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# Development of an Anthropomorphic Gripping Manipulator: The Study of Kinematics and Virtual Modeling of Grip

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**Abstract:** The article is a study into the kinematic scheme of a newly developed anthropomorphic manipulator designed to perform gripping and holding tasks on items from a predefined set. Within the study is the implementation of a mathematical model describing the kinematics of a multilink manipulator using the GraspIt package. The method used in this study allows for the calculation of design parameters for manipulator grip functions at an early stage of the creation process as well as to verify the effectiveness of the kinematic scheme of the manipulator on how adequately it can perform its primary functions of griping and holding certain objects, which is vitally important in the design of universal anthropomorphic handling manipulators for special applications, such as bionic prostheses as well as manipulators with arbitrary kinematic schemes. The presented program model provides a preliminary calculation of the motion trajectories of the manipulator unit through the so-called eigengrasp (synonym-synergy, synchronous motion) and can be used as a virtual model for building embedded control systems for robot manipulators. It is shown that in the development of anthropomorphic handling manipulators for operating with small-sized objects it is more efficient to use the monkey scheme, but if the main group of target objects is primarily large items, then it is better to use the human scheme.

**Keywords:** Anthropomorphic Grip, Kinematics of the Manipulator, Method of Modeling of Robot's Manipulator, Object Grasping, GraspIt, RUbionic

## Introduction

Modern society is increasingly confronted with problems related to the increasing costs of low-skilled labor.

We are currently living in the sixth techno-economic paradigm and the leading role in it is given to the development of personal and service robotics. Intellectual robots are gradually penetrating into all corners of daily life-from robotic toys to robotic assistants for personal waiters and nurses who perform household duties in the care of people with limited mobility. Additionally, these robots can be used to carry out low-skilled jobs such as sorting products on an assembly line, loading/unloading conveyor belts, packing finished products or pre-packing. As an effect of this, with the widespread rise in price of low-skilled labor, the task of automation in carrying out routine work is becoming very real and almost necessary.

The need within companies for production line universal handling devices and intelligent control systems becomes more and more urgent with each passing year. According to expert estimates (ANO, 2015) in the coming years, more than 90% of assembling technological lines will be equipped with such handling devices. One of the options for increasing the performance of such technological lines is the use of anthropomorphic type universal grippers, capable of adapting to complex geometrically shaped objects and having the ability to develop and sustain the grip and able to change the profile of the grip (maneuver).

A universal solution is anthropomorphic robots that are able to perform all the necessary manipulations of surrounding objects with the freedoms inherent in humans.

Usually in works involving grippers, universal controllers with only partial resemblance to the kinematics of the human hand, meaning that the manipulators only have limited function, are used, for example the Barrett Hand (Chinellato *et al*., 2003). However, there are a significant number of anthropomorphic manipulators such as the Meka Hand, DLR II (Provenzale *et al*., 2014), Robonaut (Lovchik and Diftler, 1999) and the Shadow Dexterous Hand (Karnati *et al*., 2013). The actual task is the optimization of the design of a manipulator to achieve a balance between the number of independently controlled degrees of freedom and the ability to adapt the manipulator to a complicated or variable object shape.

There is currently a large amount of activity and a significant increase in the number of developments and primary scientific research into the field of humanoid robots and grip manipulators. The human hand represents a universal biomechanical tool that allows for the performance of power operations as well as to grip objects of arbitrary shape reliably through complex coordination operations through use of the fingers. That is why the principles of bionics (biomimetics) are becoming increasingly popular among developers of technical devices and systems (Ciocarlie *et al*., 2008).

In the development of anthropomorphic gripping devices the following contrasting tendencies are often employed:

- An increase in the number of independently controlled degrees of freedom in the hand. Gripping devices with many degrees of freedom have greater flexibility, mobility and can be used to perform more complex tasks, which require the precise manipulation of objects with complex shape. This is especially typical for remote-controlled anthropomorphic robots, working in a mode which mimics the movements of the operator and which is used in special conditions-space research, security and so forth. To realize the full potential of constructive complex multistage grippers a complex support system is often necessary, such as machine vision, etc
- A reduction in the number of independent degrees of freedom. A large number of independent degrees of freedom and feedback sensors significantly complicate the manipulator control system. It is worth noting that the total number of degrees of freedom of a manipulator may exceed the number of independently controlled extents, this is ensured by the kinematic connection links. For example this tendency is characteristic for bionic hand prostheses

When using kinematically connected transmission of motion from median to distal phalanx the functional power of the grip, while holding objects, is significantly limited, especially with objects of small geometric dimensions, because with full flexion of the finger the distal phalanx is in turn fully bent adjoining the proximal phalanx. Thus, the main working surfaces employed when gripping small-sized objects are the distal and the proximal phalanx, while the median phalanx is mainly intended to provide a greater degree of mobility to the distal phalanx and generate adaptability to the surface of the object.

Manipulators with kinematically connected swivel nodes have a limited ability to adapt to the shape of an object. But nevertheless, the difference in the gripping efficiency may become an insufficient argument for their use in independent anthropomorphic manipulator designs because additional controlled degrees of freedom require more actuators that, structurally, are not always justified.

The primary research objective of this study is an estimation of the effectiveness of the chosen kinematic scheme of a manipulator designed for gripping objects. The task of this paper is to summarize the current approaches to the modeling procedure related to the gripping of objects from a predetermined set, as well as the study of the quality of hold upon an object shown by the manipulator on the basis of the metric proposed (Miller and Allen, 1999) in relation to an newly developed anthropomorphic handling manipulator.

In nature, an anthropomorphic hand has some differences compared with the hand of primates (monkeys). In humans the plane of the thumb is opposed to the little finger, which allows the little finger and the thumb to be bent along the same plane in oncoming movement. In primates, the thumb is opposed to the middle finger. One of the research objectives of this paper is a quantitative assessment of these two characteristics (schemes).

