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Experimental Study of 7-DOF bionic forearm prosthesis

Ivan Krechetov [#1], Arkady Skvortsov [#2], Ivan Poselsky [#3]

[#1] Researcher, Office of Scientific Research and Development, Moscow Polytechnic University, Moscow, Russia
[#2] Head of OSRD, Ph.D., Professor, Office of Scientific Research and Development, Moscow Polytechnic University, Moscow, Russia
[#3] Head of NTC "Automated Technical Systems," Moscow Polytechnic University, Moscow, Russia

[1]ivan.krechetov.63@mail.ru

Abstract : *In this work, an experimental study on the grip of complex shape objects by the developed hand module of the bionic prosthesis has been conducted. A description of the seven-degree-of-freedom (7-DOF) control system of the hand module has been presented. The hand module is designed for the use in forearm and shoulder prostheses; finger modules can be used separately in the manufacture of hand prostheses. Developed programming units can be used in the building control systems of the gripping anthropomorphic manipulator, which has a kinematic structure similar to the human hand but a different number of controlled and dependent degrees of freedom. The project aims at the development of a bionic forearm prosthesis which has reliability and performance close to a healthy human hand.*

Keywords: *bionic hand, module, dexterous hand, upper limb prostheses.*

I. INTRODUCTION

A. Introduction to the problem

Millions of people in the world (~9.2 million people) suffer from loss of upper limbs, resulting in loss of labour capacity, job loss, and, as a consequence, a significant decline in quality of life.

The causes of the loss of the upper limbs are:

1) Traumatic and non-traumatic amputations (~57%);
2) Acquired diseases (myodystrophy, contractures, limb paralysis after stroke) (~39%);
3) Congenital diseases (Duchenne muscular dystrophy, various forms of Amelia) (~4%).

Effective solutions for prosthetics of upper limbs are electromechanical robotic (bionic) prostheses, which copy the kinematics and motor skills of a healthy person hand when each finger can move separately, allowing the gripping of differently shaped objects.

B. The problem significance study

At the moment, such high-tech bionic prostheses have an extremely high cost (from $25,000), which significantly limits their use in the social sphere.

The prostheses of the upper limbs are divided into two main groups:

1) Passive (cosmetic and functional);
2) Active (body-powered and myoelectric).

Cosmetic prostheses are high-quality models of a healthy hand; however, they allow you to perform some of the actions, for example, the supporting and pushing of objects. It is worth mentioning that the technologies of cosmetic prostheses can be used in the manufacturing technology of removable coats of active prostheses.

C. Related works

Our previous work [1] on this project has demonstrated that the application of servo actuators integrated inside the finger structure can achieve several advantages:

– More complex prostheses can be manufactured for a part of the hand, and it is possible to make prosthetic appliances for individual fingers;
– It is possible to reduce the size of the prosthesis and manufacture more standard sizes;
– It is possible to provide higher reparability;
– Due to the space vacated inside the palm of the prosthesis, additional actuators for the thumb movement and rotation of the wrist around the forearm can be arranged.

Traditionally, angular feedback sensors are not applied in upper limb prostheses because it is difficult to integrate them into the structure of the finger. The position of the fingers in such prostheses is determined through the visual feedback of the user, i.e. the moment when the pattern finishes its movement is selected by the user "by eye". The implemented bionic hand control system uses two types of sensors:

– Digital Hall sensors (placed at the base of the fingers);
– Current sensors (placed directly on the control board).

Application of these types of sensors makes it possible to implement precise finger position control (with an accuracy of 0.044 degrees) with smooth acceleration and deceleration at the beginning and end of the trajectory, respectively.

As a rule, the gripping of the objects is a difficult task for manipulators. However, in the prosthesis, this task can be reduced to control the elements that carry out the closing of actuating elements (fingers) around an object placed inside the geometric center of the hand. Then the task of gripping an object is reduced to controlling the movement of fingers according to the corresponding configuration (pattern) of movement.

Application of proportional-integral-derivative (PID) controllers is a widely used control method of direct current motors, according to papers [2], [3], [4], [5], [6].

It has been demonstrated in papers [7], [8] that the adaptive control system based on an artificial neural network, as compared to the classical PID controller, provides significantly (up to three times) less time required for the motor to reach the specified control mode and also provides a low level of overcontrolling. The level of overcontrolling of the PID controller is ranged from 0 to 10%; at the same time, the level of overcontrolling of the controller based on the neural network is equal to 0%.

