The concept of developing the structure of a highly functional bionic hand prosthesis based on IoT technologies

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Abstract

The paper analyzes approaches to solving the main problems of designing highly functional bionic hand prostheses. The main tasks, which must be solved at the same time, have been formed. As a result of the analysis of the constructions and principles of operation of today's common bionic hand prostheses, their main shortcomings have been identified, which are either related to the imperfection of the design or information processes aimed at providing tactile sensations and the selection and processing of biosignals for the formation of control signals for the elements of the bionic prosthesis, etc. The concept of the bionic prosthesis structure development is proposed, which involves the combination of the prosthesis electromechanical design based on the endoskeleton proposed by the authors with sensors of tactile sensations and special designs of EMG sensors and actuators, which are combined into a single network according to the principle of IoT, which includes the use of specialized information support for the accumulation and processing of such signals and formation of corresponding control signals for both prosthesis executive mechanisms and actuators based on the application of artificial intelligence and cloud technologies elements.

Keywords

bionic prosthesis, endoskeleton, IoT, actuator, tactile sensations

1. Introduction

An urgent task today in the field of medical apparatus construction and rehabilitation engineering, both in Ukraine and throughout the world, is the development of highly

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functional upper limbs prostheses. Research in this direction is carried out with particular intensity, which is connected with the growing need for the most complete recovery of the working capacity of people with upper limb amputations, the need to restore their social status and the ability to perform both everyday and special work functions. At the same time, known constructions have inherent disadvantages that are associated with one-sided directions of research and design of such bionic prostheses. This is connected, in particular, with the need to simultaneously and comprehensively solve a number of problems that relate to various fields of science and technology and require the involvement of relevant highly qualified specialists. Thus, the main tasks, the complex solution of which will make it possible to develop a highly functional bionic prosthesis of the hand, are the choice of prosthesis moving elements design, the optimal drive of the moving elements, provision of sensations by the prosthesis elements, the method of biosignals selection and processing from the hand part that remained after amputation and ensuring the possibility changeability of prosthesis individual elements when they are damaged, in particular individual fingers (Figure 1).

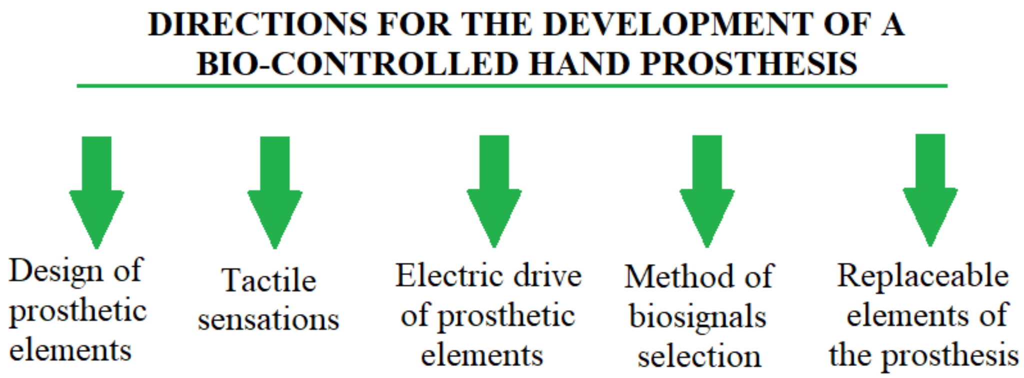

Figure 1: The main tasks of designing highly functional bionic prostheses

The paper substantiates the concept of developing the structure of a highly functional bionic hand prosthesis based on IoT technologies.

2. Analysis of known research results

Thus, there are practically no domestically produced highly functional bionic hand prostheses on the market of prosthetic equipment (as of 2020, only 58 enterprises in Ukraine produced prostheses, and only 6 of them were highly functional prostheses). This is due to the difficulty of ensuring the necessary number of individual movements of the prosthesis, which is determined by means of selection and methods of processing biosignals of residual muscle activity of the amputated limb. As for foreign analogues, they are expensive and involve the installation, adjustment and further maintenance of prostheses exclusively abroad.

With regard to the concept of development the structures of upper limbs prostheses available on the market, it is based on a structure that has already become classic and is based on the use of so-called shell models of the fingers phalanges as well as the palm.

Such models are hollow, inside which additional drive elements are placed, which greatly complicates the prosthesis design and makes it less reliable.

