Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2025, № 3 (119) https://doi.org/10.33108/visnyk_tntu2025.03
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 612.741.1

STRUCTURE OF THE BIONIC HAND PROSTHESIS CONTROL SYSTEM WITH SENSOR FEEDBACK

Leonid Dediv; Serhii Kovalyk

Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

Abstract. *The article analyzes the state of the problem of creating highly functional bionic prostheses and the relevance of creating an adaptive control system for such prostheses based on the results of biosignal processing is shown. The advantages and disadvantages of the method of direct signals registration from the motor departments of the human cerebral cortex, the use of specialized so-called nerve cuffs to receive signals directly from peripheral nerve fibers, as well as implanted electrodes and registration of surface electromyographic signals (sEMG) were considered. Taking into account the non-invasiveness, safety and simplicity of technical implementation, the sEMG registration method was used as the basis for the work of the designed system. However, to increase the informativeness of the source material and the possibility of isolating a greater number of informative signs of individual phantom movements, it is proposed to use a multi-electrode system, and to ensure the adaptability of the prosthesis, it is proposed to implement sensory feedback in the proposed control system structure. For this purpose, it is proposed to use signals from tactile sensors, which will be placed at the prosthesis fingers ends. The structure of the control system is proposed, which includes two related data exchange channels and four main elements: a multielectrode system with sEMG sensors; a stump-receiving sleeve with actuators; a smartphone or PC with appropriate software; a bionic prosthesis with a processor module, motor drivers and a module for registering tactile sensors signals. It is proposed to implement the main structural elements, such as the multielectrode system, the stump-receiving sleeve and the bionic prosthesis itself, as separate independent elements that are interconnected via separate wireless data exchange channels. The elements of the multielectrode system for recording sEMG and sensory feedback signals were developed.*
Key words: *sensory feedback, bionic prosthesis, sEMG, stump-receiving sleeve, tactile sensor.*

https://doi.org/10.33108/visnyk_tntu2025.03.045 *Received 16.07.2025*

1. INTRODUCTION

Among all amputations in the world, about a quarter of people undergo amputation of the upper limbs. The number of people with this type of amputation is growing especially rapidly in Ukraine, during the war. Amputation of the hand seriously impairs people's daily activities, in particular due to the loss of mobility and sensory perception. At the same time, there is an increase in demand for highly functional upper limb prostheses. Classic prostheses with drives from the body, which are moved by traction systems, despite their relative availability, have very limited functional capabilities, in particular regarding the number of movements performed, dexterity, compensation for lost fine motor skills of both the entire hand and individual fingers, the ability to sense external objects, etc. [1].

A promising alternative is the use of bionic prostheses, which are a complex biomechatronic system - a combination of the prosthesis mechanical design with electric drives and a system for registering and processing biosignals with the subsequent formation of corresponding electric drives control signals [2, 3]. At the same time, developers use different approaches to implementing the prosthesis mechanical design, biosignals registering methods, types of biosignals (based on which the prosthesis is controlled), methods of processing these biosignals and forming signals to control the prosthesis electric drives. As a result, various types of bionic prostheses available on the market of technical rehabilitation equipment differ in functionality, cost, duration of patient adaptation, etc.

Particularly difficult in terms of subsequent technical implementation is the task of creating an effective control system for a bionic prosthesis with maximum approximation to the functionality of a natural human hand. In this case, it is necessary to use specialized systems for registering biosignals, processing them and forming the prosthesis controlling signals. Here, developers use a number of approaches to organizing the corresponding control systems. The most promising approach is considered to be the one in which signals from the motor areas of the human cerebral cortex are directly registered, since these signals will contain information about the patient's intentions to perform the corresponding movements with the hand (up to the elements of fine motor skills) [4]. However, the main limitation of this approach is the invasiveness of the procedure for obtaining such biosignals, which makes this approach inaccessible to most amputees. This approach is also the most difficult in terms of subsequent biosignals processing, highlighting informative signs of movements in their structure and forming signals for controlling the prosthesis. This is due in particular to the fact that the registered signals will be a complex mixture of electropotential responses of the work of billions of neuronal structures of the cerebral cortex, and not only those responsible for performing hand movements. At the same time, methods for processing these signals should give an unambiguous and repeatable result with minimal time delays. Research in this direction is ongoing.

The next in terms of informativeness is the use of specialized so-called nerve cuffs to receive signals directly from peripheral nerve fibers, as well as implanted electrodes (IMES) (Fig. 1–3) [2, 5].