Addition to the classical PID controller scheme of only one nonlinear element – a neuron, as is proven in the paper [9] makes it possible to reduce the duration of the transition process by 30% on the average, as well as to adapt to external disturbances providing that there is an accurate mathematical model of the control object.

Application of neural networks in the function of the nonlinear control system in addition to PID controllers, as demonstrated in the paper [10] makes it possible to adapt dynamically to external effects, to compensate for non-determination of parameters of the control object, significantly simplifies the construction of control devices due to the lack of the requirement for the accurate analytical description of physical parameters of the model.

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II. METHODS

A. Bionic hand control system

In the function of the algorithm of the control system for the individual finger of the bionic prosthesis, a three-stage master controller with position, speed and developed torque control loops (see Fig. 1) has been implemented;

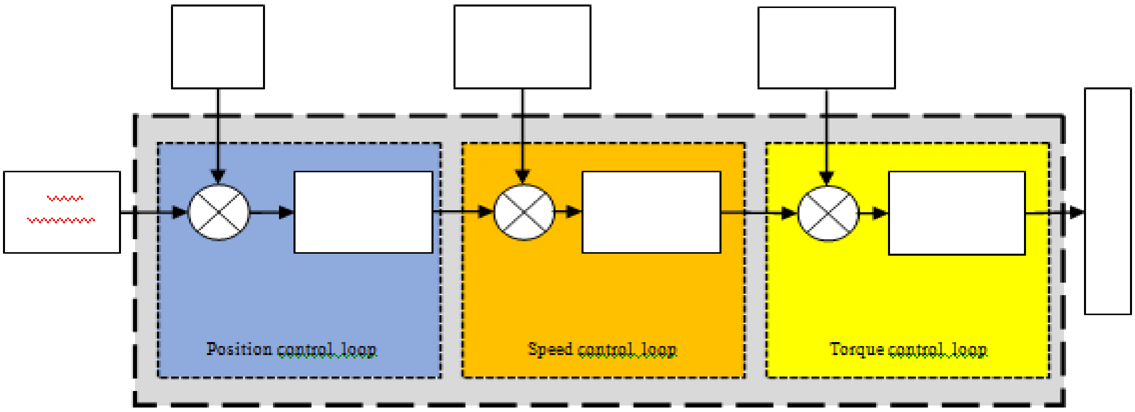

Fig. 1: Servo actuator control system

The rotation direction of the output shaft of the electric actuator is characterized by the sign of the control magnitude P_{ctrl}:

$$\begin{cases} sign(P_{ctrl}) > 0 - \text{clock wise rotation} \\ sign(P_{ctrl}) < 0 - \text{counterclockwise rotation} \end{cases} \quad (1)$$

However, the rotation direction of the output shaft of the servo actuator reducer (joint) may have the opposite sign due to the consecutive change in rotation directions of the gear unit stages. This may lead to the fact that the actual positive desynchronization of the joint angular position at the control loop input will require the sign reversal to the negative value. For automation and the subsequent possibility of using the algorithm being developed, we will enter an additional variable Rot_{sign} with the property that:

$$\begin{cases} Rot_{sign} = 1, \text{ if in case of } sign(P_{ctrl}) > 0, \text{the angular position sensor readings increase} \\ Rot_{sign} = -1, \text{if in case of } sign(P_{ctrl}) > 0, \text{the angular position sensor readings decrease} \end{cases} \quad (2)$$

Subsequently, the input signal of the first control loop *PID*1 (position-based) will represent the value:

$$d\varphi = \left(\varphi_{pos} - \varphi_{target}\right) * Rot_{sign} \quad (3)$$

where φ_{pos} is the actual angular position sensor value; φ_{target} is the joint target angular position.

Therefore, the output signal of the first control loop represents the value:

$$PID1 = K_{P1} * \Delta\varphi + K_{I1} * \int_0^t \Delta\varphi(t)dt + K_{D1} * \frac{d\Delta\varphi(t)}{dt}$$

The input signal of the second loop control *PID*2 (rotation speed-based) is desynchronization between the output of the first loop and the current value of the joint angular speed can be found from the expression:

$$d\omega = PID1 - \omega_0 \qquad (4)$$

where ω_0 is the joint angular rotation speed.