As an example, we can mention a design that is "open source", can be downloaded from the Internet and be used as a prototype for the next improvement [1-4]. Its design is shown in Figure 2.

Figure 2: Design of a bionic prosthesis prototype

According to Figure 2 supporting elements of the structure are hollow and hinged, inside which are placed electric motors, groups of gear and belt gear elements, which in a complex provide bending and extension movements of the fingers phalanges elements. At the same time, it is worth noting that during movement, simultaneous bending occurs in all hinged joints.

According to a similar principle, the designs of the most common today's bionic prostheses were developed. Thus, bionic prostheses of the Bebionic series can be considered the most available today, which is a group of bionic prostheses with an electromechanical drive and microprocessor control and control of the performed movements [2-5]. Functionally, these prostheses can perform 14 types of grips. The view of the Bebionic series prosthetics design from Ottobock is shown in Figure 3, a. Also unique in its nature and functional capabilities is the bionic prosthesis "Michelangelo's hand" (Figure 3, b) of the new generation [2-6].

a) b)

Figure 3: Design of prostheses: Bebionic series (a) and "Michelangelo's hand" (b) [2-6]

In terms of information, a feature of the considered two groups of prostheses is support for Myo Plus pattern recognition thanks to the digital interface implemented by a Bluetooth adapter.

The group of biocontrolled I-Limb prostheses of the company "Touch Bionics" (Great Britain) is considered the most functional today [2-7]. The appearance of the design of such a prosthesis is shown in Figure 4.

Figure 4: Design of the I-Limb prosthesis [7]

A kind of innovative approach in the concept of such a prosthesis is the use of special software in the form of a mobile application, after installing which on the user's smartphone it becomes possible to adapt the functions and adjust the operation of the prosthesis by the user himself.

The editors of Time magazine included the Esper Bionics prosthesis in the list of the 200 best inventions for 2022, which is a development of Ukrainian researchers and differs from the structures analyzed above in a number of innovative solutions that have been practically implemented [8]. In particular, it is a modular design that allows you to quickly replace individual elements, such as fingers, independently, without going to specialized service centers. Also important is the approach to a kind of intellectualization the prosthesis functions itself. The Esper Bionics prosthesis (Figure 5) includes 24 sensors that register residual muscle activity, on the basis of which (as the developers claim) a brain-computer interface is implemented. Also, the prosthesis training and control software uses cloud technology and machine learning algorithms to personalize the control of the prosthesis. In this way, frequently repeated algorithms of human movements are singled out and the prosthesis is trained to predict them.

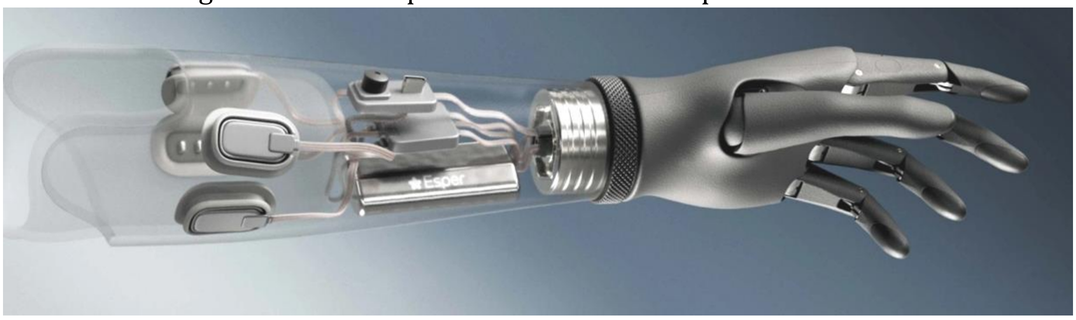

Figure 5: Design of the Esper Bionics prosthesis [8]

A significant disadvantage of the considered designs is the use of shell models of the fingers phalanges and the palm. Such designs use a significant number of force transmission elements (gears, shafts), which reduces the reliability of the prosthesis itself. In addition, in such designs (except the Esper Bionics design) it is difficult or almost impossible to make the fingers removable, so that in case of damage they can be replaced, rather than sending the entire hand prosthesis for service or repair. Another disadvantage is the inefficient use of the fingers phalanges volume, inside which sensors could be placed to realize the possibility of providing tactile sensations in the prosthesis.