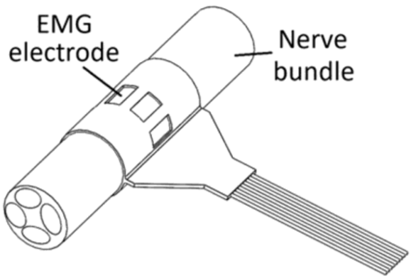


Figure 1. Nerve cuff electrode [2]

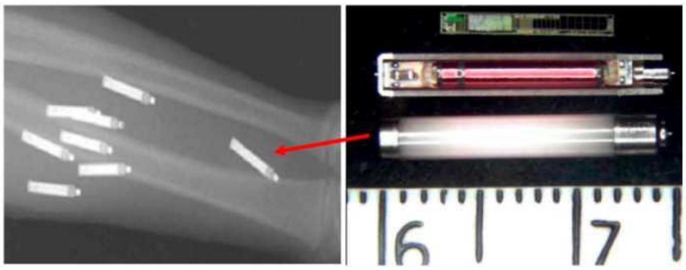


Figure 2. Example of IMES implantation in the arm of a person with an upper limb amputee [2]

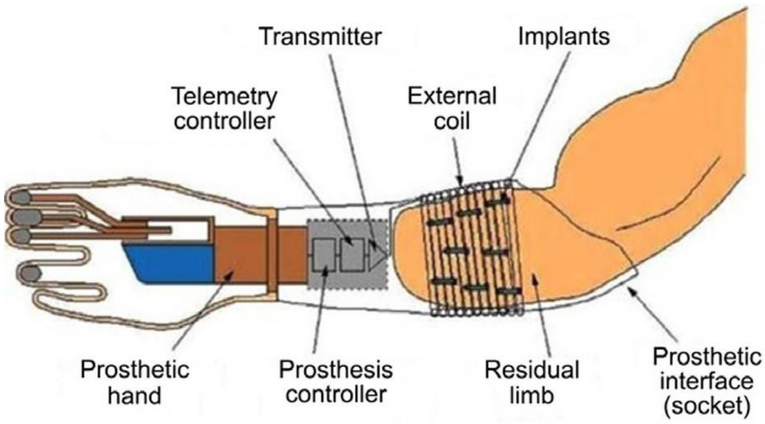


Figure 3. Illustration of the implementation of a bionic prosthesis with IMES [2]

However, the use of such cuffs and IMES also involves surgical interventions, despite the fact that the subsequent processing of the received signals will be simpler, since the information about the phantom movements performed by the patient will be better localized and more pronounced.

Particularly promising (taking into account non-invasiveness and safety) and widespread is the approach based on the use of the surface electromyography (sEMG) method [6–9]. In this case, indirectly, using sEMG electrodes, muscle activity signals are recorded from the skin surface of the arm area remaining after amputation. Most of the available bionic prostheses work on this principle. However, the main difficulty here is to obtain information about fine motor skills when the patient performs phantom movements, since the signals recorded in this way will be the summed responses of those real nerve signals that will flow in anatomically lower nerve fibers.

Also, in all the described approaches there is no so-called sensory feedback, which would provide the prosthesis user with the opportunity to control the moments of touching various objects, the force of prosthesis gripping, control of holding these objects, etc. (in the natural hand this function is performed by groups of receptors, in particular mechanoreceptors).

The actual purpose of the research is to develop the structure of the bionic prosthesis control system based on the registration of a group of sEMG signals and the implementation of sensory feedback.

2. ANALYSIS OF KNOWN TECHNICAL SOLUTIONS

2.1. Methods and means of semg signals recording

In commercially available bionic prostheses, iEMG signals are most often used as an input signali.

Fig. 4 shows the Bebionic stump-receiving sleeve and the 13E200=50/13E200=60 myoelectrodes installed in it [10]. As shown in the schematic image of Fig. 5, two myoelectrodes are used; they send the registered signals via cables to the microprocessors integrated in the prosthesis.

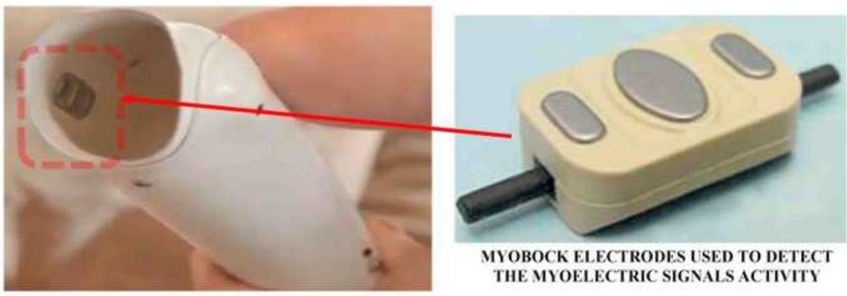


Figure 4. Myoelectrodes (MyoBock) from Ottobock installed in the prosthesis sleeve [10]

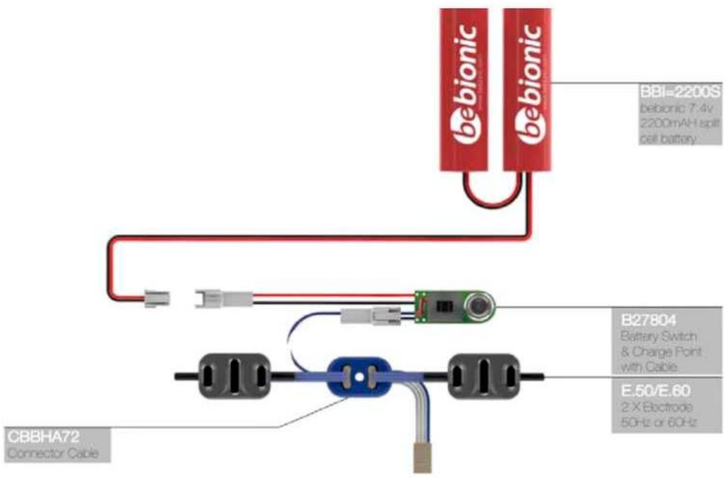


Figure 5. Connection diagram of two myo-electrodes installed in the prosthesis [10]