When performing grip functions on objects with complex shape it is necessary to control the position and orientation of the executive gripping body, usually such grippers have a much greater number of degrees of freedom. The task of managing a lot of finger grips is reduced to such management at which the executive body of each finger moves only in the space on its individual trajectory. The trajectory of movement describes the coordinates and the orientation in space for each moment in time. The coordinated actions of several fingers form a pattern of movement. Commands for the drive control of the executive bodies are formed by solving the inverse kinematic problem of each finger.

Section 2 describes the direct kinematic model of the manipulator.

Section 3 contains a plan of experiments to investigate the effectiveness of object retention as well as a description of the set of reference objects.

The results of the experiments are presented in section 4.

There are prototypes of anthropomorphic robots with arms and multilink grippers capable of performing complex manipulation of objects within the given environment. In the international market a significant range of different robotic handling devices is represented. From the list of handling devices the most closely related to the one presented in this study in terms of technology and design are: Shadow Hand made by SHADOW ROBOT COMPANY LTD, Anthropomorphic Hand SAH made by SCHUNK and the DLR Hand II developed by the German Aerospace Center.

Through use of the principles of biomimetics such manipulators allow for the adaptation and wide application of new advanced robotic systems in an environment shaped by human activities, providing the ability to grip, hold and manipulate objects of arbitrary geometric shape. The main disadvantage of these manipulators is their limited availability mainly due to their primary purpose which is research related to multilink manipulator control problems.

In order to ensure that industrial and personal anthropomorphic manipulator robotics technology is accessible, much more development in this direction is required. Our development is one of them. Using the experience of creating a gripping manipulator (Lovchik and Diftler, 1999; Chinellato *et al*., 2003; Grebenstein *et al*., 2011; Karnati *et al*., 2013; Provenzale *et al*., 2014), the approaches to mathematical modeling (Dung *et al*., 2010; Crenganis *et al*., 2012; Dean-Leon *et al*., 2012) and management of the procedure of handling objects (Tomovic *et al*., 1987), we are doing work whose primary purpose is the study and development of a kinematic scheme for a manipulator to grip objects represented by the simplest geometric shapes: Cube, sphere, cylinder. The results of this work will be used to develop a number of finished products:

- Bionic prosthetic hand
- Universal anthropomorphic gripping device with adaptations to perform gripping tasks for operation in robotic systems and as personal social robotic assistants

The main approaches in the development of algorithms for control used when gripping objects are:

- The synthesis of a fixed set of movement patterns for gripping a limited class of objects with a known or pre-defined shape using compression force
- An adaptive synthesis of commands to control the grip using tactile sensory information
- Perform movements which mimic an operator's actions controlled by data retrieved from a motion capture system

Forming a database of movement patterns for the manipulator (Provenzale *et al*., 2014; Castellini and van der Smagt, 2014), which contains the path of movement of individual links can be implemented through virtual reality gloves and an analysis of the movements made by the operator while performing manipulations of various objects. Analysis of the data permits the choice of the most appropriate pattern in the performance of initial placement of the grip around the object, as well as to generate the synchronization of movements between the individual gripping fingers.

The contact areas that are located on the distal and medial phalanges of the fingers of the manipulator, inside its construction, include tactile sensors that provide a measure of the effort applied when gripping objects.

The presented method (Bernardino *et al*., 2013) of the synchronous movement control of a multilink manipulator can be applied to the control of the grip of objects with different shapes providing several types of handling. There are two approaches to the procedure of grip control. The first (classical) approach is based on defining a set of points on the surface of the gripped object in such a way that their relative position, relative to the center of mass at the application of external forces, provides static equilibrium, or the so-called geometric grip. In this case the gripping of an object and the calculation of trajectories of motion of the fingers use the inverse kinematics method. The second approach, which is based on human experience, is empirical and based on the classification of objects. The object grasping process is divided into several phases: A preliminary grasp, direct grasp of the object and further stabilization of the object. The methodology (Bernardino *et al*., 2013) of synchronization for the motion of separate fingers is based on receiving data from a system of tactile sensors and its analysis during the grasping phase (direct grasp). When making contact with the object the direction of vectors of developed power (normal and tangential components) at the point of contact are determined and the trajectory of the links are given corrections which can reduce the magnitude of the tangential component of force which in turn increases the developing effort of compression on the object and increases the energy efficiency of the actuator's drive mechanism.

Design of the control system for gripping objects with different shape, size and texture is computationally a difficult task because the parameters of movement and required ongoing efforts of individual links can not be accurately determined. The mathematical formulation of the problem of gripping an object by the multilink manipulator is reduced to solving systems of linear equations (Murray *et al*., 1994) linking the space of contact points on the surface of the object, taking into account the spatial constraints imposed by the kinematical scheme of manipulator.

In order to minimize the computational complexity of this task, most designs involving handling manipulators of robot are calculated in such way as to work only with a certain set of template objects (Goldfeder *et al.*, 2009). The position of the object relative to the manipulator, its weight, orientation and shape are pre-defined for such templates. Using this information, the manipulator moves along a predetermined trajectory to reach the coverage area and to grab an object using its fingers (or related mechanism) with pre-established force. Thus it maintains constant integrity on the object during manipulations. If the existing efforts of the fingers are not enough the object can slip, while if the force applied is too great it can damage or destroy the object. Moreover for successful manipulation and to avoiding slipping, the fingers of the manipulator must come into contact with the object at a predetermined position and with the correct orientation.

The mathematical description of the motion trajectories of the links related to a specific pattern of movement can be performed by specifying the initial and final position in space and the angular values for the rotary nodes can be determined by solving the inverse kinematic issue. In the work (Ciocarlie *et al.*, 2007; Ciocarlie and Allen, 2009) a method to reduce the factor of complexity related to the task of planning grip functions for different kinematic schemes of manipulators by using the so-called eigengrasp was presented. With regard to developing a handling manipulator the control task can be summarized and presented in the form of combinations of the three groups of eingengrasp:

- Moving the fingers apart (sideward movement)
- Synchronous compression of the fingers into a closed hand position
- Moving the thumb to the side

This approach can significantly simplify and automate the process of modeling the gripping of objects while providing a formation principle for complex coordinated movements by the manipulator.

