Indian Journal of Science and Technology, Vol 9(42), DOI: 10.17485/ijst/2016/v9i42/104218, November 2016
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Development of an Anthropomorphic Gripping Manipulator: Experimental Research

Ivan Vladimirovich Krechetov[1*], Pavel Sergeevich Lavrikov[2] and Arkadii Alekseevich Skvortsov[1]

[1]Office of scientific research and development, Moscow State University of Mechanical Engineering (MAMI), Moscow, Russia; krechetov_ivan@mail.ru, skvortsov@mami.ru
[2]RU. Robotics, Moscow, Russia; pavel_lavrikov@rurobotics.com

Abstract

Background/Objectives: This article deals with the experimental research of the newly developed anthropomorphic manipulator for gripping items out of the predetermined set. The project aims at developing an anthropomorphic gripping manipulator to a high accuracy of copying dynamics and kinematics of a human hand. **Methods:** Application of method of planning movement trajectory allows pre-calculating the parameters of joint movement over time. The movement trajectory approximation methods were used to fulfill the preset conditions. Harrington's desirability function was applied for the generalized response estimation. Random errors were screened using the Student's t-test. **Findings:** Results of gripping rigid and soft items of sophisticated shape are provided. According to this research, a number of shortcomings of mechanical structure were discovered and eliminated. Microprocessor modules, feedback sensor system, and power electronic module were developed and may be broadly used in educational robotics for building various robotic systems of low power (up to 150 W) for each swiveling block. Developed software modules may be used for building control system of an anthropomorphic gripping manipulator of kinematic configuration that resembles a human hand, but involving a varying number of controlled and dependent degrees of freedom. **Improvements/Application:** This hand may be applied in industrial robots to replace people in production, personal robotic assistants and bionic prosthetic appliances. At the same time, this development focuses on the use of popular and cheap component parts, and simplification of the structure to ensure low production cost.

Keywords: Anthropomorphic Gripping Manipulator, Bionic Hand Prosthetic, Gripping of Items, Robotics

1. Introduction

1.1 Problem Description

Currently, high activity and significant growth in the number of developments and research to create human-like robots and grippers is observed. Prototypes of anthropomorphic robots that include hands and multilink grippers and are capable of complicated manipulations with items around. A great variety of robotized grippers as sets for assembly and ready-to-use devices is represented at the world market. The following are the most technically advanced grippers that are closest to the developed experimental model of the anthropomorphic gripper: Shadow C6p Dexterous Hand based on artificial muscles and Shadow C6M Smart Motor Hand[1] based on electric drives by SHADOW ROBOT COMPANY LTD and DLR Hand II.[2]

Thus, it may be assumed relevant to implement a multilink anthropomorphic gripper (artificial hand) and intellectual positioning, gripping and item-applied pressure control system of gripper joints to include control algorithms for electric drive-based dynamic systems, data processing of distributed sensor system, planning of gripping unit movement trajectory, with regard to mutual coordination of movement of several fingers, for secure gripping of items of sophisticated geometric form. These algorithms may be built upon artificial neuron network apparatus to ensure adaptivity, resistance to uncertainties of controlled object specification, capability of self-learning and decision-making.

*Author for correspondence

1.2 Theoretical Basis and Research Tasks

1.2.1 Item Gripping Control System

At the moment, there is a number of approaches to creating gripping control systems, which differ in their control methods, including input data used for solving the control task. One should distinguish between two different classes of gripping control systems:

1. control systems that use sensor data;[3,4]
2. control systems that use a video signal;[5-7]

Item gripping is a difficult task for robots. This complex gripping task may be defined as a task of contact with an item and manipulation task. The task of contact the item is the ability of gripping fingers to follow the trajectory accurately. The task of item manipulation is determined from the point of view of force applied by the fingers to the item.

The following difficulties are encountered in design of the first class control systems:

1. no a priori knowledge of item size, texture, softness, or contact dynamics;
2. the necessity to grip the item relatively fast and carefully to prevent any damage to the item.

Preliminary contact with the item is required and appropriate gripping forces must be applied by each gripping finger before manipulating the item. Appropriate conditions must be determined for successful manipulation, while information about the item type is not available. Thus and so, the gripping control system must be adaptive.

Human fingers manipulate items with the help of appropriate forces, even when the weight and friction coefficient in the point of contact with the item is not known. Moreover, human fingers allow for tactile sensing to feel the item texture in a way for the required finger forces to be applied for item manipulation, excluding any slipping. Several control methods were suggested for item gripping, based on gripping operations done by a human in usual conditions.[8-11] These methods involve establishing a contact with the item in the necessary point and gripping orientation, following the predetermined path, while guided by the accurate known item specifications and shape.