For better differentiation of fine motor signs in the structure of sEMG signals and, accordingly, the formation of a larger number of bionic prosthesis control signals and, ultimately, increasing its functionality, it is possible to use multi-electrode systems for recording sEMG signals. Thus, the Ottobock company offers a system for recognizing sEMG signal patterns - Myo Plus (Fig. 6) [11]. The system includes a special cuff with electrodes for the actual recording of EMG and a software application that can be installed on a smartphone, tablet or laptop. The latter is designed to process EMG, select signal patterns that correspond to individual movements and adapt these patterns to control bebionic prostheses.

Figure 6. Myo Plus complex [11]

Another example of a multi-electrode sEMG recording system is the Myo Armband [10].

Figure 7. Myo Armband [10]

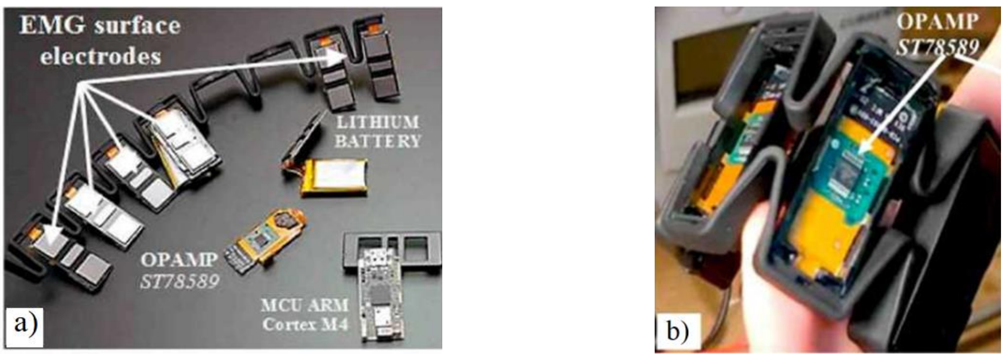


Figure 8. Myo Armband structure (a) and one electrode structure (b) [10]

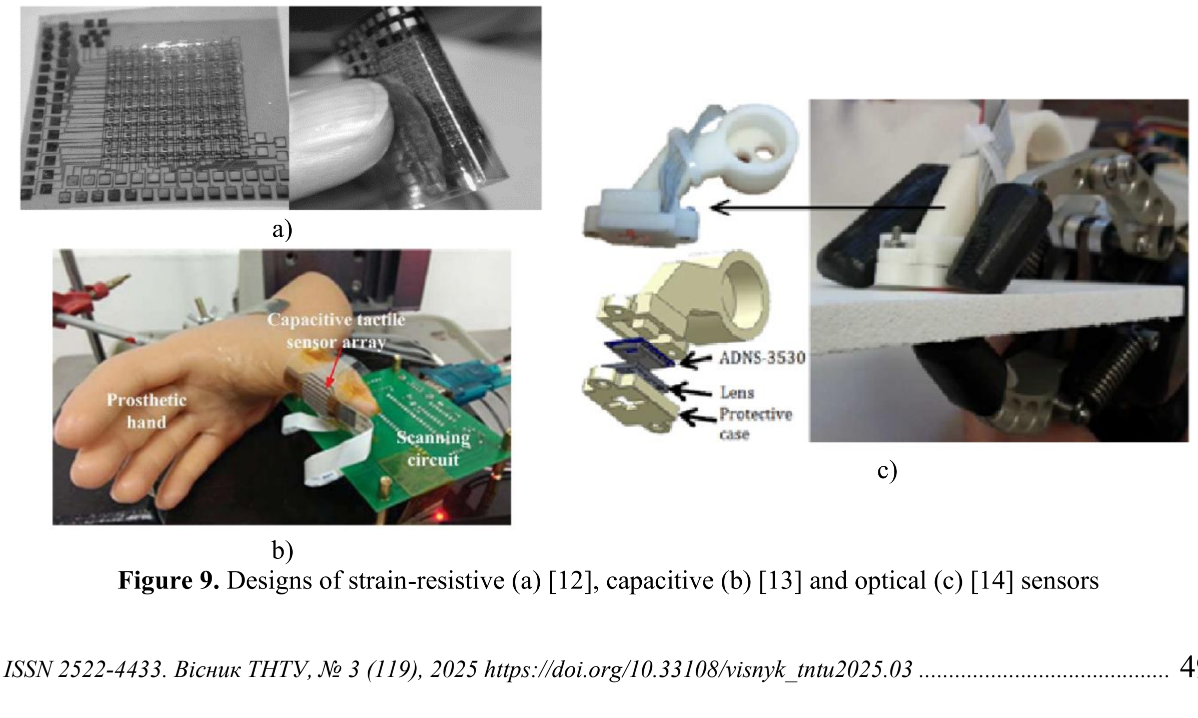
This is a wearable device from Thalmic Labs Inc., equipped with eight EMG electrodes, a 9-axis inertial measurement unit (IMU) (3-axis gyroscope, 3-axis accelerometer and 3-axis magnetometer) and a transmission module [10].