The joint angular rotation speed can be obtained through differentiation of the angular position change within a predetermined period of time can be found from the expression:

$$\omega_0 = \frac{\varphi(t+\tau) - \varphi(\tau)}{d\tau} \qquad (5)$$

The output signal of the second control loop represents the value: (6)

$$PID2 = K_{P2} * d\omega + K_{I2} * \int_0^t d\omega dt + K_{D2} * \frac{d\omega}{dt}$$

The input signal of the third control loop *PID*3 (torque-based) is the desynchronization between the output of the second loop and the current value of the servo actuator torque (proportionally to the current consumption) can be found from the expression:

$$dTq = PID2 - Tq_0 \qquad (7)$$

Therefore, the output signal of the three-loop control system represents the value:

$$P_{ctrl} = PID3 = K_{P3} * dTq + K_{I3} * \int_0^t dTqdt + K_{D3} * \frac{dTq}{dt} \qquad (8)$$

To ensure a smooth acceleration at the start and deceleration at the end, we took advantage of the motion trajectory generation method with maximum speed control and acceleration/deceleration control. It provides a so-called trapezoidal speed profile. The input values are:

φ_{target} is the joint target angular position;

φ_0 is the actual value of the angular position sensor;

τ is the access time of the predetermined position;

ω_{MAX} is the maximum joint angular rotation speed;

a_{MAX} is the maximum acceleration/deceleration.

Therefore, the input signal for the first stage is not the target predetermined position but the intermediate one, the value of which is determined by the law of motion.

$$\varphi(t) = \varphi_0 + \omega(t) * t \qquad (8)$$

$$\omega(t) = \begin{cases} a * t \text{ is the first 30\% of trajectory (acceleration)} \\ a * \tau/_3 \text{ is the steady state mode} \\ -a * t \text{ is the last 30\% of trajectory (deceleration)} \end{cases} \qquad (9)$$

In the bionic prosthesis control system, the most representative set of patterns has been implemented, which, as a rule, is actually standard in this very composition and is used in prosthetic robots of upper limbs:

1) Power grip is when all five fingers clench into the fist. It is the primary mode of operation for the performance of most manipulations, the grip of volumetric objects and carrying of the bag;

2) Gripping with a pinch involves three fingers (thumb, index, and middle) and is performed by opposing of the thumb to the index finger and the middle finger. It is usually used for long items like pen or cutlery;

3) A key grip is when the index, middle, nameless and little finger bend by half of the range. The thumb pulled aside presses the object against the side of the index finger. It is usually used to hold keys and tableware.

4) A precision grip is when the thumb and index finger converge to a point. It is usually used to grip small objects.

5) The "Pointer" is when the index finger is in the initial position with all other fingers fully squeezed. It is used when you press the keys.

6) Holding a mouse pointing device is a specific pattern for gripping the mouse body and pressing the left mouse button.

7) "Fine" is when the thumb is raised with a clenched fist. It is an informative gesture for interacting.

8) "Come to me" is the periodic bending and extension of the index finger with a clenched fist.

9) "Okay" is when the thumb and index finger are brought together in a plane, and they make a ring. The middle, nameless and little finger are taken aside to form a wave.

10) A user-defined pattern is saving of arbitrary configurations of finger movements in the prosthesis database to perform specific tasks or to copy a preset pattern and adjust intermediate values more precisely.

Implementation of the specified motion patterns is an array that stores data on the initial and end points of each pattern. The control of the direct complexly combined motion of the individual fingers in the execution of the gesture is implemented by generating intermediate target positions of the joints and loading them into the respective motor controllers (see Figure 2).

To implement the bionic prosthetic control program, a control board for 7 (seven) servo actuators has been developed (see Fig. 3).