1.2.2 Planning Movement Trajectory

Control operation synthesis is possible by way of direct control commands generated by servomotors according to the determined law, while the position and dimensional orientation of the gripper end-effector is determined by direct kinematics. Such method of trajectory generation is fit for simplest grippers like a claw, consisting of two fingers driven by a single (independent kinematic chain) or two (independent control) drives.

To grip items of sophisticated shape, one should control position and orientation of the gripper end-effector, usually, such grippers offer more degrees of freedom. The task of controlling such gripper (multi-finger grip) is reduced to control that would allow end-effector of each finger to move in space along its own trajectory. The movement trajectory describes a coordinate and orientation at any time. At the same time, control commands of servomotors are generated by means of solving an inverse kinematic task of each finger.

A set of movements that are typical for a human performing most item manipulations in everyday life are inputs for movement trajectory generation.

Let us consider gripping items with the help of eight (8) different item gripping patterns on a test scene. These patterns are the most representative set of grips that should allow estimating the efficiency of the developed control system to be used for development of bioprosthetic appliances. This set is de facto standard and it is used in other countries to test bioprosthetic appliance and anthropomorphic gripper control system functionalities. Manipulator finger designations are the same as human fingers: thumb, index finger, middle finger, ring and little finger. Manipulator fingers are straight and at rest by default.

1. gripping by all five fingers. For gripping by force, all five hand fingers are bent towards the center of the palm and their movement trajectory is shaped like a sphere.
2. Plain palm gripping (option 1). Four palm fingers are bent in a way to form a plane and the thumb is bent towards them for the movement of the *index finger and thumb* to be in the same plane.
3. Plain palm gripping (option 2). Four palm fingers are bent in a way to form a plane and the thumb is bent towards them for the movement of the *middle finger and thumb* to be in the same plane.
4. Cylinder-like palm gripping (options 1 and 2). Four palm fingers are bent in a way to form a cylinder side face and the thumb is bent towards them for the movement of the middle finger and thumb to be in the same plane; movement of the index and thumb are in the same plane for the other option.

5. Gripping by three fingers. This grip is done by simultaneous opposing movement of the middle finger, index finger and thumb.
6. Precision gripping (options 1 and 2). The index finger is locked with the opposed thumb, while all other fingers remain at rest; the middle finger and thumb are interlocked for the other option.

Predetermined gripping patterns generally allow for holding non-deformable items of simple geometrical shapes, such as:

1. a flat item (a sheet of paper, plate);
2. a cube or 3D cube;
3. a thin cylindrical item (a pen, pencil, fork, spoon); or
4. a thick cylindrical item (a tube, hammer).

Overall, joint group control algorithm may be presented with the help of the following movement phases:

1. primary phase: bending the proximal phalange till contact groups of the phalange interact directly with the item;
2. secondary phase: bending the medial phalange till contact groups of the phalange interact directly with the item; and
3. final phase: bending the distal phalange.

For synchronous movement of separate joints of one finger, the approximation algorithm may be modified by means of normalizing their movement speeds till the given position is reached for the φ_i specified time τ.

Movement of all joints within the working area, i.e. all movements being in the range of definition of working space of the manipulator is the principal advantage of this method based on direct manipulator kinematics.

Application of method of planning movement trajectory allows to pre-calculate the following parameters of joint movement over time:

1. Angular position;
2. Movement speed; and
3. Acceleration.

Non-linear approximation

The following are limiting conditions of the approximating function:

$$\varphi(0)=0,\ \varphi(T)=1,\ \varphi'(0)=0,\ \varphi''(0)=0,\ \varphi'(1)=0,\ \varphi'(1)=0 \quad (1)$$

The following movement trajectory approximation methods may be used to fulfill the given condition:

1. polynomial approximation;
2. cycloidal approximation
3. approximation using radial basis functions.

Polynomial approximation (3-4-5)

As provided in[12], the following expression may be used as an approximating polygon:

$$\varphi(\tau) = 6\cdot\tau^5 - 15\cdot\tau^4 + 10\cdot\tau^3 \quad (2)$$

$$t = \frac{t}{T} \quad (3)$$

Where,

T – time for the the end-effector to go from the initial to the final position;

t – current time.