However, existing commercialized cuffs or bracelets with a larger number of EMG electrodes, such as Myo Armband and Myo Plus, have a number of disadvantages. In particular, the first bracelet is quite expensive with a large number of additional functions, including for analyzing the position of the hand in space. These are not portable functions for prosthesis controlling, which significantly increase the cost of the bracelet, reduce the life of the internal batteries and require additional hardware and software for docking with the prosthesis itself. The Myo Plus cuff is bulky and inconvenient for constant use. The main disadvantage of both systems is the electrodes design, which have the form of metal plates with a special coating. Such plates will not adhere well to the skin surface, especially when there is a lot of hair on the arm. Such plates will also be sensitive to perspiration, salts on the skin surface, or contamination. There will also be a significant level of artifacts from hand movements and minor displacements of the electrode plates on the skin surface.

2.2. Sensory feedback implementing approaches

Regarding the task of implementing sensory feedback, it is proposed to use sensors that will be placed inside the fingertips and will perceive dynamic loads when in contact with objects during their capture by the prosthesis. It is the dynamic load sensors that will make it possible to feel the touch of objects by generating the corresponding signals and will not create signals during the process of holding these objects. This will be useful in that the constant generation of signals during the objects holding by the prosthesis will be redundant, and will be important only the determination of the time moment of touching the object with the possibility of subsequent adjustment of the force of capture or holding these objects according to the prosthesis user sEMG signals.

At this stage, individual sensor designs were analyzed that were implemented in prostheses experimental prototypes with tactile sensations. In particular, the designs of strain-resistive, optical, capacitive and piezosensors were considered (Fig. 9). It is the latter type of sensors that are dynamic load sensors, and its advantage is that its output signal will be the change in charge on its surface proportional to the change in load on this surface. No additional nodes or signal type conversion circuits are required here (as, for example, in the case of capacitive sensors, when resonant circuits are required to convert the change in capacitance into a change in an electrical signal). It is enough to install charge amplifiers.



b)

Figure 9. Designs of strain-resistive (a) [12], capacitive (b) [13] and optical (c) [14] sensors

The next stage involved the development of the control system structure for a bionic hand prosthesis with sensory feedback and the practical implementation of its individual components.

3. RESEARCH RESULTS

This article presents the results that are a continuation of the research presented in [15]. In this work, a concept for developing a bionic prosthesis structure was proposed. In particular, it was proposed to organize two independent and oppositely directed data exchange channels and cloud technologies (Fig. 10). Thus, channel 1 is intended for transmitting registered signals from sEMG sensors (located in the stump-receiving sleeve) to a smartphone or PC, where these signals will be processed, and subsequent transmission of the generated control signals to the corresponding drivers of the bionic prosthesis. Return channel 2 is intended for receiving signals from bionic prosthesis tactile sensors, transmitting them to a smartphone or PC, where they will be processed, with subsequent transmission of the signals obtained as a result of processing to actuators located in the stump-receiving sleeve.

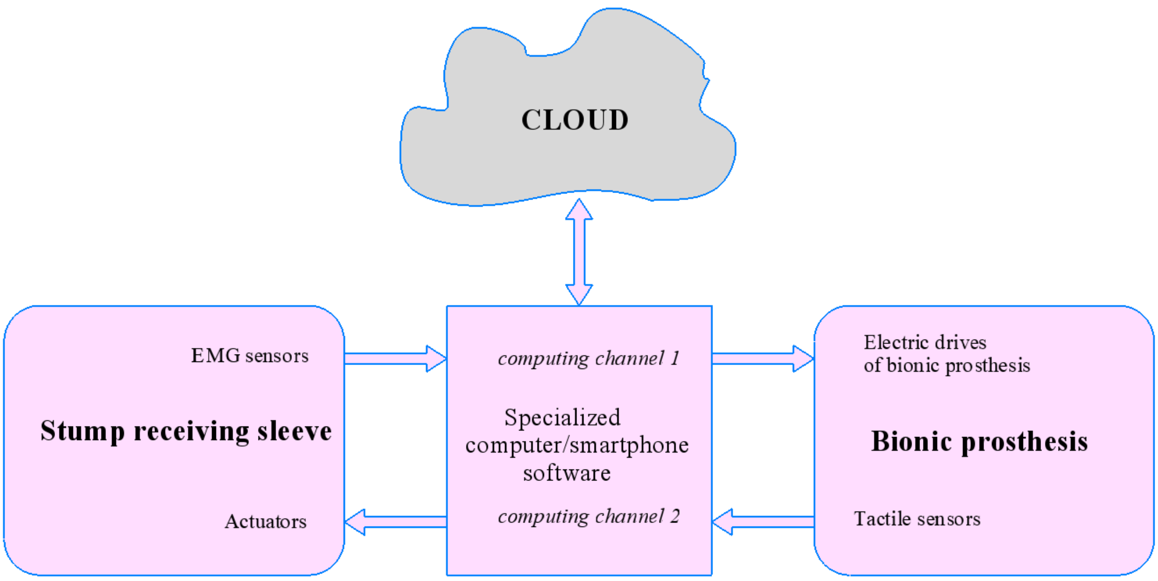


Figure 10. Signal routing structure proposed in [15]