3. Research results

Currently, the team of authors is researching the possibility of solving these problems. In contrast to the traditional prosthesis design in the form of shelled hollow elements of the fingers phalanges, inside which the drive elements are placed, the design of the mobile skeleton (endoskeleton) is being developed, on the surface of which elastomeric nozzles are placed to give the prosthesis elements a natural shape and surface softness. In this case, the number of moving elements of each individual finger and the prosthesis as a whole is significantly reduced, and it is also possible to replace each finger when it is damaged [9-11]. An example of the designed endoskeleton construction, the elements of which are made by the 3D printing method, is shown in Figure 6.

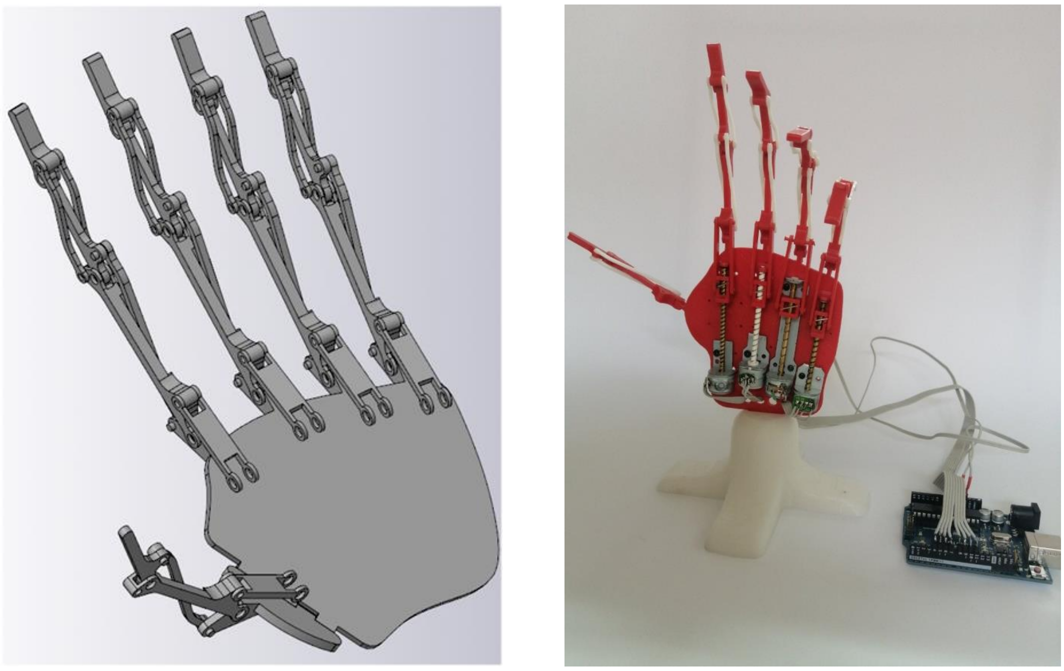

Figure 6: 3D image of the proposed endoskeleton construction and the appearance of construction made by the 3D printing method

It is also proposed to use highly efficient linear electric motors, particularly piezoelectric ones, as drive elements. Such motors have a low weight and are characterized by a significant acceleration of linear movement, which will ensure a significantly higher speed of individual movements of the prosthesis.

The use of silicone inserts, which will imitate the natural ends of the fingers, will make it possible to place various types of sensors in them. So, if a piezoelectric transducer is placed in the distal part of such an insert, the prosthesis will be able to "feel" objects by touch (the phenomenon of direct piezoelectric effect is used). At the same time, the authors suggested using a group of actuators, which will be placed either in a stump-receiving sleeve. The actuators will be in contact with the surface of the patient's skin. It is also proposed to use piezoelectric transducers as actuators, which will work according to the principle of the reverse piezo effect. The signal from each piezoelectric sensor, which will be modulated noise, is sent to the pre-amplifier and nodes for extracting the signal component. After that, bypass signal component must be modulated by high-frequency oscillations, amplified in power and sent to a separate actuator. The frequency of the modulating oscillations, their shape and the power of the modulated signal will be set individually for each individual patient and depending on the piezoelectric transducers of the sensors and actuators used. In the final case, slight deformations of such piezoelectric sensors will lead to corresponding mechanical vibrations of the actuators, which will be perceived by patients due to mechanical effects on the skin. In the future, the patient will be able to learn to distinguish individual objects by touch over time. This approach will provide an additional type of feedback when controlling the prosthesis (besides visual).