Polynomial approximation (4-5-6-7)

For an additional requirement $\varphi'''(0)=0, \varphi'''(1)=1$, a polynomial of higher order must be used.

$$\varphi(\tau) = -20\cdot\tau^7 + 70\cdot\tau^6 - 84\cdot\tau^5 + 35\cdot\tau^4 \quad (4)$$

According to Figure 1, the basic difference between two alternative polynomial approximations is the value of acceleration for acceleration and braking. For polynomial 4-5-6-7, joint acceleration and braking time is up to 40% of total movement time. This measure is ca. 20% of total movement time with polynomial 3-4-5.

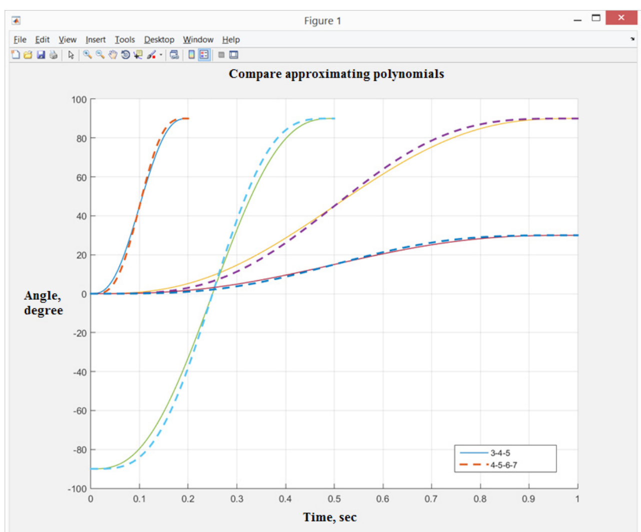

Figure 1. Comparing trajectories, using polynomials 3-4-5 and 4-5-6-7

For the task of generating movement trajectory of manipulator finger, 3-4-5 polynomial approximation is enough, as long as this polynomial order is enough to describe the trajectory connecting two dots (initial and final position).

According to the developed joint group control system program model, the control algorithm may be stated as follows:

1. Wait for target indication
2. Receive a target angle into the control system;
3. Receive a limit force on the contact platform into the control system;
4. Verify the given values with view to direct kinematics limitations;
   a) If the indicated targets cannot be reached, initiate an error command and go back to step 1 of this algorithm;
   b) If the indicated targets can be reached, go to step 5;
5. Process an angle sensor;
   a) Determine the angle - receive data from the angle sensor and convert the physical value;
   b) Determine angular velocity of joint rotation - differentiate angle sensor reads;
   c) Determine possible force on the contact platform of the phalange, based on solid body rotation dynamics
6. Process a tactile sensor
   a) Determine current value of external applied force for current joint
7. Joint angle position controller
   a) If the indicated target was not reached, the following iteration is done to calculate drive control signals and transmit the control signal to the output power electronics circuit cascades; go to step 5
   b) If the indicated target was reached, stop the motor and switch to position hold mode, go back to step 5
   c) If the generated force limit was reached on the contact platform of the finger phalange, perform emergency stop, generate an error command and go to step 1

A mechanical gripping manipulator structure was developed as result of this research, and it comprises 4 groups of front joints (fingers) and one opposite group.

Electric motors that were used as servomotors ensure higher energy efficiency, as compared to commutator motors used in similar developments.

QTC material that is sensitive to elastomer pressure and makes it possible to obtain data about external interaction, using twenty five (25) electrodes forming a 5x5 matrix, is used in tactile sensors.

Gripping manipulator hardware and software comprise an integrated gripping and joint position control system, which makes it different from similar solutions that involve exclusively a software interface for individual manipulator joint position control and an external gripping control unit.

According to our mathematic simulation and virtual simulation of the gripping procedure for a variety of items, it is reasonable to use kinematically dependent relations in distal phalanges, thus and so, in accordance with the principal kinematic configuration, the manipulator comprises 16 independent degrees of freedom and 4 kinematically connected degrees of freedom in distal phalanges.

Basic specifics of the selected manipulator configuration:

1. Ensuring movement transmission to joints, while servomotors are located outside of the gripping hand structure;
2. Using servomotors based on commutatorless motors as servomotors;
3. Using elastic gears to transmit movement in kinematically connected joint pairs for enhanced adaptation to sophisticated item shape;
4. Reducing relative structure weight to generated force by using commutatorless motors.

