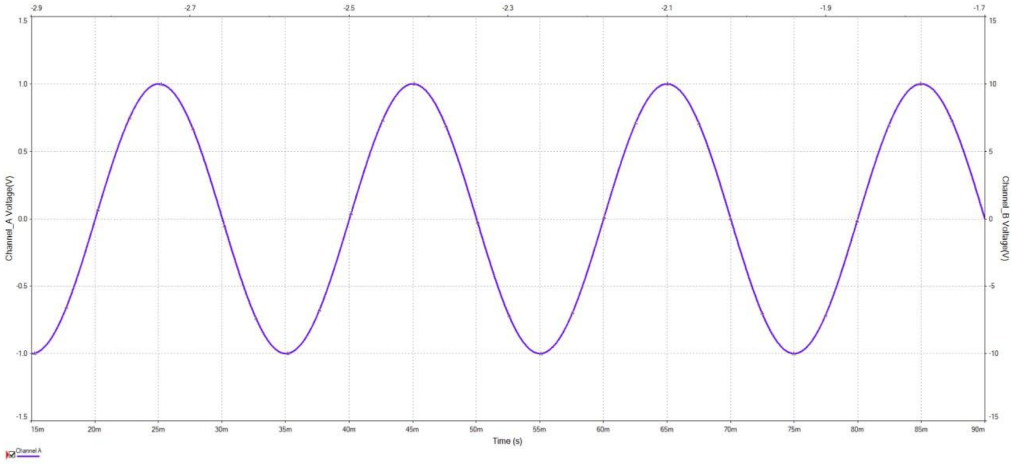

Figure 11 - Sinusoidal signal simulating power-line interference

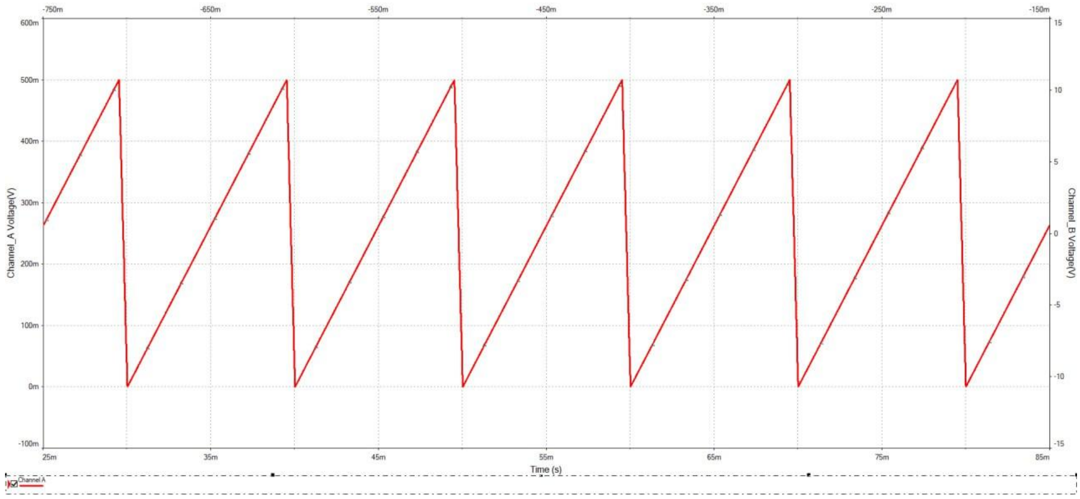

Figure 12 - Sawtooth signal simulating respiratory interference

The signals were summed using an operational amplifier–based summing circuit, which made it possible to obtain a noisy electromyographic signal approximating real acquisition conditions (Figure 13).

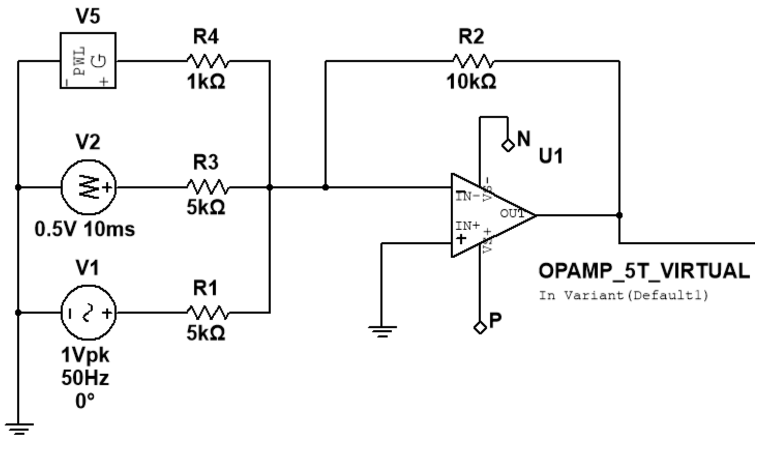

Figure 13 - Operational amplifier summing circuit

At the next stage, the operation of the second-order band-pass filter was simulated. The analysis revealed two suppression bands: below 60 Hz and above 485 Hz. Thus, effective suppression of respiratory and power-line interference is achieved while preserving the useful signal spectrum [8].