A schematic representation of the proposed bionic prosthesis design is shown in Figure 7.

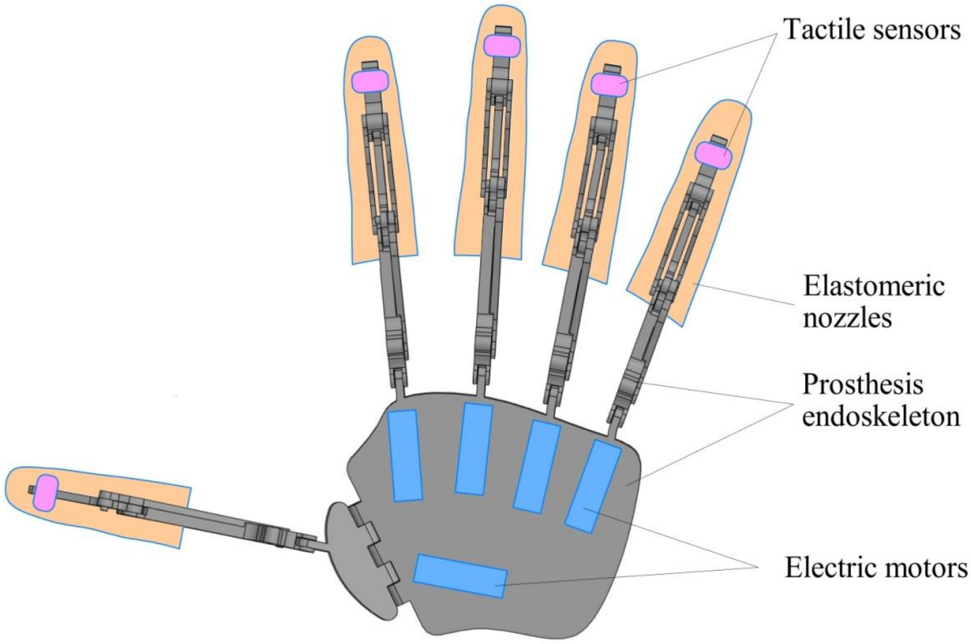

Figure 7: Schematic representation of the proposed bionic prosthesis design

In Figure 7 shows the prosthesis endoskeleton, on which parts of the elastomeric nozzles are conditionally placed. In the distal parts of these nozzles, tactile sensors are conventionally shown, and electric motors are shown on the elements of the palm. Actuators in Figure 7 are not shown.

In terms of selecting biosignals for controlling such a prosthesis, the authors of the work developed designs of active electrodes for selecting surface electromyographic (EMG) signals, the shape of the sensitive surface of which is needle-like with rounded tops. The developed structure and its advantages are described in detail in the work [12]. To record EMG signals, a design with a group of electrodes (at least eight) will be used, which will be in contact with the surface of the patient's hand radially. This choice of placement of the electrodes is justified by the provisions of Raoul Yusson's neurochronax theory, the generalization of which is the assumption of separate both in structure and in time with phase delays in the propagation of nerve impulses through nerve fibers. In this way, it becomes possible to recognize the signs of fine motor skills and realize a greater number of movements performed by the prosthesis. It is also planned to use the processing methods described in the works [13, 14].

Important for the practical implementation of all the above-mentioned elements of the designed structure of a highly functional bionic prosthesis is the solution to the task of organizing a single information system for the organization of selection, accumulation, processing and formation of all signals necessary for the full functioning of the prosthesis. For this, it was decided to use approaches, which are partially implemented in the bionic prostheses analyzed above, in particular, Bebionic, "Michelangelo's hand" and I-Limb. The concept of organizing such an information system can have the following options. Taking into account the advantages and prospects of using IoT technologies, it is proposed to select and process both signals from tactile sensors and from EMG sensors with the help of specialized software, which will be installed either on a computer or on a smartphone. At the same time, significantly greater computing power will be used for processing than that which could technically be placed inside the structure of the prosthesis in the form of a separate module, which will make it possible to use elements of artificial neural networks and artificial intelligence to process EMG signals and generate appropriate control signals for the elements of the bionic prosthesis. Also, the energy consumption of the prosthesis will be significantly reduced and the time of its autonomous operation from internal batteries will increase. The exchange of signals between the prosthesis and the computer/smartphone will be carried out over a wireless network. In addition, cloud technologies will be used to accumulate, store and process data. At the same time, it is envisaged to implement data exchange in two ways via wireless channels:

1) EMG sensors – specialized computer/smartphone software – bionic prosthesis;
2) tactile sensors – specialized computer/smartphone software – actuators.