Providing that the gripping of an object is based on a template (pattern) of movements it can be reduced to the following three phases:

- Determine the trajectory of the hand to put the handling manipulator in the correct position around the object
- Determine the trajectory so that the fingers to come into contact with the object in the right place and with the correct orientation
- Apply the optimum effort, on the object, that is required for a sustained hold

In practice, researchers are faced with the need to develop a large number of patterns for different objects. In the result of the analysis (Feix *et al.*, 2009), the literature on the biomechanics of the human hand, 17 unique classes of movements (patterns) which a person uses while manipulating environmental objects encountered in daily life has been cataloged. These classes of patterns may be a standard set for management control systems of anthropomorphic grippers. This classification system will be used by the authors of this work in the design during the next phase of the manipulator control system.

Control systems based on the patterns of movements can be enhanced by a system of tactile sensory communication for more precise coordination of the movement of individual fingers prior to and during contact with the object. Such control systems do not require high-performance computing and can be implemented as a compact embedded solution for use in the development of autonomous grippers, with human bionic prostheses being the primary focus. When using movement patterns for gripping objects, the most important phase is the choice of the most suitable pattern. It is proposed (Tomovic *et al.*, 1987), for the pre-select option of the gripping pattern, to use a comparative analysis of the size of the palm of the manipulator and the object and depending on the mutual proportion of the sizes to use either a 3-finger or 5-finger grip, as is commonly used by people in everyday life. Special formats with only 2 or 4 fingers are rarely used.

During the direct grasping phase, when the movement of the fingers of the manipulator begins along the pre-defined trajectories, there is the issue of synchronizing the movements of individual links to provide uniform coverage of the gripped object. The method of synchronous control of an anthropomorphic manipulator's fingers and analysis of the telemetry data from a sample task of unscrewing lids from multiple cylindrical shaped objects (Karnati *et al.*, 2013) has been studied. With the help of virtual reality gloves the telemetry data archive of the angular positions of the joints in the hand of the operator while carrying out the loosening and tightening of caps from varying shaped bottles was collected. The analysis of this telemetry data showed that in all experiments the time schedule describing the trajectory of the movements of the different fingers coincides in frequency and differs only in amplitude and phase. On the basis of an archive of experimentally determined data, a set of sinusoidal trajectories approximating the movements of links for the control of an anthropomorphic manipulator has been developed. A feature of the developed control algorithm is the ability to have flexible adjustment in the resulting pattern of movement for different

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dimensions of object by changing the value of the angular displacement for the rotating nodes of the fingers. The time of execution for the unscrewing operation at sinusoidal approximation is determined by knowing the magnitude of the angular velocity. Thus, in the presence of some sets of movement patterns corresponding to a certain pre-defined set of objects this method (Karnati *et al.*, 2013) of approximation of trajectories can be used for adapting patterns enabling the gripping of new objects similar to the pre-predefined objects while having arbitrary geometric dimensions.

The predefined patterns of gripping in general allows for the retention of non deformable objects of simple geometric shapes, such as:

- A flat object (a sheet of paper, plate)
- Cube or a box
- A thin cylindrical object (pen, pencil, fork, spoon)
- Thick cylindrical object (pipe, a hammer)

Using movement patterns often implies some flexibility when the same pattern can be successfully applied to the gripping of similar objects. Ciocarlie *et al.* (2007; Miller *et al.*, 2003) showed that a three-dimensional model of an arbitrary object being gripped can be presented in the form of a hierarchical graph, the basic elements of which are simple geometric primitives, such as a box (cube in this particular case), a sphere and a cylinder. Thus, the generalized task of gripping an object with arbitrary shape can be reduced to the analysis of separate primitives (Goldfeder *et al.*, 2007) and by selecting from them the most suitable for efficient gripping. As a criterion for gripping efficiency, contact point analysis can serve in the formation of performance while gripping an object using the pattern of power gripping (Miller and Allen, 1999). In this case one might encounter an error in the calculation of the grasp, due to differences between the actual geometry of the object and its equivalent representation. It is possible to compensate for this error by adapting the trajectories of movement of individual executive links of the manipulator by controlling the data received from the system of tactile sensors already active in the direct grasp phase.

In the works (Dung *et al.*, 2010; Crenganis *et al.*, 2012; Dean-Leon *et al.*, 2012), approaches are shown which highlight the mathematical modeling of kinematics and dynamics, the control systems of multilink manipulators and three-dimensional visualization through the use of MATLAB software tools. The possibility of integrating popular models from CAD solid modeling allows both the flexibility to customize the parameters of magmatic models describing the kinematics of the movement and make changes to the technical documentation. If it is impossible to describe the mathematical model when considering the nonlinear internal parameters of the actuators in the late stages of design (when the model sample is made), it is possible to use functions from the Simulink package to solve the task of identifying the control object at the expense of the analysis of input and output data measured in real time by the layout. The main disadvantage of MATLAB is the lack of a simulation environment for contact interaction between solid models. However, MATLAB provides extensive opportunities for object identification and modeling nonlinear control systems in real time as well as the generation of program models for integration into embedded computing systems.

Among the developers of control systems for gripping devices (Pelossof *et al.*, 2004), to aid in the modeling of contact interaction between the gripper head and the object, the simulator GraspIt! is a popular choice due to its functionality and usability (Miller and Allen, 2004; Miller *et al.*, 2005).

## *Kinematic Scheme of the Manipulator*

During the analysis of the biomechanics of the human hand the authors developed a kinematic scheme for a many-fingered hand. The manipulator is composed of 5 finger sections, each of which has four degrees of freedom.

As mentioned above, this paper additionally examines the impact which the orientation plane of the thumb has on the overall outcome. In Fig. 1 the thumb rotation angle (F5) is 45 degrees (*human scheme*). In the study a thumb rotation angle of 22.5 degrees was also used (*monkey scheme*).