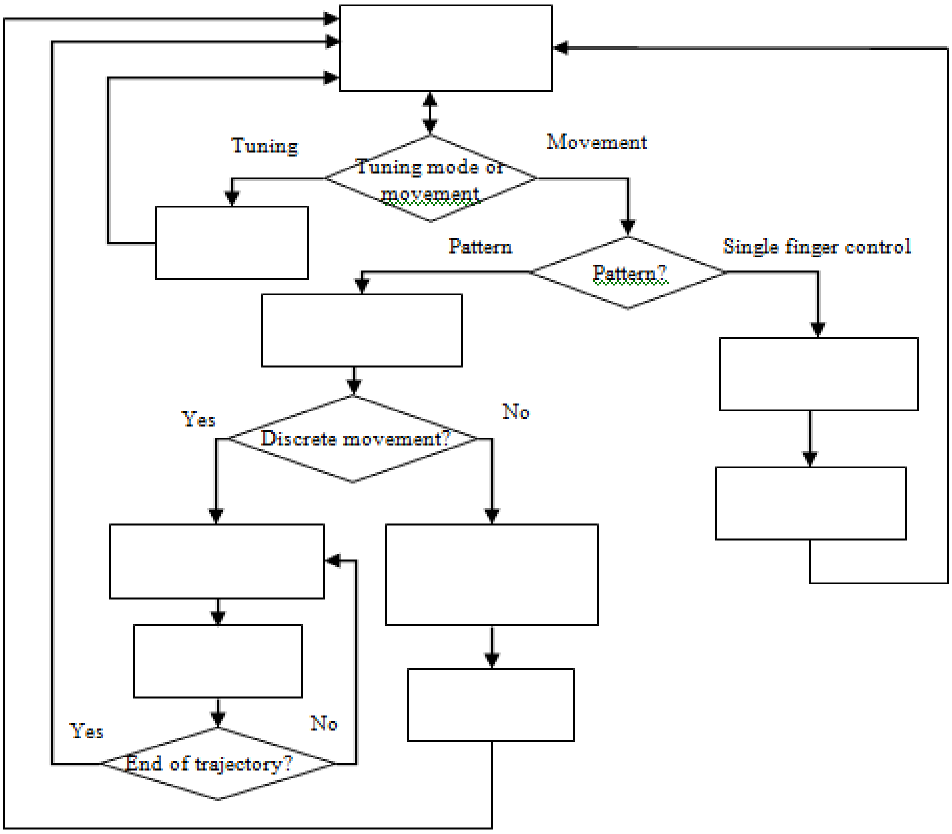

Fig. 2: Flowchart of the control system algorithm for the bionic prosthesis

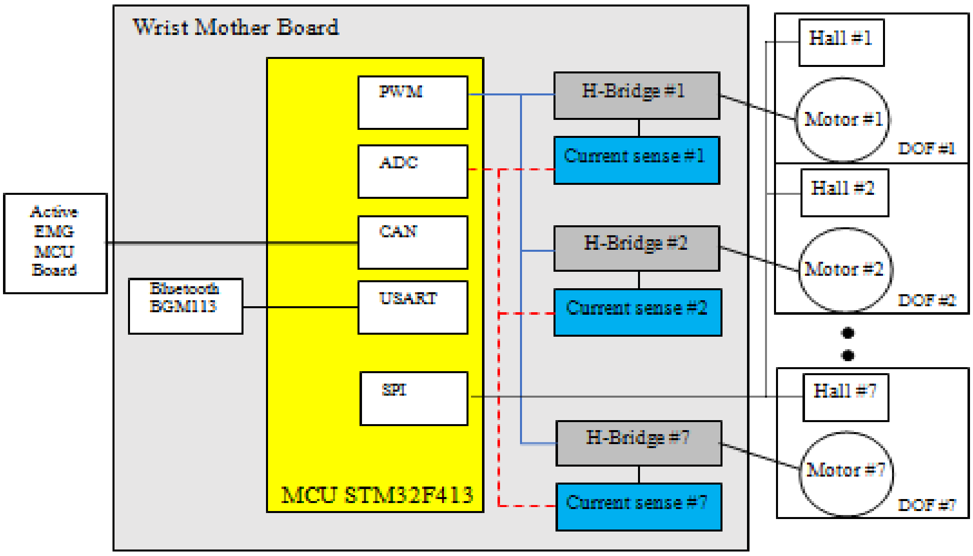

Fig. 3: Functional diagram of the control board for the bionic prosthesis

The main characteristics of the control board:

1) STM32F413VGT6 microprocessor;

2) CAN transceiver TCAN334 for data exchange with EMG processing module and connection to PC;

3) Bluetooth module BGM113 for data exchange with mobile application;

4) 5 power channels for motor control on the basis of MAX14871 (direct current up to 2.8A) for bending the index finger, middle finger, ring finger, little finger and for the thumb abduction;

5) 2 H-Bridge power control channels built on IRF7389 field-effect transistors (direct current up to 5.3A) (for thumb bending and rotation module);

6) 7 measuring circuits of current consumption by electric motors on INA199;

7) LSM6DS3TR gyroscope/accelerometer;

8) 7 SPI connection modules for digital Hall sensors AMS5047P.