A comparison of the noisy signal waveform (Fig. 14) and the signal after filtering (Fig. 15) demonstrated a significant reduction in the amplitude of unwanted harmonics and stabilization of the baseline.

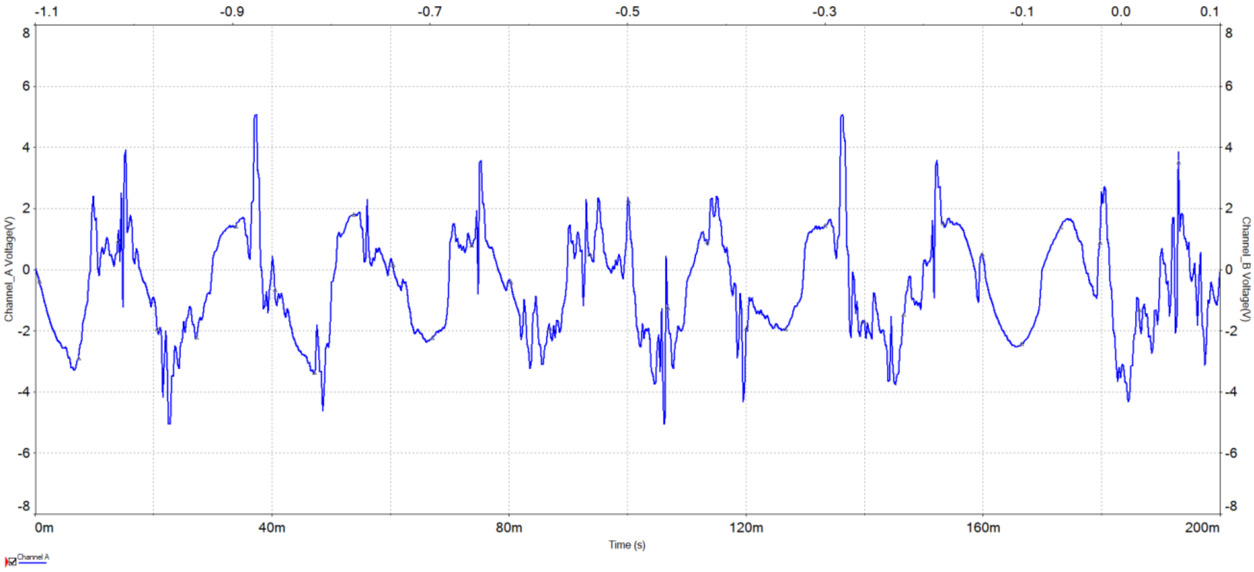

Figure 14 - Noisy electromyographic signal

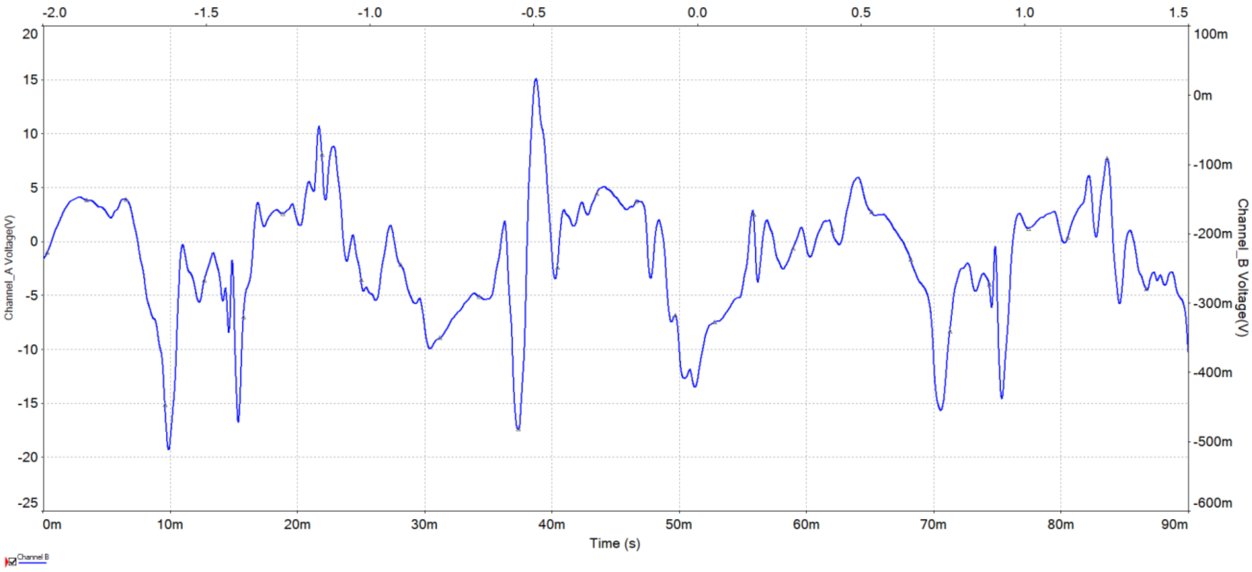

Figure 15 - Signal obtained at the filter output

At the final stage, the operation of the final amplification stage was verified. Oscilloscope simulation showed an increase in the amplitude of the output signal and a phase shift characteristic of an inverting amplifier circuit (Fig. 16). The obtained results confirm the correct operation of the amplification stage and its compliance with the calculated parameters.

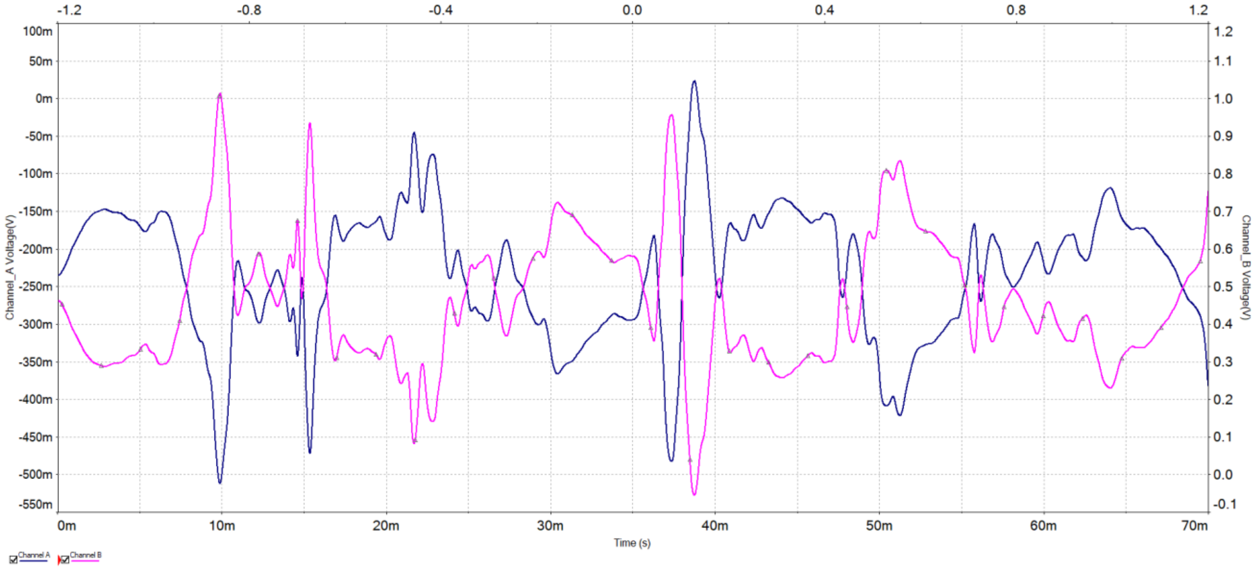

Figure 16 - Signal at the output of the final amplifier

Discussion.

In this study, hardware architecture for the control system of an upper-limb bionic prosthesis based on the acquisition and processing of surface electromyographic signals was developed. The functional architecture includes a preamplification stage based on an instrumentation amplifier, a common-mode interference suppression circuit, active band-pass filtering, an adjustable amplification stage, analog-to-digital conversion, and a stabilized power supply system. Similar hardware solutions are widely used in the development of control systems for bionic prostheses based on EMG signal analysis.

A component-level selection was carried out considering parameters such as input impedance, noise level, current consumption, and physical dimensions. The use of a high-resolution medical-grade sigma–delta analog-to-digital converter was justified to ensure the required dynamic range for EMG signal acquisition. Circuit simulation performed in the Multisim environment confirmed the correctness of the selected component values, the effectiveness of low-frequency and power-line interference suppression, and compliance with the calculated requirements for filter bandwidth and amplification gain.