## *Description of the Kinematics of a Single Finger*

For generality we consider the direct kinematic task for a finger, consisting of three phalanges, at the same time that we consider the motion in all four joints. We have denoted the angles of rotation in these joints as $q_0$, $q_1$, $q_2$ and $q_3$ accordingly (Fig. 2).

It is important to note that the ranges of admissible values for $q_0$, $q_1$, $q_2$ and $q_3$ should be strictly defined. Specifically, it is important to satisfy the condition $q_i \geq 0$, $i \in \{1,2,3\}$

The lengths of the phalanges we have denoted as $l_1$, $l_2$ and $l_3$. Every joint is associated with the coordinate system by a proper index. Fixed coordinate systems are denoted as $O_f x_f y_f z_f$. In Fig. 2 the origin of coordinates $O_f$ is associated with the first joint. The hand lies in the plane $O_f x_f z_f$.

To solve the direct kinematic issue we used the method that is associated with the concepts by Denavit-Hartenberg (Denavit, 1955).

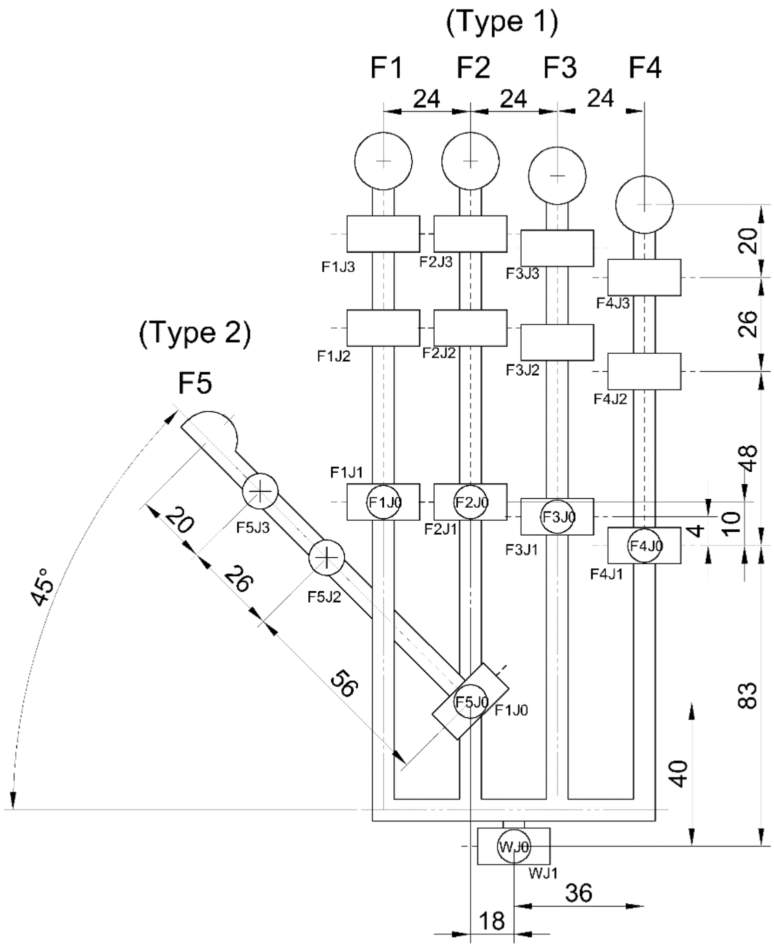


Fig. 1. Kinematic scheme of the manipulator

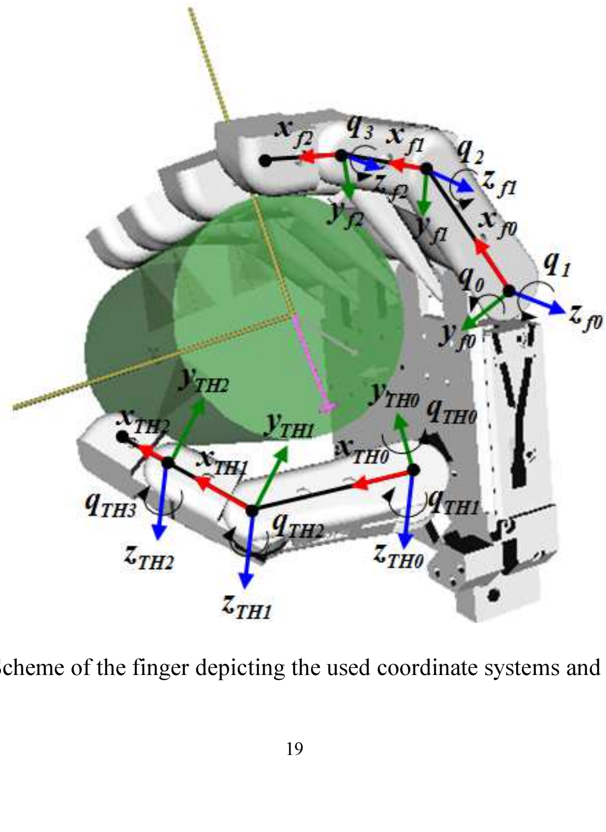


Fig. 2. Scheme of the finger depicting the used coordinate systems and angles

We write the coordinate transformation matrix $A_i^j$ from i-th coordinate system in the j-th. In the three-dimensional homogeneous, the coordinate dimension is a 4×4 matix.

$$A_f^0 = \begin{pmatrix} cos\,q_0 & 0 & -sin\,q_0 & 0 \\ sin\,q_0 & 0 & cos\,q_0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

$$A_{i-1}^i = \begin{pmatrix} cos\,q_i & -sin\,q_i & 0 & l_i\,cos\,q_i \\ sin\,q_i & cos\,q_i & 0 & l_i\,sin\,q_i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, i \in \{1,2,3\} \quad (2)$$

The matrix of coordinate transformation by definition is a matrix for which the coordinates of a new basis for expansion are determined by multiplying this matrix by a column consisting of the coordinates of expansion in the old basis.