Also common to both channels is the use of cloud technologies. Taking into account the separation of the bionic prosthesis, specialized computer/smartphone software, and the stump of the receiving sleeve, the structure of the passage of signals in such a design can be illustrated by the diagram shown in Figure 8.

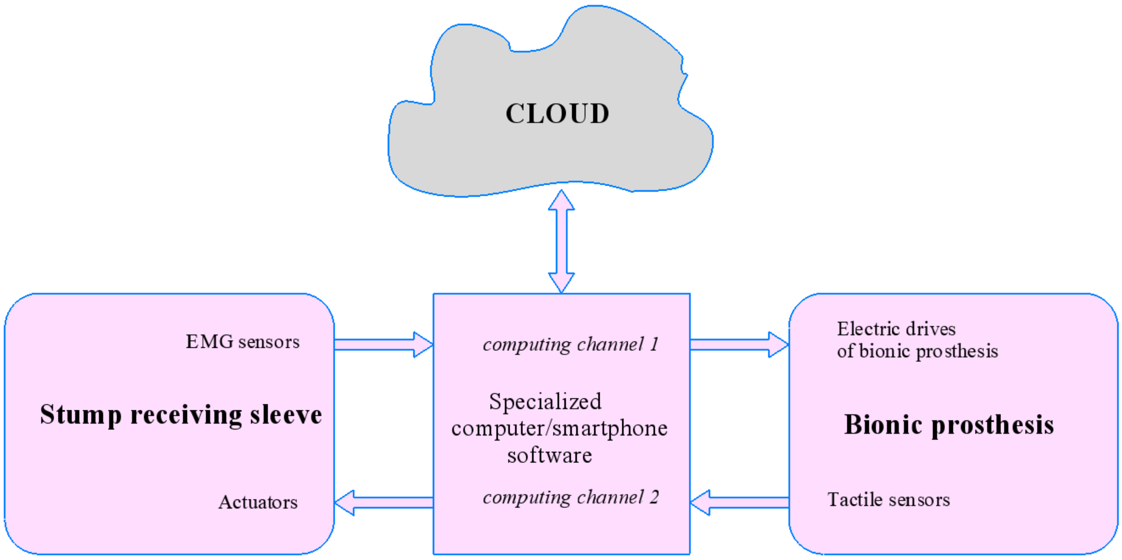

Figure 8: Structure of signal transmission in the proposed bionic prosthesis design

A variant of the functional diagram of the proposed bionic prosthesis design with the main elements of information support is shown in Figure 9.