The basic construction principles of the hand module of bionic forearm prosthesis:

1) Finger actuators are placed inside proximal phalanxes;

2) Application of the own design of micro-servo actuators with high torque (cycloid reducer) of the output shaft, upon placement of which inside the fingers the overall power supply capacity of the product does not lose compared to the traditional placement of actuators inside the palm;

3) Finger design is implemented with kinematically interlocked articulation joints;

4) The feedback sensor system integrates the position (angle sensor) and force (current sensor) sensors;

5) The rotator module integrates the pronation and supination of the hand (rotation around the axis) inside the hand

B. Bionic hand module manufacture

For the manufacture of parts of the bionic hand module, a three-axis CNC-controlled milling machine has been used. Control of the CNC machine is carried out by means of specially developed programs, which contain a list of trajectories of the machine tool movement.

For the development of the control program of the CNC machine, the SolidCAM package integrated into the SOLIDWORKS computer-aided design system was used. SolidCAM makes it possible to update motion trajectories on the trajectory-by-trajectory basis for each machining tool, to form tool change instructions, to adjust in a flexible manner similar actions for group machining of several parts, to calculate machining time, and to optimize time and accuracy of part machining. A handy feature is the virtual 3D simulation of the part's machining procedure over time, which provides a visual inspection of the correct preparation of the machining program and timely error tracking. The developed program is exported to the program in the G-code language, which is the industry standard in CNC machines' control. For ease of machining, all the same-type parts have been placed close together on the same workpiece and connected by thin jumper bars that hold them together

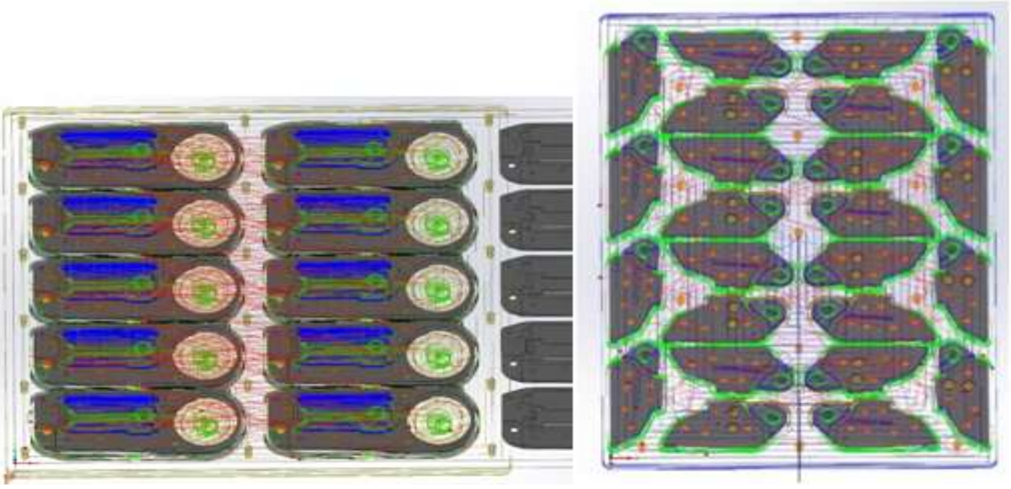

Fig. 4: Program segment for CNC

C. Investigational plan

For a qualitative estimation of the efficiency of subjects' holding, we will use the estimation method of generalized response based on Harrington's desirability function, according to the paper [11]. The transformation of natural sizes of measured parameter into dimensionless quantity on a scale of desirability lies in its basis. Let us use the ready table constructed empirically (see Table 1).