The authors assumed that these two channels would be independent of each other, i.e. the first channel would be intended only for controlling the prosthesis using sEMG, and the second would only provide tactile sensations for the patient. However, there are possible situations when, during the process of object grasping with a prosthesis, the patient will experience other, stronger sensations (for example, pain from squeezing a finger of a healthy hand) and the brain will perceive them first, ignoring the operation of the prosthesis actuators when touching the grasping object. In this case, the patient will not be able to control the process of grasping the object with the prosthesis. Therefore, the structure (Fig. 10) was changed and made adaptive.

The structure of the proposed adaptive control system for a bionic prosthesis is shown in Fig. 11.

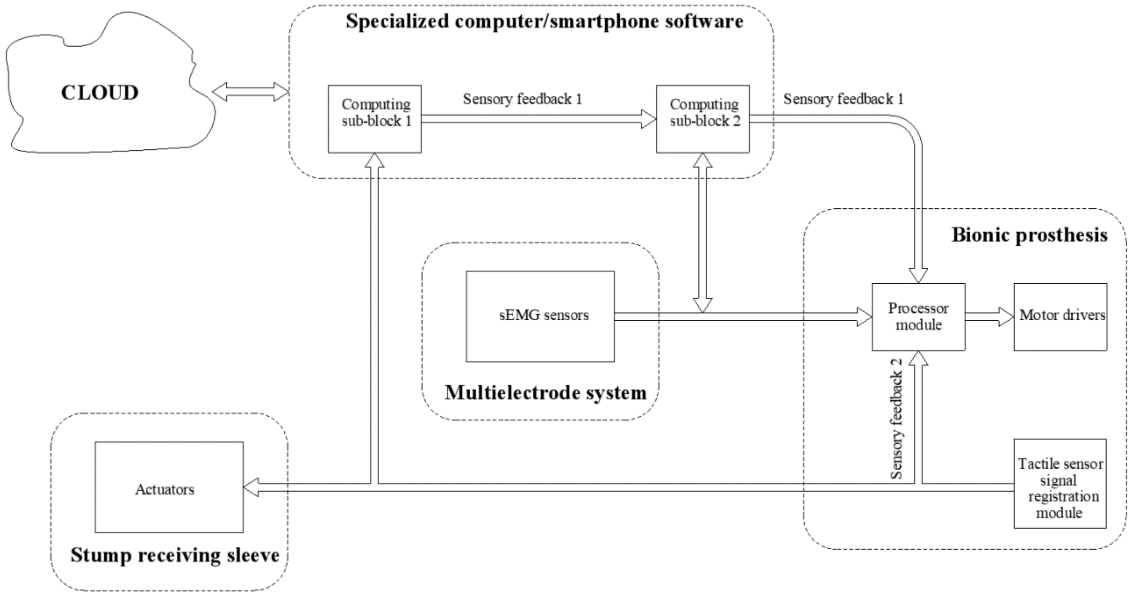


Figure 11. Structure of the proposed adaptive control system for a bionic prosthesis

According to Fig. 11, the proposed structure provides for the use of signals from tactile sensors to control the actual operation of the prosthesis. Thus, sensory feedback for the control system was implemented. The signal from tactile sensors is used to correct the control signals of the prosthesis' electric drives. In a situation where the patient tries to grasp an object with the prosthesis, the control system based on sEMG signals generates signals to control the prosthesis' electric drives and the prosthesis begins to grasp this object. At the same time, the system constantly evaluates the level of signals from tactile sensors. At the moment of touching the object, a signal from tactile sensors will appear and the system will re-evaluate the sEMG signals. If these signals continue to be generated by the patient, the process of grasping the object will continue. Otherwise, no. Thus, sensory feedback will not only provide tactile sensations for the patient, but also correct the operation of the prosthesis itself, regardless of the patient. The structure of the system shown in Fig. 10, will include two independent data exchange channels and three main elements: a stump-receiving sleeve with EMG sensors and actuators; a smartphone or PC with appropriate software; a bionic prosthesis with electric drives and tactile sensors. The proposed system will already include two connected data exchange channels and four main elements: a multi-electrode system with sEMG sensors; a stump-receiving sleeve with actuators; a smartphone or PC with appropriate software; a bionic prosthesis with a processor module, motor drivers and tactile sensors signals registering module.

