

# Constructive and intellectual improvement of socially accessible grippers of manipulators

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## Abstract

Innovative improvements of grippers of industrial and anthropomorphic socially accessible manipulators are considered. A generalized design of a gripper with several fingers is developed, which implements the principle of rapid variability, provides versatility, disperses the clamping force of objects in the grip. By using one type of drives in the design of the manipulator and soft and hard rods, control versatility is ensured. An analytical mathematical model of a gripper with fingers made of elastomeric elements is constructed for working with objects that require careful clamping without damage. Based on the analytical model of the stiffness of the elastomeric element as a function of relative deformation, a model in the form of a polynomial-exponential sum is formed. It is demonstrated that due to the elastomeric properties, the model is statically indeterminate. It is proposed to reduce it, taking into account information about objects and the necessary movements of the finger points to capture the object, to a system of analytical expressions of traction forces and angular and linear displacements. The example of an electric drive presents the transient processes of movement of a single finger of a multi-finger gripper. A model and structure of the gripper are presented, allowing it to be modeled and designed as a separate, quick-change module.

## Keywords

robots, industrial-anthropomorphic, soft grippers, rapid change, multi-finger, soft surfaces, elastomeric elements, universal structure, analytical model, transient movement process.

## 1. Introduction

Versatility and specialization, unpredictability of objects' shapes to be captured, and the accuracy of their positioning - such problems faced developers of grippers for robots 50 years ago [1]. These challenges are more acute today [2-3]. The searches of scientists and manufacturers over the decades have given examples of solutions to resolve the contradictions of the problems of narrow specialization and universality, for example, in the form of quick-change grippers [4]. As the experience of practical application of unmanned technologies in various fields of human activity shows, one of the key technical components of such systems is a manipulator with a gripping device, the perfection and productivity of which determines the efficiency, accuracy and quality of work. The complexity of the tasks of industrial and non-industrial sectors of the application of robots also gives rise to new methods that ensure the redistribution of contact clamp forces in the grippers [5]. The clamping forces are controlled by the contact method and the relative movement in the gripper is recorded [6]. Such tasks are especially relevant when creating robotic devices - grippers for industrial and anthropomorphic robots [7]. They are also relevant, including for harvesting fruit and vegetable crops. The list of problems when creating a gripper consists of a large variety of shapes, sizes, surface structure [8], and the state of ripeness of agricultural crops, which requires a special approach to choosing the principle of operation and additional drive mechanisms, such as vacuum and pneumatic [9]. The latter complicates the equipment, increases

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its cost, which does not always lead to an increase in the productivity of the technological process.

Thus, the main challenge that arises during design and operation is adaptation to the variety of forms of objects of manipulation, sensing and the use of several types of drives. In this regard, in the works of the last decade, the efforts of scientists have been focused on determining ways to further solve and form the means of practical implementation of intelligent robot grippers.

## 2. Analysis of recent publications

An example of recent research aimed at improving the design of robot grippers is work [10]. It is focused on increasing the load capacity, controlling the clamping force of the object, due to the flexible grasp of the object. The latter is proposed to be carried out with flexible three-jointed fingers as in the invention [1], but with additional feedback on the magnitude of the force and using deep learning [10]. This addition expands the range of sizes and payload, increases the stability of the object position at low cost, due to the use of artificial intelligence (AI). However, the problem of the same type of drive of the kinematic pairs of the gripper and the manipulator and their control appears as a new problem that needs to be solved. A similar example of implementing the idea of a comprehensive grasp of the object [1] to improve the gripper's operation is work [11]. Their approach of combining a set of rotating elements as grouped kinematic pairs with fractal morphology to improve gripping ability uses sets of multi-joint links with limited movement in one plane [11]. The authors claim a wider scope of practical application scenarios, such as handling non-standard heavy objects, harvesting and underwater operations. However, the hierarchical principle of forming sets of kinematic pairs and the need for their coordinated movement significantly complicates its implementation [11].

Controlled means that improve the adhesion of the working surfaces of the gripper are considered in [12]. By improving the electro-adhesion, this study integrates electro-adhesion as an auxiliary function in the mechanical gripper and increases the magnitude of the friction force. The latter increases the key parameters of load capacity, productivity, but does not solve the problems of slip control and sensing.

In [13], two new robotic grippers for harvesting pitahaya are evaluated. The robot gripper uses cutting devices: a vibrating blade and pneumatic scissors and four pneumatically driven fingers. Such a combination of designs is a possible solution for a robot that harvests delicate fruits.