It is known that:

$$A_{i-1}^i A_i^{i+1} = A_{i-1}^{i+1} \quad (3)$$

Then we can write, for example, that:

$$A_f^3 = A_f^0 A_0^1 A_1^2 A_2^3 \quad (4)$$

i.e.:

$$A_f^3 = \begin{pmatrix} cos\,q_0\,cos(q_1+q_2+q_3) & -cos\,q_0\,sin(q_1+q_2+q_3) & sin\,q_0 & cos\,q_0(l_1\,cos\,q_1 + l_2\,cos(q_1+q_2) + l_3\,cos(q_1+q_2+q_3)) \\ sin\,q_0\,cos(q_1+q_2+q_3) & -sin\,q_0\,sin(q_1+q_2+q_3) & -cos\,q_0 & sin\,q_0(l_1\,cos\,q_1 + l_2\,cos(q_1+q_2) + l_3\,cos(q_1+q_2+q_3)) \\ sin(q_1+q_2+q_3) & cos(q_1+q_2+q_3) & 0 & -l_1\,sin\,q_1 - l_2\,sin(q_1+q_2) - l_3\,sin(q_1+q_2+q_3) \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5)$$

Accordingly, by using these matrices, we can use given angles $q_0$, $q_1$, $q_2$ and $q_3$ and the length of phalanges $l_1$, $l_2$ $l_3$ to determine the coordinates ($x$, $y$, $z$) of the working body of the manipulator.

A feature of this kinematic scheme is the use of identical kinematic schemes for all fingers and structurally there are only 2 distinct types of finger (Table 1 and 2):

- "The index" (Type 1)-is used for fingers 2, 3, 4 and 5;
- "The thumb" (Type 2)-is used as finger 1.

Thus, similar kinematic schemes for all fingers permits the use of a universal controller in the control system for calculating direct and inverse kinematic tasks as well as for controlling the positioning of the drive (actuator).

## Materials and Methods

### *Simulation of the Robot Kinematics*

On the basis of the kinematic scheme, using the Solidworks package, the solid modeling of the manipulator has been developed (Fig. 3). In developing model calculations, the motion parameters were studied and checked, to ensure a freedom of action similar to the freedom of movement of a human hand.

A model of the manipulator was also specially prepared for work within the GraspIt! package which was used to aid in the analysis of the effectiveness of object holding retention by different manipulators. The GraspIt! package, was designed to aid in the research of handling manipulator kinematics through use of a simulation of contact interaction between manipulator and objects and also has the ability to plot iterative calculations and plan gripping trajectories for a given configuration of robot hand with an object. GraspIt! also provides the possibility of describing the kinematically dependent links, when the movement of one or more joints is made proportionally to the movement of the driving link.

The automated calculation of trajectories and gripping patterns for a given object is carried out by calculating combinations of mutual positions for the actuators of the manipulator relative to the three-dimensional model of the object. In general, the calculation task for gripping reduces to the iterative search of all possible relative positions of two solid three-dimensional models-a model of the robot and a model of the object standard. The virtual models of the robot and the object are represented as polygonal meshes which are formed into groups of three vertices.

The order of complexity is determined by the number of polygons in the model and assessed as $o(N)$:

$$N = n_1 \cdot n_2 \cdot n_3 \cdot n_4 \quad (6)$$

Where:

$n_1$ = The number of polygons in the model of the manipulator
$n_2$ = The number of polygons in the model of the object
$n_3$ = Number of orientations for each pair of polygons under the condition of full contact interaction
$n_4$ = Quantity of arbitrary displacements for the pairs of manipulator polygons to the polygons of the object

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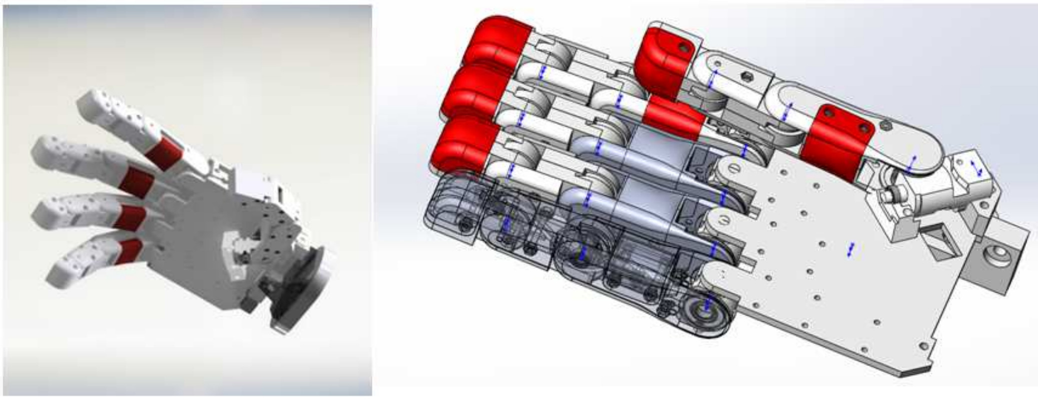


Fig. 3. The solid model of the manipulator in Solidworks (CAD)

Table 1. Transformation parameters, Denavit-Hartenberg (Type 1 Finger)

| Link (i) | d | Link angle $\alpha_{i=1}$ | Link length $a_{i-1}$ | Joint distance $d_i$ | Joint angle $q_i$ |
|---|---|---|---|---|---|
| 0 | | 0 | 0 | 0 | $q_0$ |
| 1 | | 90 | 0 | 0 | $q_1$ |
| 2 | | 0 | $l_1 = 48$ | 0 | $q_2$ |
| 3 | | 0 | $l_2 = 26$ | 0 | $q_3$ |
| 4 | | 0 | $l_3 = 14$ | 0 | 0 |