1.2.3 Data communication flowchart

Data communication protocol developed is effective for point-to-point connection of the master and slave devices. However, a combined connection (see Figure 2)

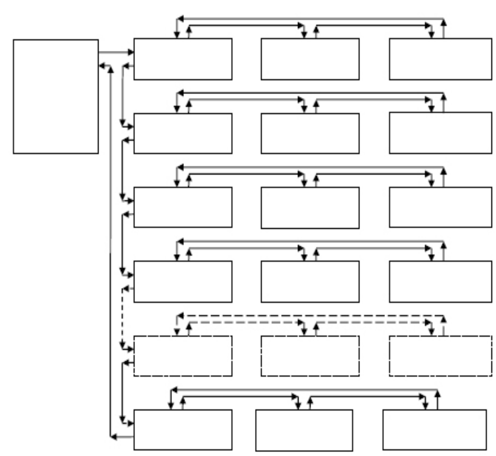

Figure 2. Combined cascade connection of NxM modules by assigning masters

was used for developing structural configuration solutions for the manipulator to ensure information exchange between microprocessor finger drive modules (slave) and manipulator microprocessor module (master).

Thus, the protocol developed must be transformed, with view to the specifics of signal distribution in SPI interface lines for the cascade connection. Particularly, for such connection, data packages must be combined for all slave devices into a common package, while dividing into fields in a way for each transmitted word (8 or 16 bites) out of the overall sequence to match the connection sequence of the slave devices (see Figure 3).

According to this flowchart, the sequence of data bites that are addressed to different devices must be reversed, as long as the cascade connection pattern operates according to the shift register principle, where the first device receives its data package last.

Thus, modification of the data communication protocol involves sets of microprocessor modules (Servocontroller) grouped according to their attribution to the same joint group (finger), while data packages that are addressed to each slave module are generated in applications of the manipulator controller.

The necessity of simultaneous control of a big number of servomotors and query of feedback sensors, including arrays of tactile sensors, imposes high requirements to performance of the manipulator controller microprocessor module. To enhance performance and ensure reliable real-time operation, software modules were optimized. In particular, direct DMA memory access channels were introduced for data exchange between peripheral processor modules and program units.

1.2.4 Manufacturing an anthropomorphic gripping manipulator

A three-axis-controlled (CNC) mill was used to manufacture an anthropomorphic gripping manipulator prototype. This mill is controlled via special developed applications that comprise a list of movement trajectories of mill tool.

CNC code for the mill was developed, using SolidCAM package, an add-on of SolidWorks CAD interface. SolidCAM provides time optimization and machining

Figure 3. Data transmission flowchart in cascade mode

accuracy of any part, editing of movement trajectories, flexible set-up of monotypic operations for group machining of several parts, calculation of movement trajectories for a variety of tools. SolidCAM also features virtual simulation of part machining procedure, which ensures visual monitoring of correct application run in the mill CNC. The program developed may be converted into control G-codes for any mill, and a special post-processor suitable for such mill is used at program export for such purpose. Thus and so, machining programs that were previously developed may be used for mass production.

To simplify machining of the workpiece and reduce milling time, all monotypic parts are placed back-to-back on the same workpiece and connected with thin connecting links to hold them together (see Figures 4-5).

The following changes were introduced as a result of further development of the manipulator structure:

a) Guiding boars were introduced on the working surfaces of joints to stabilize the flexible gear and prevent it from slipping into the movable finger joint. The guiding board is a sloping surface located along the

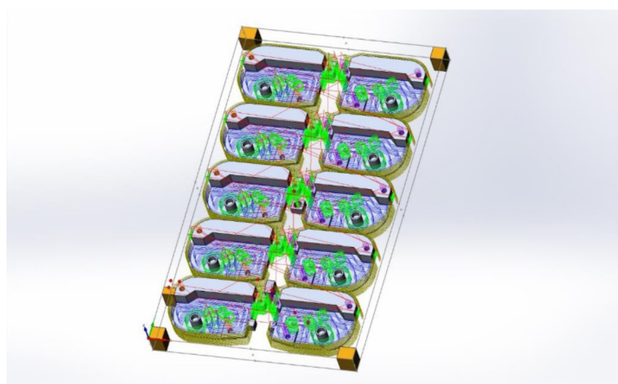

Figure 4. Assembly for group machining of parts

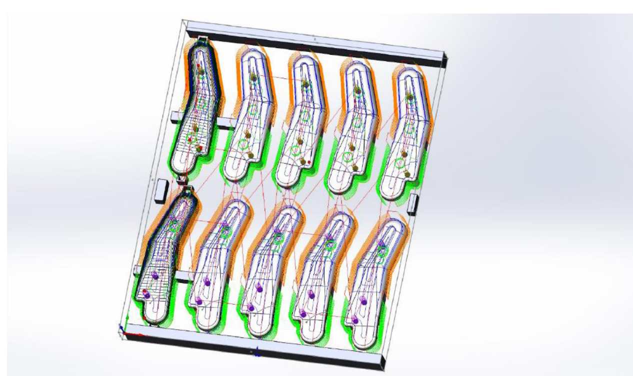

Figure 5. Assembly for group machining of parts

working pulley of the finger phalange. Guiding board is shown in Figure 6.