The proposed design also takes into account practical aspects of system operation, including the modularity of the architecture, the possibility of adjusting the gain according to the individual characteristics of the user, and the potential for scaling the system to multi-channel control. The effectiveness of filtering and amplification was confirmed through simulation using real EMG signals from the PhysioNet database [6] and synthetic disturbances, including 50 Hz power-line interference and low-frequency artifacts in the range of 0.5–3 Hz.

Conclusion.

The developed control system for the upper-limb bionic prosthesis demonstrates high adaptability, energy efficiency, and accurate acquisition of EMG signals. The results of the study indicate the feasibility of using the proposed architecture for the development of prototype autonomous bionic prostheses and for the further integration of intelligent algorithms for the recognition of motor intentions.

The modular structure and the adjustable amplification stage provide system flexibility and the potential for scalability, making the architecture suitable for the further development of multi-channel prosthetic systems with an open hardware platform. The obtained results may serve as a foundation for future research in the field of intelligent control of bionic prostheses and the development of multi-channel myoelectric control systems.

Funding

The work was carried out at the Non-profit Joint Stock Company “K.I. Satbayev Kazakh National Research Technical University” within the framework of budget program 217 “Science Development”, subprogram 101 “Program-Targeted Funding of Scientific and/or Scientific-Technical Activities”.

The research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan under the program IRN BR24992820 “Innovative medical technologies and devices for improving surgical interventions in prosthetics and rehabilitation in orthopedics and medical rehabilitation.”

Acknowledgements

The authors express their gratitude to the research team of the project and to all colleagues who provided scientific, methodological, and organizational support during the course of this study.

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ӘСКЕРИ ЖӘНЕ АЗАМАТТЫҚ ОҢАЛТУ МАҚСАТТАРЫНА АРНАЛҒАН ЖОҒАРҒЫ АЯҚ-ҚОЛДЫҢ БИОНИКАЛЫҚ ПРОТЕЗІН БАСҚАРУ ЖҮЙЕСІНІҢ АППАРАТТЫҚ АРХИТЕКТУРАСЫН ӘЗІРЛЕУ

Аңдатпа. Бұл мақалада беттік электромиография (ЭМГ) негізінде жоғарғы аяқ-қолдың бионикалық протезін басқару жүйесінің аппараттық архитектурасын әзірлеу қарастырылған. Ұсынылған жүйе қаңқа бұлшықеттері өндіретін биоэлектрлік сигналдарды тіркеуге, күшейтуге, сүзгілеуге және цифрландыруға арналған, бұл протезді басқару алгоритмдері үшін сенімді кіріс деректерін қамтамасыз етеді. Әзірленген аппараттық архитектура құрамына төмен амплитудалы ЭМГ сигналдарын қабылдауға арналған аспаптық күшейткіш, сыртқы шуды азайту үшін синфазалық кедергілерді белсенді басу схемасы, ЭМГ сигналының ақпараттық жиілік диапазонын бөліп көрсетуге арналған өткізу жолағы 60–500 Гц болатын

белсенді жолақтық сүзгі, күшейту коэффициенті реттелетін каскад және сигналдарды цифрландыруға арналған жоғары дәлдікті сигма-дельта аналогтық-цифрлық түрлендіргіш (АЦТ) кіреді.

Ұсынылып отырған шешімнің өзектілігі жарақаттар мен жауынгерлік зақымданулар салдарынан жоғарғы аяқ-қолынан айырылған азаматтық пациенттер мен әскери қызметкерлерге арналған заманауи протездеу және оңалту технологияларына деген қажеттіліктің артуымен байланысты. Әзірленген аппараттық архитектура оңалтуға бағытталған протездік жүйелерде биосигналдарды тіркеу мен өңдеудің сенімді платформасын қамтамасыз етіп, қозғалыс функцияларын қалпына келтіруге және пайдаланушылардың функционалдық тәуелсіздігін арттыруға ықпал етеді.

Ұсынылған архитектураның тиімділігін бағалау мақсатында Multisim модельдеу ортасында схемотехникалық модельдеу жүргізілді. Кіріс сигналдары ретінде PhysioNet биомедициналық сигналдар дерекқорынан алынған нақты ЭМГ жазбалары пайдаланылды. Сонымен қатар, нақты пайдалану жағдайларын модельдеу үшін сигналға 50 Гц жиіліктегі электр желісінің кедергілері мен төмен жиілікті тыныс алу артефактілері сияқты жасанды бұрмаланулар енгізілді. Модельдеу нәтижелері ЭМГ сигналының ақпараттық спектрлік құрамдастарын сақтай отырып, қажетсіз гармоникаларды тиімді басуды көрсетті.