Table 2. Transformation parameters, Denavit-Hartenberg (Type 2 finger)

| Link (i) | d | Link angle $\alpha_{i-1}$ | Link length $a_{i-1}$ | Joint distance $d_i$ | Joint angle $q_i$ |
|---|---|---|---|---|---|
| 0 | | 0 | 0 | 0 | $q_{TH0}$ |
| 1 | | 90 | 0 | 0 | $q_{TH1}$ |
| 2 | | 0 | $l_{TH1} = 56$ | 0 | $q_{TH02}$ |
| 3 | | 0 | $l_{TH2} = 32$ | 0 | $q_{TH3}$ |
| 4 | | 0 | $l_{TH3} = 20$ | 0 | 0 |

Consider a situation with a relatively small number of iterations, for example, if $n_2 = 100$, $n_3 = 24$ (a step in orientation of 15 degrees), $n_4 = 10$. It is worth noting that the solid model of the manipulator contains not less than 50 000 polygons. The total number of iterations $N$ is estimated at not less than 1.2 billion. The calculation of the mutual intersection of all polygons of the model $n_2$ is happening in every iteration. Thus, the computational complexity of the algorithm is not less than 60 trillion operations. It can be lower by several orders of magnitude by the simplification of the contact model of the manipulator, as proposed in the GraspIt! package (Miller and Allen, 1999), by presenting the final amount of contact pads using a simplified model of the friction dynamics, when each contacting pad is represented as a friction cone located perpendicular to the surface of the phalanx. On the basis of a developed solid model of the handling manipulator prototype the model has been prepared, describing the frictional contact dynamics of the distal and the proximal phalanges of the fingers and also from several contact pads located on the plane of the palm.

### *Test Objects*

According to the tasks that have been put before this project, the following reference objects, used for modeling object grasp, were selected, solid models of which have been developed (Fig. 4):

- A cube with an side 30 mm in length
- A cube with an side 60 mm in length
- A cylinder with diameter of 30 mm
- A cylinder with diameter of 60 mm
- A Pencil 7 mm thick
- A Ball with a diameter of 30 mm
- A Ball with a diameter of 50 mm

### *Plan of Experiments (Research Design)*

In this project the simulator GraspIt! has been used to analyze the kinematics for the developed manipulator (Miller and Allen, 2004). This package has been used to conduct a comparative analysis of the effectiveness of the grip function, for a given set of objects by the criterion of maximum quality metrics, of the various manipulators (Miller and Allen, 1999).

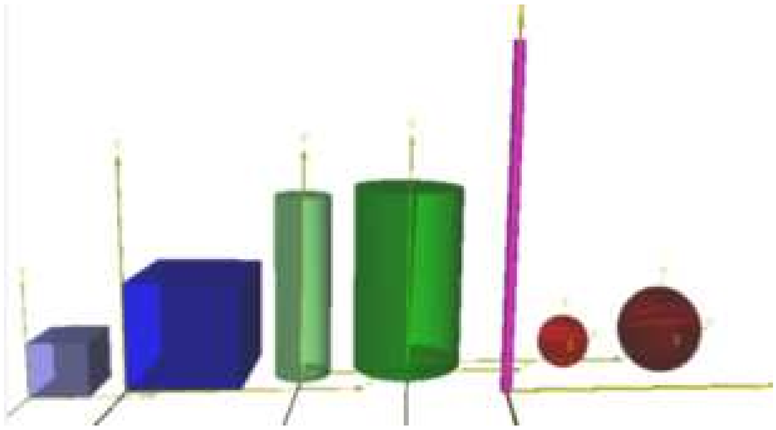


Fig. 4. Test objects these test objects have been loaded into a GraspIt! environment

In the GraspIt! package the following models of anthropomorphic manipulators are presented:

- Shadow Dexterous Hand
- Barret Hand
- Meka Hand
- Robonaut
- DLR (1st generation)

Additionally included was a pair of universal handling manipulators:

- RobotiQ
- Shunk hand

Experimental studies were carried out in accordance with the following plan:

- Import the model of the manipulator into the GraspIt! environment (description of the kinematic connection between the links, formation of the vectors of eigengrasp describing the complex combinations of movements of links, marking the virtual contact pads that simulate the tactile sensors)
- Import the object models used to test the grip function
- Start the scheduler for gripping (Eigengrasp planner) with the following parameters
- Space Search Type = Axis-angle
- Energy Formulation = Hand Contacts (Calculation of the energy on virtual contact pads)
- Max Steps = 70000 (number of iterations)
- Planner type = Sim. Ann
- For best performance 'extra-handling' (Grasp->Auto Grasp) is used and after that measure the quality of metric grasp (Grasp->Quality Measures…)

It should be noted that while importing the model of the manipulator, as well as the object to be grasped, they are placed at the beginning of the global coordinate system and therefore there is no need in to perform any manipulations with their virtual models.

Due to the fact that not all manipulators that are put into the GraspIt! package have a description of contact pads, during the experimental research on the effectiveness of kinematic schemes, the robots models of DLR, Robonaut and a virtual model simulating the human hand of Human Hand were used.

## Results

In the initial stage an investigation into the influence of the initial conditions for carrying out the experiment was conducted. The experiment was constructed as follows: As a model of the robot a virtual model of the 'HumanHand' human hand with 20° of freedom was used and as a test object a model of a sphere with a diameter of 50 mm was used. Total number of experiments-10. From the results of each experiment, the calculations for the 20 best gripping variants have been performed.

As a result of the conducted experiments with the modeling of gripping factors for the selected objects by the various manipulators, each manipulator-object pair obtained a data set that contains a group of 20 of the best variants for gripping patterns on the criterion of maximum quality metrics. For each group the extra-handling phase for the object was performed, which resulted in the links of the manipulator being brought to the moment they will have full contact with the plane of the object. At the end of the extra-handling phase the measurement of the final quality metric was made (Fig. 5). Example of gripping patterns for cylindrical objects shown on Fig. 6.