b) Rubber inserts that cover feedback tactile sensors were further developed to position such sensors on the contact surfaces of fingers and palm. These inserts are made by cast molding of two-component silicone resins. Inserts of the distal and proximal finger phalanges and the palm itself are highlighted in red in Figure 7.

c) To enhance strength of the wrist joint, central joint crosspiece was enlarged. The crosspiece is provided in Figure 8.

d) To prevent cross-impacts of flexible gears, the connection pattern for finger joints and servomotors was modified. All crossings of flexible gears and guiding spring braids were eliminated.

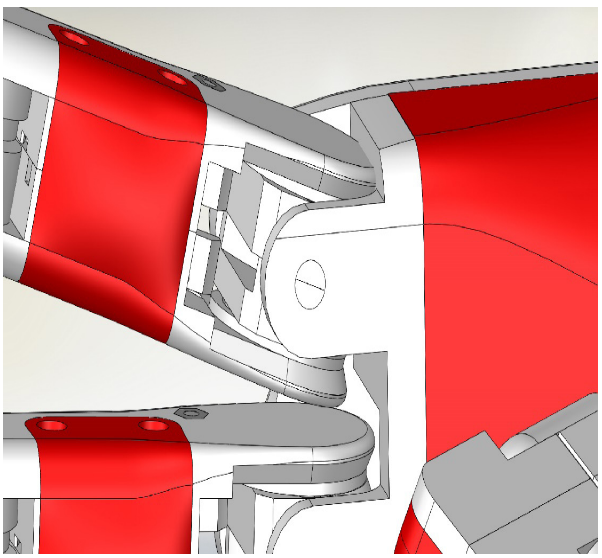

Figure 6. Guiding boards on the working surfaces of joints

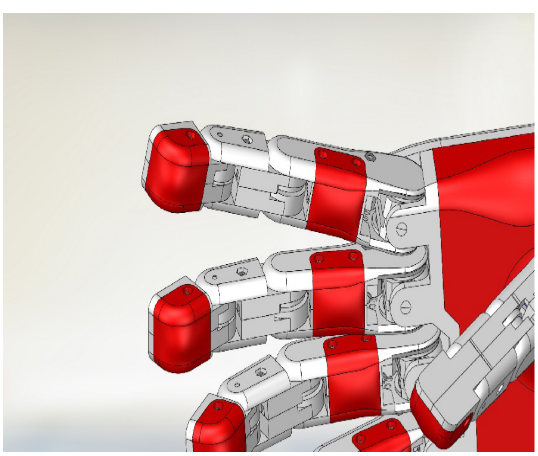

Figure 7. Rubber inserts.

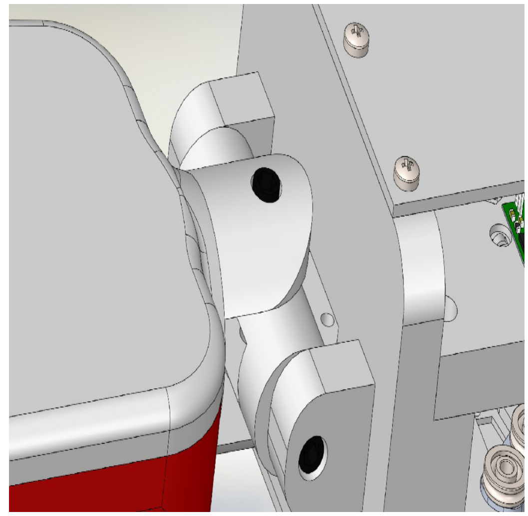

Figure 8. Wrist joint crosspiece.

e) To make drives smaller, pilot bearings were replaced and V623UU type was used, outer diameter 10 mm, inner diameter 3 mm, thickness 3 mm. A set of finger drives and measuring levers including pilot bearings is presented in Figure 9.

f) To enhance strength of flexible gears and increase allowable load, 0.5 mm working thread was replaced by 0.7 mm thread. A woven fishing line made of Dyneema PE fiber is used as the working thread. This line has high wearing and low stretching features against high structural performance; 0.8 mm line can withstand breaking load of 250 pounds or 113.4 kg.