Элементтік базаға кіретін компоненттерге кіріс кедергісі, шу сипаттамалары, қуат тұтынуы және габариттік өлшемдері сияқты параметрлер бойынша талдау жүргізілді. Әзірленген архитектура модульділігімен, күшейту коэффициентін реттеу мүмкіндігімен, энергия тиімділігімен және көпарналы жүйелерге бейімделу мүмкіндігімен ерекшеленеді.

Ұсынылған шешім азаматтық пациенттер мен әскери қызметкерлерді медициналық оңалтуға арналған автономды жоғарғы аяқ-қол бионикалық протездерін әзірлеуде қолданылуы мүмкін, сондай-ақ заманауи протездік жүйелерге интеллектуалды басқару алгоритмдерін енгізуге арналған аппараттық платформа ретінде қызмет атқара алады.

Түйінді сөздер: беттік электромиография (ЭМГ), бионикалық протез, аппараттық архитектура, медициналық оңалту, әскери медицина, оңалту технологиялары, жоғарғы аяқ-қол протездеуі, кедергілерді басу, сигма-дельта аналогтық-цифрлық түрлендіргіш

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РАЗРАБОТКА АППАРАТНОЙ АРХИТЕКТУРЫ СИСТЕМЫ УПРАВЛЕНИЯ БИОНИЧЕСКИМ ПРОТЕЗОМ ВЕРХНЕЙ КОНЕЧНОСТИ ДЛЯ ПРИМЕНЕНИЯ В ВОЕННОЙ И ГРАЖДАНСКОЙ РЕАБИЛИТАЦИИ

Аннотация. В данной статье представлена разработка аппаратной архитектуры системы управления бионическим протезом верхней конечности на основе поверхностной электромиографии (ЭМГ). Предлагаемая система предназначена для регистрации, усиления, фильтрации и оцифровки биоэлектрических сигналов, генерируемых скелетными мышцами, с целью обеспечения надежных входных данных для алгоритмов управления протезом. Разработанная аппаратная архитектура включает инструментальный усилитель для регистрации низкоамплитудных ЭМГ-сигналов, схему активного подавления синфазных помех для снижения внешних шумов, активный полосовой фильтр с полосой пропускания 60–500 Гц для выделения информативного частотного диапазона ЭМГ-сигнала, каскад регулируемого усиления и высокоточный сигма-дельта аналого-цифровой преобразователь (АЦП) для оцифровки сигналов.

Актуальность предлагаемого решения обусловлена возрастающей потребностью в современных протезно-реабилитационных технологиях для гражданских пациентов и военнослужащих с ампутациями верхних конечностей, вызванными травмами и боевыми повреждениями. Разработанная аппаратная архитектура обеспечивает надежную платформу для регистрации и обработки биосигналов в реабилитационно-ориентированных протезных системах, способствуя восстановлению двигательных функций и повышению функциональной независимости пациентов.

Для оценки эффективности предложенной архитектуры было выполнено схемотехническое моделирование в среде Multisim. В качестве входных сигналов использовались реальные записи ЭМГ, полученные из базы биомедицинских сигналов PhysioNet. Дополнительно для моделирования условий, приближенных к реальной эксплуатации, в сигнал были внесены искусственные помехи, включая сетевые наводки частотой 50 Гц и низкочастотные дыхательные артефакты. Результаты моделирования продемонстрировали эффективное подавление нежелательных гармонических составляющих при сохранении информативных спектральных компонентов ЭМГ-сигнала.

Проведен анализ элементной базы с учетом таких параметров, как входное сопротивление, шумовые характеристики, энергопотребление и габаритные размеры компонентов. Разработанная архитектура характеризуется модульностью, возможностью регулировки коэффициента усиления, энергоэффективностью и масштабируемостью для многоканальных реализаций.

Предлагаемое решение может быть использовано при разработке автономных бионических протезов верхних конечностей для медицинской реабилитации гражданских пациентов и военнослужащих, а также служить аппаратной платформой для интеграции интеллектуальных алгоритмов управления в современные протезные системы.

Ключевые слова: поверхностная электромиография (ЭМГ), бионический протез, аппаратная архитектура, медицинская реабилитация, военная медицина, реабилитационные технологии, протезирование верхних конечностей, подавление помех, сигма-дельта аналого-цифровой преобразователь (АЦП).

Received: June 02, 2026
Peer-reviewed: June 29, 2026
Accepted: June 29, 2026