### *Statistics and Data Analysis*

Results of the conducted study into the influence of the initial conditions of conducting an experiment are presented in Table 3. The results are presented by the values of the best indicators for the quality of gripping among all the experiments.

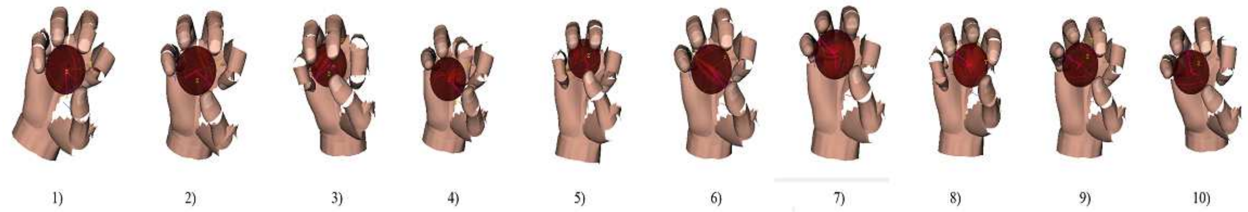


Fig. 5. The gripping patterns by results of the investigations into the influence of the initial conditions using the Human Hand virtual model

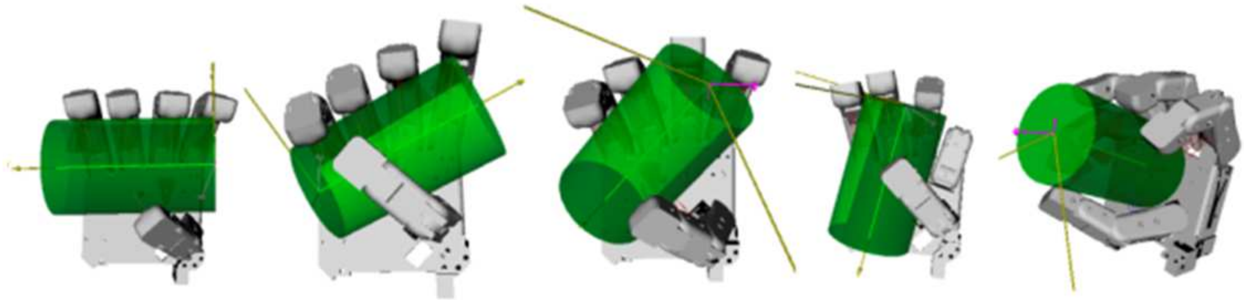


Fig. 6. The configuration of gripping patterns for the object for the RUbionic virtual model

Table 3. The effect of initial conditions on conducting the experiment

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Quality | 0,431 | 0,423 | 0,409 | 0,432 | 0,441 | 0,447 | 0,416 | 0,411 | 0,407 | 0,414 |
| Avg | 0,4231 | | | | | | | | | |
| Deviation, % | 1,87 | 0,02 | 3,33 | 2,10 | 4,23 | 5,65 | 1,68 | 2,86 | 3,81 | 2,15 |

Table 4. The quality metric of gripping for various manipulators

| Robot model | Cube 30 | Cube 60 | Pencil 7 | Sphere 30 | Sphere 50 | Cylinder 30 | Cylinder 60 |
|---|---|---|---|---|---|---|---|
| RUbionic (human) | 0,0381 | 0,197 | 0,00405 | 0,151 | 0,331 | 0,0371 | 0,241 |
| RUbionic (monkey) | 0,0412 | 0,135 | 0,00314 | 0,127 | 0,342 | 0,0217 | 0,268 |
| DLR | N/A | 0,208 | 0,00308 | N/A | 0,319 | 0,0397 | 0,263 |
| Robonaut | 0,022 | 0,172 | N/A | 0,131 | 0,292 | 0,0411 | 0,0945 |
| Virtual Human hand | 0,0362 | 0,201 | 0,0281 | 0,156 | 0,447 | 0,0471 | 0,203 |

Therein:

$$Avg = \frac{\sum_{i=1}^{10} quality_i}{10} \tag{7}$$

$$Deviation_i = \frac{quality_i}{Avg} \cdot 100\% \tag{8}$$

As is seen from the obtained data (Table 3), the average error in the deviation of quality metrics does not exceed 5.7%. Thus, in the analysis of the results of modeling for the various manipulators the quality metrics, for which the difference is less than 5.7%, can be considered as identical.

According to the accepted plan of the experiments, the research into the efficiency of object gripping from the given (specified) set has been performed; the results of which are summarized in Table 4.

Next, a series of experiments with various combinations of manipulators and objects was conducted (Table 4). The question regarding the influence of the rotation of the plane of the thumb on the quality of gripping has also been investigated (RUbionic (human) and RUbionic (monkey)).

*N/A* in the table signifies that when performing the experiments it was impossible to make a successful grip on the object with these dimensions. The reasoning behind this was the significant difference in the dimensions of the object compared to the manipulator.

An analysis of the obtained results and their comparison with the data obtained, during modeling of gripping objects using a virtual model of a human hand, leads to the conclusion that both designed kinematic schemes are adequate to solve the task of gripping objects from the pre-defined set.

As can be seen from Table 4, the developed manipulator copes efficiently with the task of gripping the smaller objects as well as with grasping the larger objects.

It is worth mentioning that the kinematic scheme which employs the *monkey scheme* thumb kinematics has several advantages over the *human* scheme:

- It allows it to grip small-sized objects better
- It provides a better grasp of long and cylindrical objects

These advantages are caused by the fact that in most patterns of movement, when performing manipulations with an object, the main digits participating in the grip are the thumb, index and middle finger. Therefore, when the thumb is opposite the index or middle finger, the plane of motion becomes parallel. This provides a more reliable grip than in the case with the *human scheme*, where the thumb is opposed to the little finger. Thus, in the development of anthropomorphic handling manipulators designed for operating with small-sized objects, it is more efficient to use the *monkey scheme*, but if the target group of objects are large objects, then it is better to use the *human scheme*. It is also possible to have a variant which can take advantage of both schemes by switching modes and changing the orientation of the longitudinal axis of the thumb.