g) To enhance measurement precision of angle position of finger joints and measuring levers, absolute magnetic encoders (angle measurement precision 0.022 degrees) were installed. A PCB model, including an encoder, is provided in Figure 10.

h) To synchronize bending of the distal and medial phalanges, diameters of driving pulleys of kinematically dependent flexible gears were adapted. New ratio of gear is 1:1.2, which allows for finger bending similar to human. When the distal phalange rotates by 90 degrees, the medial phalange rotates by 110 degrees. Inner finger driving pulleys are shown in Figure 11.

i) A high strength stainless fitting was used for manipulator assembly.

j) To improve load capacity and smooth rotation, medial phalange axles of rotation in the medial joint were installed on ball MR74 bearings with the following dimension: outer diameter 7 mm, inner diameter 3 mm, and thickness 2.5 mm.

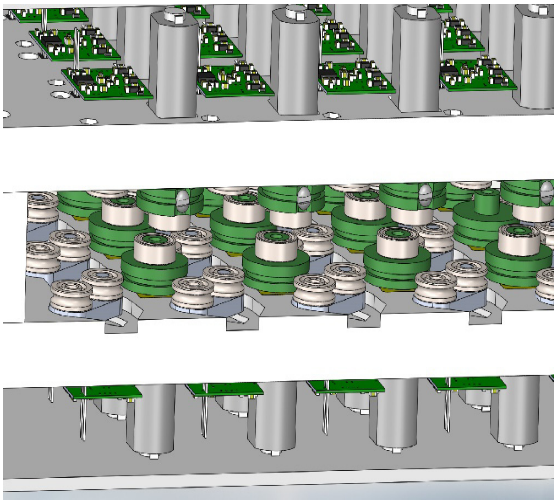

Figure 9. Finger drive set.

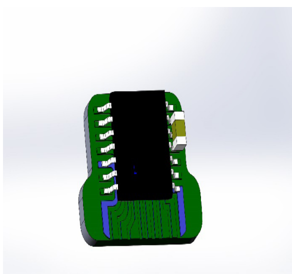

Figure 10. PCB of a magnetic encoder.

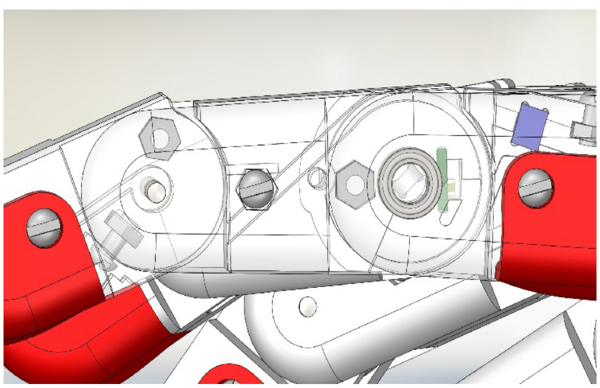

Figure 11. Finger phalange driving pulleys.

2. Methods

2.1 Planning an Experiment

The target of experimental study of manipulator functionality is:

1. Verifying conformance of the tested unit to the requirements of corresponding paragraphs of the Terms of Reference;
2. Determining gripping options adequate for gripping and holding the item.

This manipulator is considered to have successfully passed the test, provided there is at least one successful experiment. At least five trials are performed for each item conformance and gripping option combination.

Harrington's desirability function is a convenient way of estimating the generalized response. This function involves conversion of actual values of the measured parameters into a non-dimensional value, using a desirability scale. Let us use a ready-to-use table that was constructed empirically (see Table 1).

To discard random errors (defect), one may also use Student's t-test.

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

where (n-1) - number of degrees of freedom, equals to the number of trials minus one;

y - arithmetical average;

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \quad (2)$$

$$\frac{y-\bar{y}}{s} \geq t \quad (3)$$

Lists of items and gripping options are provided in Tables 2 and 3.

Table 1. Harrington's desirability scale

Desirability	Score on the desirability scale	Equivalent score
Very good	1.00 – 0.80	8
Good	0.80 – 0.63	5
Satisfactory	0.63 – 0.37	3
Bad	0.37 – 0.20	2
Very bad	0.20 – 0.00	1

Table 2. Conformance of variable items

No	Item
1	Grape
2	Sphere, diameter: 50 mm
3	Banana
4	Pear
5	Cup
6	(Flat-nose) pliers
7	Flat screwdriver

3. Findings

As a result of our experiment with the mentioned items, successful performance of gripping operations of rigid and soft items of sophisticated shape was demonstrated, including deformation in gripping (see Figures 12-13).