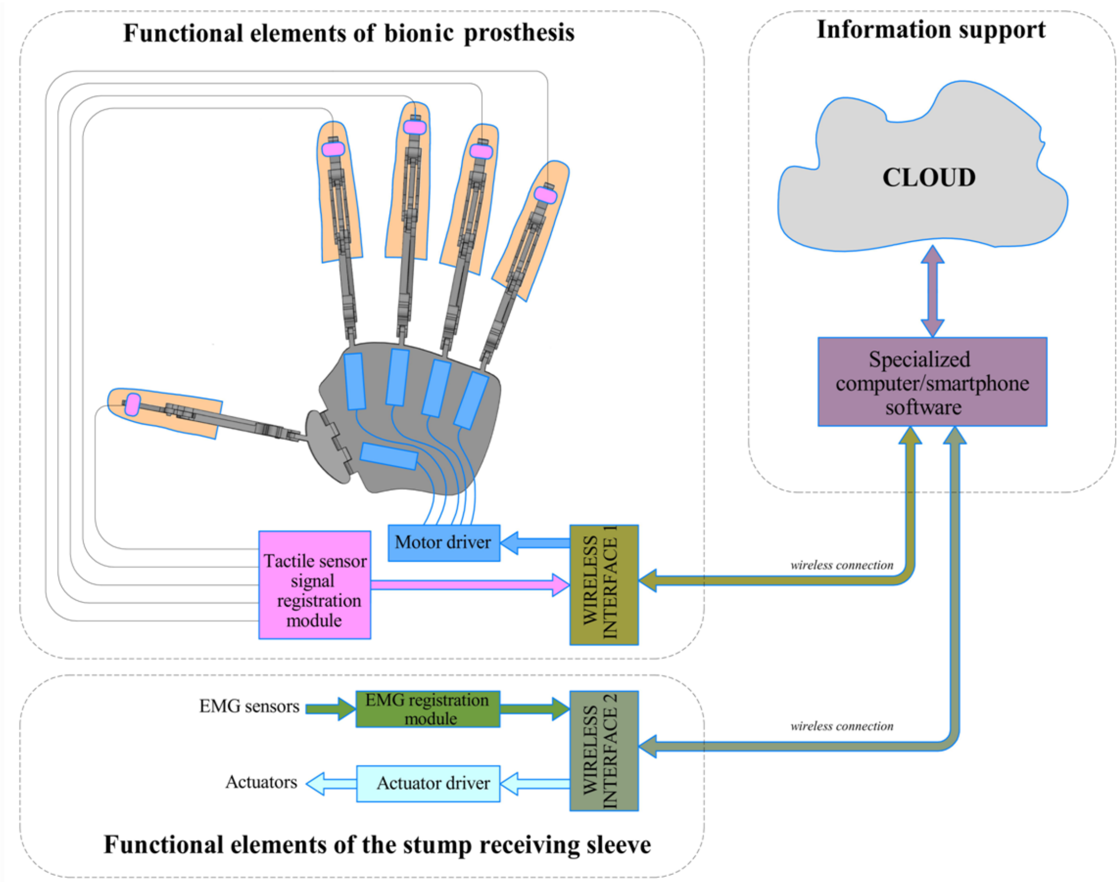

Figure 9: Functional diagram of the bionic prosthesis design

However, the disadvantage of such a design is the need for constant joint operation of the prosthetic EMG transducers, actuators and computer/smartphone. If the latter is turned off or malfunctions, the prosthesis will cease to function. To eliminate this shortcoming, it is proposed to use a concept that involves the use of a computer/smartphone at the stages of signal processing during learning to control the prosthesis and accumulating data.

There are actually two stages of using the prosthesis. At the first stage, a set of EMG signals is registered, transferred to a computer/smartphone, processed using elements of artificial intelligence, and the formation of appropriate control signals for the elements of the prosthesis during individual movements. The received control signals are entered into the memory of the processor module, which is placed in the structure of the prosthesis. At the next – main stage – continuous selection of EMG signals and selection of appropriate control signals based on their characteristics from a set of those recorded in the memory of the processor module at the previous stage is carried out. At the same time, at the main stage, the computer/smartphone will be used as an auxiliary tool for correcting errors in the operation of the prosthesis and generating new control signals for the prosthesis for its continuous self-learning and expansion of functional capabilities. A variant of the implementation of such a concept is displayed in the form of a functional diagram shown in Figure 10.