The design of an edible universal gripper using membranes for clamping and using particles in a gelatin-based hydrogel medium, polyhydroxyalkanoate (PHA) bioplastic, and starch is investigated in [14]. The modular framework, gelatin-based hydrogel membrane, and small spherical starch particles can become the basis for integrated developments of a new generation of fully edible robotic hand systems [14]. The problems of creating tools that will ensure the functioning of edible technologies today have limited application due to the lack of crucial factors: the balance of safety and reliability, cost-effectiveness, and suitability for self-monitoring of health [15]. The newly created field of edible unmanned technologies, being at the embryonic stage, creates a great scientific resonance, presenting a technology that is safe for consumption, environmentally friendly, cost-effective and decomposes in the body after performing its function, being digested or even metabolized. However, a common approach has not been formed to date, and the industry is currently united only by the use of food products or edible synthetic functional materials [15]. A critical review of the main idea and prospects, as a result of which the robotics direction will be declassified as the main one [15]. It expands the possibilities, however, and requires the creation of environmentally friendly, intelligent technologies, remote monitoring, health and security challenges, the presence of an approved list of materials, means of fast processing of information flow, nutrition, communication and interaction with the human body. In this regard, important work [16] is investigating polymers that respond to changes in external stimuli such as pH, temperature, ionic interaction, surfactants, pressure, light, biomolecules, and magnetic field [16]. These materials have been developed in various network architectures such as

block copolymers, crosslinked hydrogels, nanogels, interpenetrating networks, and dendrimers. Cationic polymers and hydrogels that respond to stimuli are an attractive class of materials that respond reversibly to changes in external pH. They have the ability to significantly expand in acidic solutions and contract in alkaline solutions [16]. This reversible swelling-contraction property induced by changes in external pH conditions makes these materials useful in a wide range of applications such as drug delivery systems and chemical sensors. Over the past few decades, the multidisciplinary field of microrobotics has undergone important changes [17]. Among the most important of these is the introduction of soft materials in the microfabrication of contactless devices. Thanks to their use, new capabilities and control strategies have been realized [17], and especially important ones are biological structures and hard-soft hybrids.

The need and idea of using soft materials today extends not only to the design of manipulator grippers, but also to the design of sensing devices [18]. The analysis presented suggests a new application that will determine the possibility of monitoring the service life of various personal protective equipment and will become a turning point for workplace safety in various contexts, including robotic systems [18].

The work [19] is devoted to an innovative approach to forming membership functions for describing fuzzy sets by transforming them with appropriate light filters as a carrier of logical information for constructing logical solutions. It is proposed to process color information that reflects different values of input data and implement the proposed structural construction of fuzzy logical elements, which significantly simplifies the process of additive and subtractive color processing [19]. A fuzzy database is formed based on the definition of the information quantum as the corresponding color set. A generalized structural diagram of an optical logical coloroid has been synthesized as a basis for creating a multi-level decision-making system for further application in artificial intelligence systems. It has been demonstrated how optical logical coloroids can be combined into serial-parallel hierarchically organized schemes for expert assessments and display of tactile information of sensory systems [19].

Thus, the set of analyzed works demonstrates that to date, the articles specified in the review have undergone a gradual development of the ideas of creating a multi-link gripper [1], quickly changeable [4], sensitive [5-6, 18], with a single type of drive and a simple regulator using machine learning and decision-making methods [7] and based on special fuzzification [19]. However, the implementation of such a problem will require the solution of design tasks: rapid change of the gripper and the separation of the sensing and power supply systems. Its solution will determine as a prerequisite the main unsolved problem: the constructive and intellectual improvement of socially accessible grippers of manipulators.

### **3. The goal and objective of the research**

To increase the efficiency of designing multi-finger quick-change grippers with a single type of drive for industrial and anthropomorphic robots by building an analytical model using elastomeric elements, which is suitable for designing a local control system with a PID controller as a module of a general intelligent system.