A summary table including best combinations of compression patterns and items that ensure best holding was compiled, according to the experimental studies of gripping manipulator functionality (see Table 4).

4. Discussion

The experimental tests of the simplified manipulator version and manipulator comprising 18 degrees of freedom

Table 3. Matching variable gripping options

No	Gripping option
1	Power grasp
2	Plane grasp
3	Cylinder grasp
4	Tripod grasp

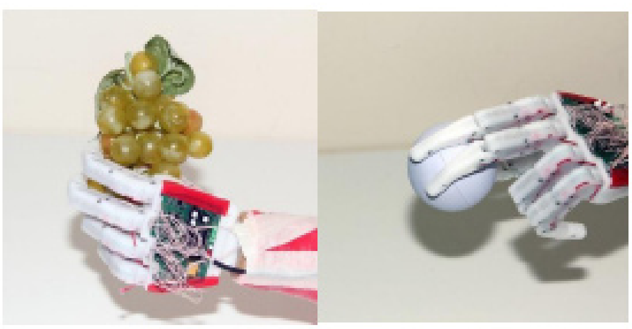

Figure 12. Gripping soft items of deformable shape

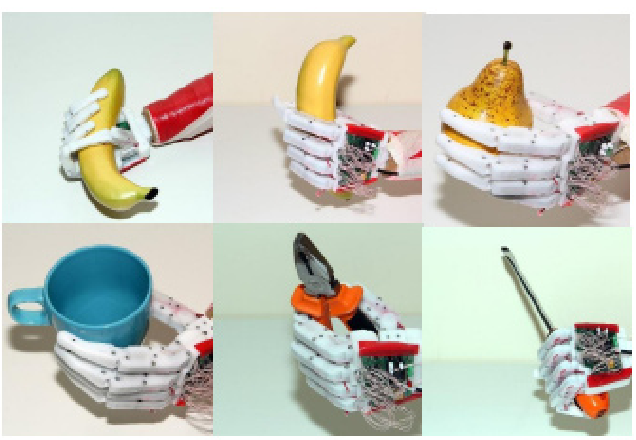

Figure 13. Gripping rigid items

Table 4. Summary table of best combinations of gripping patterns and items

	Power grasp	Plane grasp	Cylinder grasp	Tripod grasp
Grape	+	+	+	+
Sphere, diameter: 50 mm	+	n/a	+	+
Banana	+	+	+	n/a
Pear	+	n/a	+	n/a
Cup	+	n/a	n/a	n/a
(Flat-nose) pliers	+	n/a	n/a	n/a
Flat screwdriver	+	n/a	n/a	n/a

demonstrated compliance of the obtained capabilities with the established requirements, and the following hypotheses of manipulator appearance and control principles were confirmed:

a) finger movement synchronization (distributed pressure control) due to tactile sensors leads to adaptation to item form
b) the use of elastic gears in the distal phalange leads to improved secure holding of the item in the gripping head
c) sufficiency of the selected set of patterns to hold the given set of items
d) joints that are involved in a pattern must be placed around the geometrical center of the item to ensure secure gripping of items.

5. Conclusion

According to our testing of the simplified manipulator version and manipulator comprising 18 degrees of freedom, recommendations were made to further develop the manipulator comprising 18 degrees of freedom to ensure the preset engineering data. The following changes were introduced to technical documentation, based on the further development:

a) Re-configuring the forearm to avoid cross impact of various degrees of freedom on flexible gears
b) Changing pulley diameters to adjust the transmission ratio, with view to the requirements to the generations force to replace commutatorless motors by commutator motors.
c) Installing a thicker drive thread (0.8 mm instead of 0.5 mm) to ensure higher load capacity

d) Reducing redundant degrees of freedom at distal phalanges to ensure adaptivity to the form of gripped item and reducing cross impact of flexible gears, it was decided to redevelop the control principle for the distal phalange by installed an elastic kinematically connected gear
e) Changing the data communication protocol, i.e. enhancing efficiency, with view to the specifics of drive control circuit connection by combining serial and parallel connections
f) Enhancing accuracy of determination of angle joint group position up to 0.022 degrees.

Microprocessor modules, feedback sensor system, and power electronic module were developed and may be broadly used in educational robotics for building various robotic systems of low power (up to 150 W) for each swiveling block.