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TABLE 1.
HARRINGTON'S SCALE OF DESIRABILITY

Desirability	Marks on the scale of desirability	Equivalent mark
Very well	1.00 – 0.80	8
Okay	0.80 – 0.63	5
Satisfactorily	0.63 – 0.37	3
Bad	0.37 – 0.20	2
Very bad	0.20 – 0.00	1

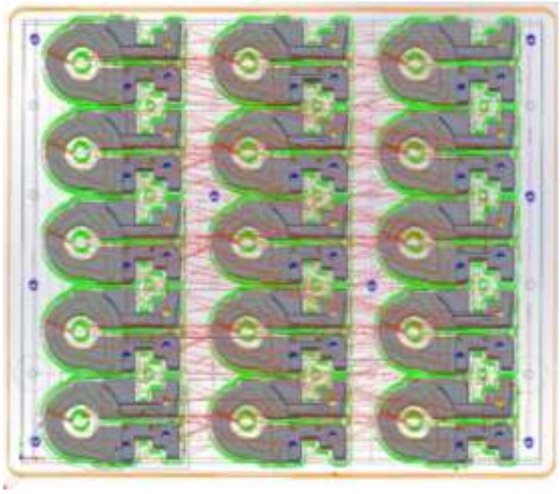

Fig.5: Program segment for CNC

Fig. 6: Bionic (dexterous) hand module

Desirability	**Marks on the scale of desirability**	**Equivalent mark**
Very well	1.00 – 0.80	8
Okay	0.80 – 0.63	5
Satisfactorily	0.63 – 0.37	3
Bad	0.37 – 0.20	2
Very bad	0.20 – 0.00	1

For elimination of random errors (defective values) it is also possible to use Student's t-test.

$$s = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}} \qquad \mathbf{(10)}$$

where (n-1) is the number of degrees of freedom which is equal to the number of experiments minus one;

$\bar{y}$ is the arithmetic mean:

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \qquad (11)$$

$$\frac{y - \bar{y}}{s} \geq t \qquad (12)$$

To test the functionality, a set of the following test objects was prepared:

1) "Sphere 30 mm";
2) "Sphere 40 mm";
3) "Cylinder 20 mm";
4) "Cylinder 60 mm";
5) "Light bulb";
6) "Fruit";
7) "Glass";
8) "Bottle";
9) "Bottle cap";
10) "Sheet of paper";
11) "Plastic card";
12) "Plate";
13) "Door key";
(14) "Coin 25 cents";
15) "Pen";
16) "Knife";
17) "Fork";
18) "Spoon".

The following set of grip options was selected as the most representative set of grips:

1) "Force grip";
2) "Pinch grip";
3) "Key grip";
4) "Precision grip";
5) "Trigger grip".

Figure 6 presents the appearance of the prosthesis when performing different grip options.

III. RESULTS

As the result of the experiments, summary data have been collected and presented in the form of Table 2.

As the result of the experiment, the technical characteristics of the bionic hand module have been measured and compared with similar products on the market (Table 3).

IV. DISCUSSION

Hypotheses about the conceptual design of the bionic hand and the principles of control have been confirmed during experimental studies:

1) Synchronization of finger movements due to the system of angle and current sensors leads to adaptation to the shape of the object;
2) The selected set of patterns is sufficient to hold the specified set of objects;
3) In order to securely grip the objects, it is necessary to place the executive element