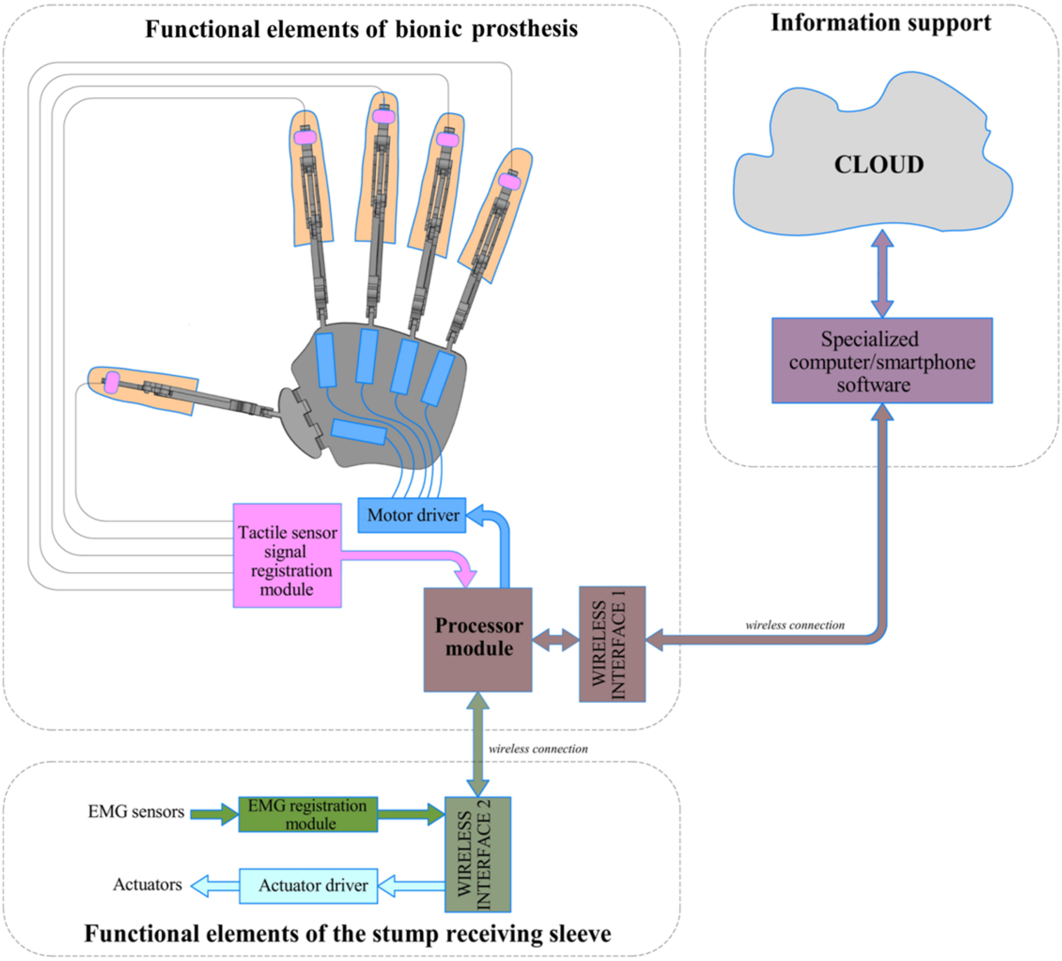

Figure 10: Functional diagram of the proposed bionic prosthesis design

In this way, the proposed concept of the bionic prosthesis design development takes into account and provides for the solution of the shown in fig. 1 tasks and opens up prospects for the creation of a highly functional bionic prosthesis, which would have advantages over analogues. The use of IoT and cloud technologies opens the way to self-learning the prosthesis to perform new movements due to the use of artificial intelligence during data processing and the concentration of main computing power outside the prosthesis (on a computer/smartphone).

4. Prospects for further research

To implement the proposed concept, the main elements of the prosthesis design are planned to be manufactured using 3D printing methods, in particular, filaments reinforced with carbon fiber, which will provide the possibility of reducing the mass of the entire prosthesis and increasing strength indicators. TPU filament will be used as material for elastomeric nozzles, the Shore strength of which will be selected individually for each patient depending on their lifestyle and additional needs. Features of possible 3D printing technologies are described in works [15-20].

Artificial intelligence technologies will be used to process EMG signals in combination with appropriately modified mathematical processing methods, which are described in work [21]. Also, to implement the function of tactile sensations, the methods described in the works [22-26] will be applied. The development of an effective interface for the structure of a bionic prosthesis is promising in the direction of using sensors [23, 24], in particular for monitoring important indicators of a person, assessing his functional state. An important characteristic of different types of biosensors is stability [25, 26]. Scientific studies [27] give examples of modeling sensor reviews. Numerical modeling in cyber-physical biosensor systems [27] is important at the stage of their design.

5. Conclusions

The paper presents the main results of the organization of approaches to the task of designing a highly functional bionic prosthesis of the hand, which is embodied in the form of the concept of data selection, their exchange between the functional nodes of the prosthesis, processing using artificial intelligence remotely, on a computer/smartphone at the stages of training, realizing the ability to self-learning at the main stage of using a prosthesis, as well as realizing the function of tactile sensations. For this purpose, it is proposed to organize separate channels of wireless data exchange between the prosthesis, active EMG electrodes and actuators, as well as a computer/smartphone, which, together with the use of cloud technologies, will be combined into a single network based on the IoT principle. The technical implementation of the proposed concept will provide an opportunity to develop a bionic prosthesis that will have no analogues and will satisfy the needs of patients to a greater extent.

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