Developed software modules may be used for building control system of an anthropomorphic gripping manipulator of kinematic configuration that resembles a human hand, but involving a varying number of controlled and dependent degrees of freedom.

Positive results were obtained, and due to the fact that manipulator shortages were discovered and eliminated, one may further proceed with tuning series production process of anthropomorphic gripping manipulators with the following applications:

1. in household robotics - installation onto mobile robotic sets for remote complicated contact operations;
2. in industry, in industrial robot development - for automation of assembly and contact operations;
3. in rehabilitation medicine, as the basis for development of bioprosthetic appliances of upper human extremities;
4. in educational robotics, for studying principles of build-up and control of multilink manipulators of various configurations.

Our own element base developments in the final product will enable significant cut in final product cost.

6. Acknowledgments

This research was financially supported by the Ministry of Education and Science of the Russian Federation under the Grant agreement # 14.577.21.0136 as of "24" November 2014 (Unique identifier of the agreement: RFMEFI57714X0136); the grant is provided to perform the applied research on the topic: "Development of universal gripping device for performing an anthropomorphic type contact operations with high accuracy and reliability". Work on the project is carried out at the Moscow State University of Mechanical Engineering (MAMI).

7. References

1. Shadow Dexterous Hand E1 Series. Technical Specification, Shadow Robotics. 2013. Available from: http://www.shadowrobot.com/wp-content/uploads/shadow_dexterous_hand_technical_specification_E1_20130101.pdf. Date accessed: 27/08/2016.
2. Liu H, Wu K, Meusel P, Seitz N, Hirzinger G, Jin MH, Chen ZP. Multisensory five-finger dexterous hand: The DLR/HIT Hand II. 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems. 2008 Sep. p. 3692–7. Available from: https://core.ac.uk/download/pdf/11135194.pdf. Date accessed: 27/08/2016.
3. Fishel JA, Loeb GE. Sensing tactile microvibrations with the BioTac—Comparison with human sensitivity. 4th IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob). 2012 Jun. p. 1122–7. Doi: 10.1109/BioRob.2012.6290741.
4. Wettels N, Parnandi AR, Moon JH, Loeb GE, Sukhatme GS. Grip control using biomimetic tactile sensing systems. IEEE/ASME Transactions on Mechatronics. 2009; 14(6):718–23. Available from: http://www.syntouchllc.com/Media/_publications/2009_Wettels_ASMETransMech.pdf. Date accessed: 27/08/2016.
5. Kheng ES, Hassan AHA, Ranjbaran A. Stereo vision with 3D coordinates for robot arm application guide. 2010 IEEE Conference on Sustainable Utilization and Development in Engineering and Technology (STUDENT). 2010 Nov. p. 102–5. **Doi:** 10.1109/STUDENT.2010.5686996.
6. Fan X, Wang X, Xiao Y. A combined 2D-3D vision system for automatic robot picking. Proceedings of the 2014 International Conference on Advanced Mechatronic Systems. 2014 Aug. p. 513–6. Doi: 10.1109/ICAMechS.2014.6911599.
7. Anglani A, Taurisano F, De Giuseppe R, Distante C. Learning to grasp by using visual information. CIRA'99. Proceedings IEEE International Symposium on Computational Intelligence in Robotics and Automation. 1999; 7–14. Doi: 10.1109/CIRA.1999.809933.
8. Yoshikawa T, Nagai K. Manipulating and grasping forces in manipulation by multifingered robot hands. IEEE Transactions on Robotics and Automation. 1991; 7(1):67–77. Doi: 10.1109/70.68071.

9. Li Z, Hsu P, Sastry S. Grasping and coordinated manipulation by a multifingered robot hand. The International Journal of Robotics Research. 1989; 8(4):33–50. Doi: 10.1177/027836498900800402.
10. Lewis FW, Jagannathan S, Yesildirak A. Neural network control of robot manipulators and non-linear systems. CRC Press. 1998. Available from: http://www.uta.edu/utari/acs/FL%20books/Lewis_Jagannathan_Yesildirek%20-%20neural%20network%20control%201999.pdf. Date accessed: 17/05/2016.
11. Arimoto S, Nguyen PTA, Han HY, Doulgeri Z. Dynamics and control of a set of dual fingers with soft tips. Robotica. 2000; 18(01):71–80. Doi:10.1017/S0263574799002441.
12. Angeles J. Fundamentals of robotic mechanical systems. Theory, Methods, and Algorithms. 4th ed. (Vol. 124). New York: Springer-Verlag, 2014. Doi: 10.1007/978-3-319-01851-5.