4. PRACTICAL IMPLEMENTATION OF INDIVIDUAL ELEMENTS OF THE PROPOSED BIONIC PROSTHESIS CONTROL SYSTEM

At this stage of the research, the elements of the multielectrode system for recording sEMG and sensory feedback signals were developed. The Myo Armband structure was used as the basis for the design of the multielectrode system. At the same time, the dimensions of the electrode housings were reduced and their number was increased to 10. Also, unlike plate contact plates, sensitive contact elements with an uneven surface shape were used. This approach was described in detail in [16]. An example of the design of such a sensitive contact element is shown in Fig. 12.

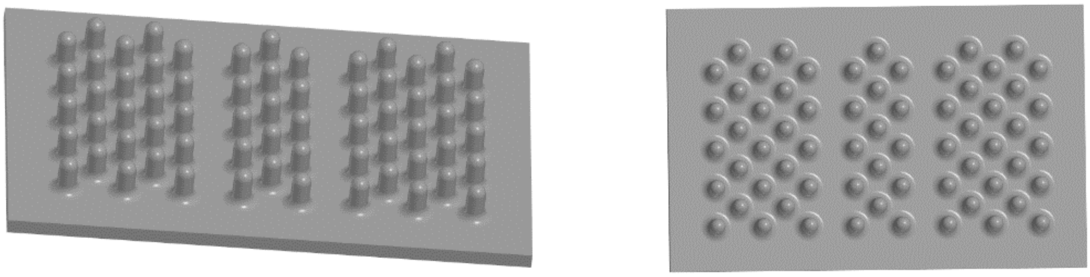


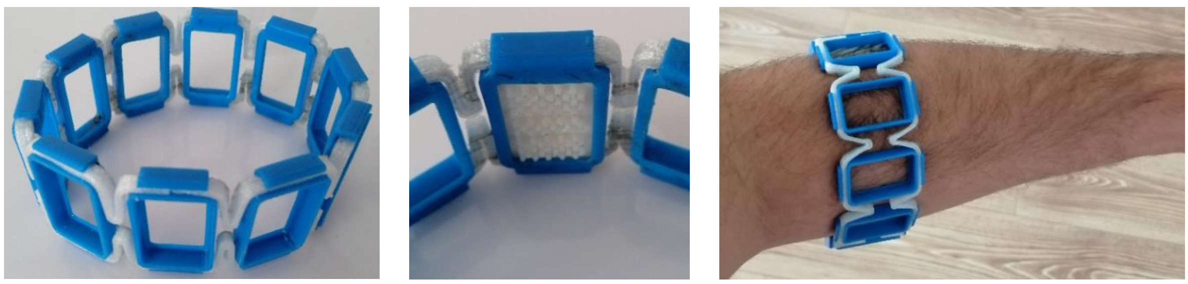
Figure 12. Design of the proposed sensitive contact element

The entire sensitive element is proposed to be made solid from ABS filament, which has a high resistivity and will not affect the quality of the registered signals, and its actual manufacture is possible by 3D printing. Next, the contact element itself is metallized, but sectionally, in order to obtain three sensitive conductive zones on one dielectric base of ABS plastic - the two extreme ones will be grounded, the middle one will be signal. This will simplify the process of manufacturing each of the 10 electrodes.

Each such sensitive element is placed in the electrode housing, which is hollow and inside which additional nodes of the entire multi-electrode system are placed. In particular, it becomes possible to distribute such elements as buffer amplifiers, amplifiers themselves, a signal pre-coding unit, ADC, batteries and a wireless interface module across all 10 electrodes.

All 10 electrodes are interconnected mechanically using special elements with a shape similar to the shape of the same elements in the Myo Armband. These elements are also made by 3D printing from TPU80 filament. When applied, these elements will stretch and contract on the patient's hand under the action of the elastic properties of the filament itself. The shape of these elements will ensure a uniform distribution of electrodes radially on the patient's hand.

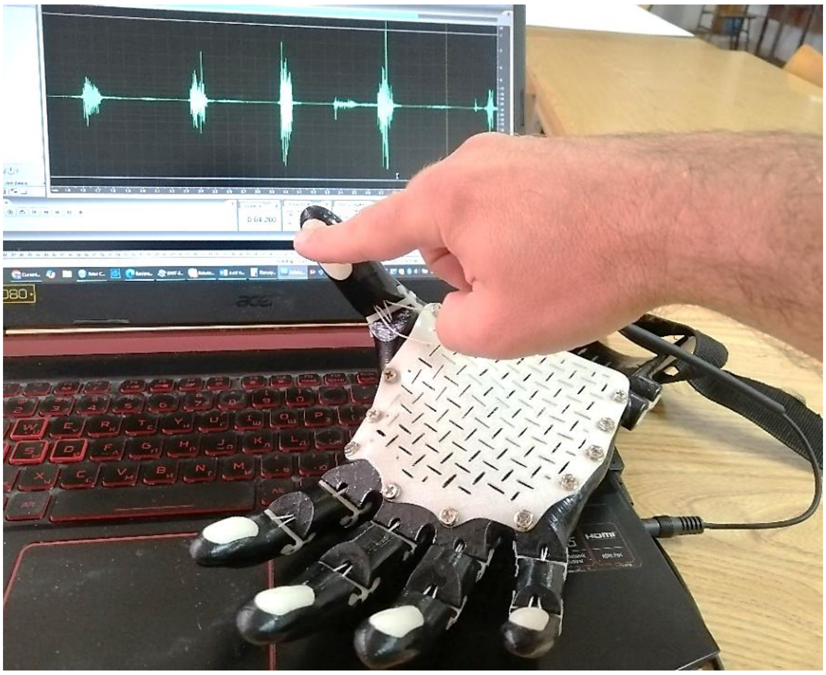
Fig. 13 shows the appearance of the manufactured structure (a) with a sensitive contact element (without metallization) installed in the body of one electrode (b) and the structure applied to the hand (c)



a) b) c)