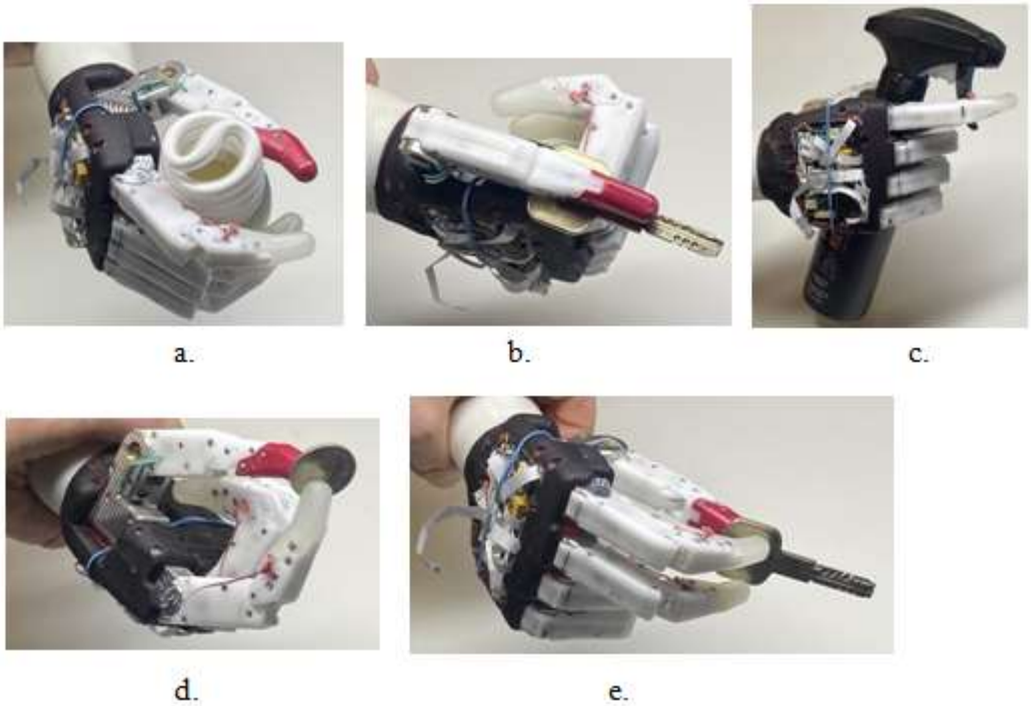

Fig. 7: Different grip options: (a) – "Force grip", (b) – "Key grip", (c) – “Trigger grip”, (d) – "Precision grip", (e) – "Pinch grip"

TABLE 2:
SUMMARY TABLE OF THE BEST COMBINATIONS OF OPTIONS FOR GRIPS AND OBJECTS

Objects	Grip options (patterns)				
	"Force grip"	"Pinch grip"	"Key grip"	"Precision grip"	“Trigger grip”
Sphere 30 mm	+	+	-	-	-
Sphere 60 mm	+	+	-	-	-
Cylinder 20 mm	+	+	-	-	+
Cylinder 60 mm	+	+	-	-	-
Light bulb	+	+	-	-	-
Fruit	+	+	-	-	-
Glass	+	+	-	-	-
Bottle	+	+	-	-	-
Bottle cap	+	+	+	+	-
Sheet of paper	-	+	+	+	+
Plastic card	+	+	+	+	+
Plate	+	-	+	-	-
Door key	-	-	+	+	-
Coin 25 cents	-	-	+	+	-
Pencil	+	+	+	+	+
Knife	+	+	+	-	-
Fork	+	+	+	-	+
Spoon	+	+	+	-	+

participating in the pattern around the geometrical center of the object.

As the result of experimental studies of the bionic hand module, the correctness of the selected research directions, described in our previous paper [1] on the development of construction principles of the upper limb bionic prostheses for prosthetics of patients with partial hand and forearm amputations have been confirmed:

1) Individual executive elements (fingers) made on the basis of micro-reducers embedded inside the proximal phalanx;

2) Bionic hand module, which consists of an executive complex of 5 (five) fingers and the bionic prosthesis control module;