## Discussion

As a result of the study, the efficiency of the developed kinematic scheme of the anthropomorphic manipulator, for gripping a predefined set of objects, has been confirmed. On the basis of this kinematic scheme the solid model of the manipulator prototype has been designed. It is during the next phase of this project that the prototype manipulator will be constructed. Further development of the control algorithms and their experimental research will be carried out using both the presented approach to the modeling as well as directly debugging the prototype. Described in this study is the methodology of research for manipulator kinematics which can be used in the initial stages of development for multilink handling manipulators, including those that have other kinematics schemes.

During the modeling procedure for gripping objects the following limitations have been applied:

- Only the kinematics movements of the links of the manipulator have been taken into account
- The use of geometric calculations for the collisions of virtual models to determine which elements come in contact

At this stage of the project the dynamic model of the manipulator, taking into account the physical interaction, has not been used. This model will be explored in further detail in the following papers.

The presented method and the results of the manipulator modeling will be used in the next stages of work on the development of an anthropomorphic manipulator, for performing contact operations with objects, with a high degree of accuracy and reliability.

In the results from the analysis of the obtained experimental data and based on the works (Wöhlke, 1992; Miller *et al*., 2003), the development of the control systems will take into account the fact that the procedure for gripping objects can be divided into several phases (Fig. 7):

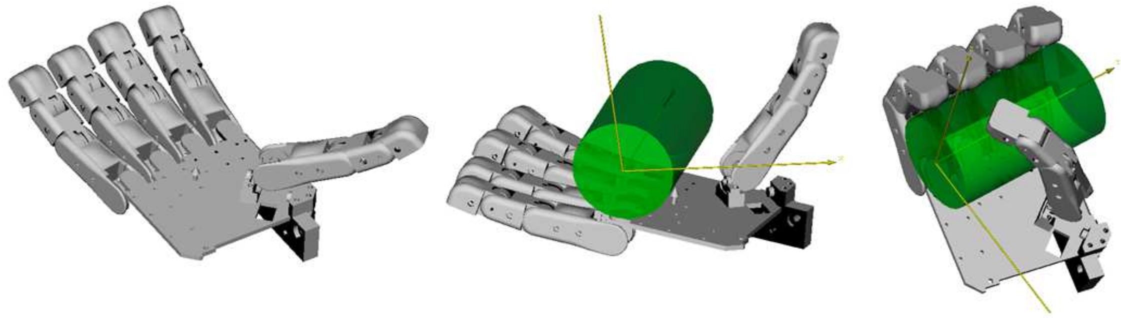
- Formation of the pattern for the initial position (preshape)
- Pregrasp, placing the gripping head near the object (pregrasp)
- Direct grasp (grasp execution)

For the stage of pregrasp the following geometric patterns can be entered:

- The geometric center of the object being gripped coincides with the geometric center formed by the final stage of the gripping pattern
- The plane of the palm is parallel to the edge of the parallelepiped (box or cube) bounding the three-dimensional model of the object grasped
- The number of fingers participating in the pattern of movement is determined by the mutual relation between the size of the palm and the dimensions of the object

Use of the method (Karnati *et al*., 2013) in the control systems of the manipulator is based on predefined patterns which allows for an adaptation of the existing patterns of movement when gripping objects with arbitrary geometrical dimensions.

For gripping objects with complex shapes, brittle or flexible objects, the adaptive synthesis of controlling actions, including the individual characteristics of the design and the materials properties of the object, can be used. As a consequence, for manipulations with objects without using priori information about the size, weight, texture and the contact dynamics, it requires the building of a complex system of control and consequently, increased requirements in the productivity of the computational system of the controller. Thus, the most important requirement for solving the task of manipulating a large set of object classifications with different characteristics becomes the development of the managing controller, by giving it the ability to learn. In the next stage of work on this project the team of authors will start research on the control algorithms for the grip and the development of an adaptive controller for grip management.



(a) (b) (c)

Fig. 7. Stages of the procedure for gripping objects applied to the developed manipulator (a) preshape (b) pregrasp (c) grasp execution

Since three-dimensional models of any object can be represented as a hierarchical model consisting of simple geometric primitives (Miller *et al*., 2003), then building an adaptive control system for gripping objects of arbitrary shape is necessary additionally to exploit the potential of three-dimensional viewing to provide priori information about the shape and type of object to be gripped. Thus, the manipulator of the robot, the system of control and the plan for gripping an object as well as a system of three-dimensional technical vision are strongly interrelated, which means that they represent the integral parts of a single system for the management of an anthropomorphic robot.

## Conclusion

The tools and methods used in this phase of the project by way of assessing the quality of the grip presented in section 3 will further allow to authors to flexibility configure the parameters of the kinematic scheme in the design of a universal anthropomorphic handling manipulator as well as manipulators for specialized applications, such as bionic prosthetics.

At this stage of the work the method for investigating the function and usability of the kinematic schemes of the manipulator for gripping has been successfully worked out (Krechetov, 2015). In the future, to determine the optimal number of actuators for the executive links an additional study of the impact on the quality of retaining objects and kinematic connections between pairs of links will be conducted, as well as the value of the transmission ratio between such units.

From the results of this study the development of the software for movement trajectory planning and control of a multi-finger manipulator will be done. On the basis of the developed movement patterns the embedded software for the control systems of the anthropomorphic manipulator will be developed.

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## Author's Contributions

**Ivan Krechetov:** Designed the plan of research, modeling graps patterns on virtual subjects, examined the quality of metric grasp patterns.

**Arkady Skvortsov:** Organized the study, data collection of the study sample, analysis and writing of the manuscript.

**Pavel Lavrikov:** Designed robot hand model for GraspIt!.

**Danil Yatskin:** Developed mathematical model of the manipulator.

## Ethics

The authors have no conflicts of interest in the development and publication of current research.

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