Figure 13. View of the manufactured structure (a) with a sensitive contact element installed in the body of one electrode (b) and the structure placed on the hand (c)

Regarding sensory feedback, the Kinetic Hand prosthesis was used as a prototype, with elastic inserts installed in the fingertips, inside of which piezo transducers were placed. Low-frequency piezo emitters were used as the latter, and the signal was recorded through the microphone input of the laptop. Fig. 14 shows the appearance of such a design and the actual process of recording tactile signals.



a) b)

Figure 14. Design of the insert with a piezosensor and the process of recording tactile signals

The approach used based on piezosensors provides signal generation at the moments of contact with the prosthesis insert, and this signal can be used to automate the process of gripping and holding objects with the prosthesis.

Regarding the prospects of further research, it should be indicated that research will be conducted on the stability of the prosthesis, in accordance with the articles [17,18].

5. CONCLUSIONS

The structure of the bionic prosthesis control system, that proposed in the research, differs from similar systems available on the bionic prosthesis market in that it uses a multi-electrode system for recording sEMG signals and provides for the organization of sensory feedback to automate the process of capturing objects. The proposed structure also provides for the formation of tactile feedback, which is used to ensure the patient feels objects and to form signals to control the bionic prosthesis electric drives. The main structural elements, such as the multi-electrode system, the stump-receiving sleeve and the bionic prosthesis itself, are separate independent elements that are interconnected via separate wireless data exchange channels. At the same time, the design of the Myo Armband multi-electrode system was improved, and piezoelectric transducers were used to implement sensory feedback.

References

1. Ziegler-Graham K., MacKenzie E. J., Ephraim P. L., Travison T. G., Brookmeyer R. Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050. Arch. Phys. Med. Rehabil. 2008, 89, pp. 422–429. https://doi.org/10.1016/j.apmr.2007.11.005
2. HANDBOOK OF BIOMECHATRONICS. JACOB SEGIL. Academic Press is an imprint of Elsevier. 2019, Elsevier Inc., 603 p.
3. THE MECHATRONICS HANDBOOK / Editor-in-Chief Robert H. Bishop. The University of Texas at Austin. Austin, Texas, 2002, 1229 p.
4. Collinger J. L., Wodlinger B., Downey J. E., Wang W., Tyler-Kabara E. C., Weber D. J., McMorland A. J. C., Velliste M., Boninger M. L., Schwartz A. B. (2013) High-performance neuroprosthetic control by an individual with tetraplegia. Lancet, 381, pp. 557–564. https://doi.org/10.1016/S0140-6736(12)61816-9