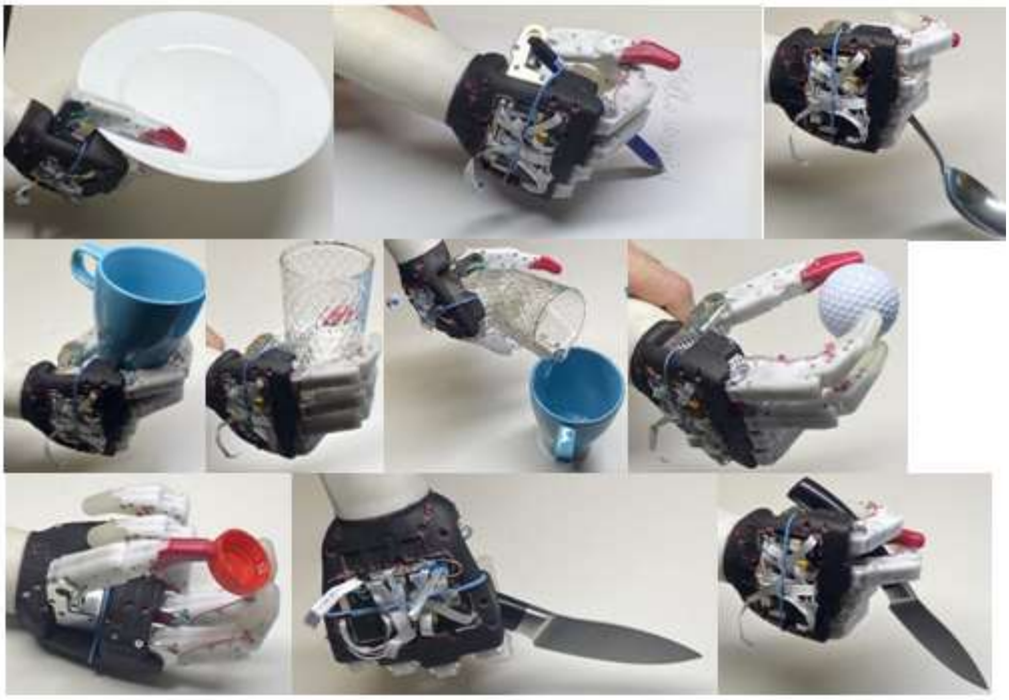

Fig. 6: Patterns to hold objects

TABLE 3
COMPARISON OF THE HAND MODULE WITH SIMILAR PRODUCTS

No.	Parameter	Developed hand module	BeBionic 3 [12] (Ottobock)	i-Limb Ultra [13] (OSSUR)	SensorHand [14] (Ottobock)	Vincent Evolution [15] (Vincent SYSTEMS)
1	Number of fingers	5	5	5	2	5
2	Number of independent finger actuators	6	5	6	1	6
3	Thumb abduction	Motorized	Manual, lock	Motorized	No	Motorized
4	Rotation module availability	Yes, it embedded inside the hand	No	No	No	No
5	Compression force	130H	128H	120H	100H	120H
6	Finger angular position control	Yes, 14-bit Hall sensors	No	No	No	No
7	Possibility of using for prosthetics of part of a hand	Yes, servo actuators embedded inside fingers	No	Yes, servo actuators embedded inside fingers	No	Yes, servo actuators embedded inside fingers
8	Full compression time, sec.	1.07	1.0	1.2	0.5	1.5
9	Touch feedback	Yes, vibrating motors are inside the prosthetic socket	No	No	No	No

3) Prosthetic control algorithms implemented in the software of the bionic prosthetic control module;

4) The built-in electronic control module of the bionic prosthesis, which performs the current commutation to the electrical motor windings, generation of smooth signals to control the rotation of electrical motors, providing rotation of 7 (seven) electrical motors in both clockwise and counterclockwise direction and data exchange with the module of multichannel processing of biopotentials

V. CONCLUSIONS

Developed programming units can be used in the building control systems of the gripping anthropomorphic manipulator, which has a kinematic structure similar to the human hand but a different number of controlled and dependent degrees of freedom.

The principles of constructing design-layout solutions in the field of high torque servo actuators on the output shaft, as well as methods and algorithms for controlling the movement of the servo actuators developed as part of the bionic hand module, can be used in the implementation of a whole range of products located at the junction of several technological directions:

1) Bioelectric prostheses of the upper limbs for various degrees of amputation of the hand, forearm, shoulder and the shoulder complete amputation;

2) Bioelectric prostheses of the lower limbs (robotic knee and foot modules) for patients with different degrees of below-knee amputation and femur amputation;

3) Manipulators of service and collaboration robots for household use and business problems solution;

4) Exoskeletons of the upper and lower limbs for application in rehabilitation medicine.

Implementation of the project results makes it possible to achieve several goals:

1) Market launch of new products in the field of upper limb prosthetics;

2) Recovery of lost ability and improvement of quality of life for disabled people;

3) Provision of multifunctional and at the same time affordable prosthetic and orthopedic products for disabled people who have lost their upper limbs to varying degrees, their socialization and integration into full social and economic activities;

4) Increasing the affordability of convalescent facilities due to cost reduction below the state reimbursement limits.

The resulting groundwork in the field of design and development of robotic joints will have a significant impact on the adjacent field of light personal and service robotics (with weight of up to 2 kg). The key factor for the success of the developed products in the domestic and world markets, besides the performance and user characteristics, is the cost of the product.

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