5. Smith L. H.; Kuiken T. A.; Hargrove L. J. (2014) Real-time simultaneous and proportional myoelectric control using intramuscular EMG. J. Neural. Eng, 11, 66013. https://doi.org/10.1088/1741-2560/11/6/066013
6. Milosevic B., Benatti S., Farella E. (2017) Design challenges for wearable EMG applications. In Proceedings of the Design, Automation & Test in Europe Conference & Exhibition (DATE), Lausanne, Switzerland, 27–31, pp. 1432–1437. https://doi.org/10.23919/DATE.2017.7927217
7. Tucker M. R., Olivier J., Pagel A., Bleuler H., Bouri M., Lambercy O., del R Millбn J., Riener R., Vallery H., Gassert R. (2015) Control strategies for active lower extremity prosthetics and orthotics: A review. J. Neuroeng. Rehabil, 12, 1. https://doi.org/10.1186/1743-0003-12-1
8. Mesa I., Rubio A., Tubia I., De No J., Diaz J. (2014) Channel and feature selection for a surface electromyographic pattern recognition task. Expert Syst. Appl, 41, pp. 5190–5200. https://doi.org/10.1016/j.eswa.2014.03.014
9. McCool P., Petropoulakis L., Soraghan J. J., Chatlani N. (2015) Improved pattern recognition classification accuracy for surface myoelectric signals using spectral enhancement. Biomed. Signal Process. Control, 18, pp. 61–68. https://doi.org/10.1016/j.bspc.2014.12.001
10. Paolo Visconti, Federico Gaetani, Giovanni Antonio Zappatore, Patrizio Primiceri, 2018. Technical Features and Functionalities of Myo Armband: An Overview on Related Literature and Advanced Applications of Myoelectric Armbands Mainly Focused on Arm Prostheses. International journal on smart sensing and intelligent systems. P. 1–25. https://doi.org/10.21307/ijssis-2018-005
11. Available at: https://www.ottobock.com/en-au/Prosthetics/UpperLimb_MyoPlus.
12. E.-S. Hwang, J.-h. Seo and Y.-J. Kim (2007) "A polymer-based flexible tactile sensor for both normal and shear load detections and its application for robotics", J. microelectromechanical systems, vol. 16, no. 3, pp. 556–563. https://doi.org/10.1109/JMEMS.2007.896716
13. Y. Wang, K. Xi, G. Liang, M. Mei and Z. Chen (2014). "A flexible capacitive tactile sensor array for prosthetic hand real-time contact force measurement," in Information and Automation (ICIA), IEEE International Conference on, pp. 937–942, IEEE, 2014. https://doi.org/10.1109/ICInfA.2014.6932786
14. H. N. Sani and S. G. Meek (2011) "Characterizing the performance of an optical slip sensor for grip control in a prosthesis," in 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1927–1932, IEEE, 2011. https://doi.org/10.1109/IROS.2011.6095181
15. Vasil Dozorskyi, Vasyl Martsenyuk, Oksana Dozorska, Leonid Dediv, Nataliya Klymuk. The concept of developing the structure of a highly functional bionic hand prosthesis based on IoT technologies. Proceedings of the 1st international workshop on "Bioinformatics and Applied Information Technologies"(BAIT-2024). P. 268–280.
16. Oksana Dozorska, Evhenia Yavorska, Vasil Dozorskyi, Vyacheslav Nykytyuk, Leonid Dediv (2020). The Method of Selection and Pre-processing of Electromyographic Signals for Bio-controlled Prosthetic of Hand. Proc. of the 2020 IEEE 15th International Conference on Computer Sciences and Information Technologies (CSIT), 23–26 September 2020, pp. 188–192. Lviv-Zbarazh, Ukraine. https://doi.org/10.1109/CSIT49958.2020.9321935
17. Martsenyuk V., Soldatkin O., Klos-Witkowska A., Sverstiuk A., & Berketa K. (2024) Operational stability study of lactate biosensors: modeling, parameter identification, and stability analysis. In Frontiers in Bioengineering and Biotechnology, vol. 12. Frontiers Media SA. https://doi.org/10.3389/fbioe.2024.1385459
18. Martsenyuk V., Klos-Witkowska A., Dzyadevych S., Sverstiuk A. (2022) Nonlinear Analytics for Electrochemical Biosensor Design Using Enzyme Aggregates and Delayed Mass Action. Sensors, 22 (3), 980. https://doi.org/10.3390/s22030980

УДК 612.741.1

СТРУКТУРА СИСТЕМИ КЕРУВАННЯ БІОНІЧНИМ ПРОТЕЗОМ КИСТІ РУКИ З СЕНСОРНИМ ЗВОРОТНИМ ЗВ'ЯЗКОМ

Леонід Дедів; Сергій Ковалик

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Проведено аналіз стану проблеми створення високофункціональних біонічних протезів та показано актуальність створення адаптивної системи керування такими протезами за результатами опрацювання біосигналів. Розглянуто переваги та недоліки методу прямої реєстрації сигналів з моторних відділів кори головного мозку людини, застосування спеціалізованих так званих* *нервових манжет для отримання сигналів безпосередньо від периферійних нервових волокон, а також імплантованих електродів та реєстрації поверхневих електроміографічних сигналів (пЕМГ). Враховуючи неінвазивність, безпечність та простоту технічної реалізації в основі роботи проєктованої системи використано метод реєстрації саме пЕМГ. Однак для підвищення інформативності вихідного матеріалу та можливості виділення більшої кількості інформативних ознак окремих фантомних рухів запропоновано використати мультиелектродну систему, а також для забезпечення адаптивності роботи протеза запропоновано в розробленій структурі системи керування реалізувати сенсорний зворотний зв'язок. Для цього запропоновано використати сигнали з тактильних сенсорів, які розміщуватимуться на кінцях пальців протеза. Запропоновано структуру системи керування, яка включає в себе два пов'язані канали обміну даними та чотири основні елементи: мультиелектродну систему із пЕМГ сенсорами; куксоприймаючу гільзу із актуаторами; смартфон чи ПК із відповідним програмним забезпеченням; біонічний протез із процесорним модулем, драйверами двигунів та модулем реєстрації сигналів з тактильних сенсорів. Запропоновано основні структурні елементи, такі, як мультиелектродна система, куксоприймаюча гільза та власне біонічний протез виконати як окремі незалежні елементи, які з'єднуються між собою по окремих безпровідних каналах обміну даними. Розроблено елементи мультиелектродної системи записування пЕМГ та записування сигналів сенсорного зворотного зв'язку.*

Ключові слова: *сенсорний зворотний зв'язок, біонічний протез, пЕМГ, куксоприймаюча гільза, тактильний сенсор.*

https://doi.org/10.33108/visnyk_tntu2025.03.045 *Отримано 16.07.2025*