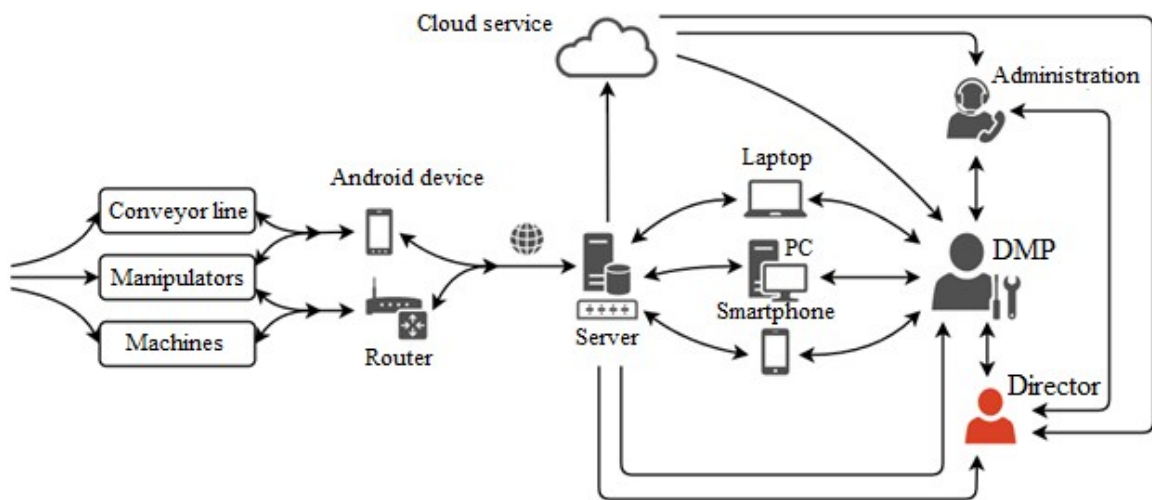
To achieve this goal, the following tasks were formulated:

- to develop a generalized design of a universal gripper;
- to develop a mathematical model of the finger drive of the soft touch gripper;
- to construct a transfer function.

## 4. Formulation and solution of the problem of forming a mathematical model the soft touch gripper

### 4.1. Development of the design of manipulator grippers suitable for flexible object capture

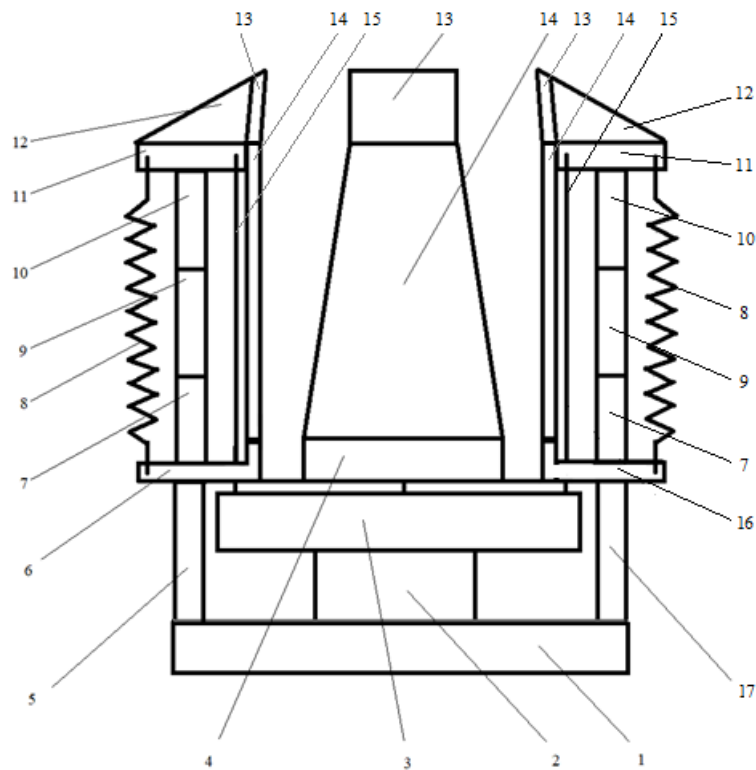
Based on the analysis of recent research on robotic systems and consideration of the designs of existing analogues [2-3, 5-13] and solutions that have been patented [1, 4] and implemented, the improvement of the gripper design was identified as one of the leading directions of their development. The experience of implementing and servicing unmanned technologies in production areas in accordance with the modern level of scientific and technical development was also taken into account. In this regard, the structure of the automated control system (ACS) was generalized. It allows visualization, modeling and provides analysis of the needs of practical implementations of the gripper as a replaceable robot device in the production area. An example of integration into the ACS of the enterprise is shown in Figure 1.



**Figure 1:** Fragment of a visual representation of the communication interaction of the elements of the block diagram of the technological process of the ACS at the site, the director and the administration of the corporation

Thus, taking into account the significant growth of interest in automated enterprises and the growth of the share of uninhabited areas, a generalized gripper was developed. The principle of generalization provides for the possibility of choosing from a set of necessary properties:

- work as part of industrial and anthropomorphic robots;
- sensitivity according to the specified parameters from the list and according to the principle of a designer from a specified set without modifications;
- work as a quick-change gripper, with a drive of the same type as the manipulator drives and a local control system with a PID regulator;
- work with connection to a general intellectualized system that implements machine learning and decision-making. The scheme of the generalized gripper is presented in Figure 2.

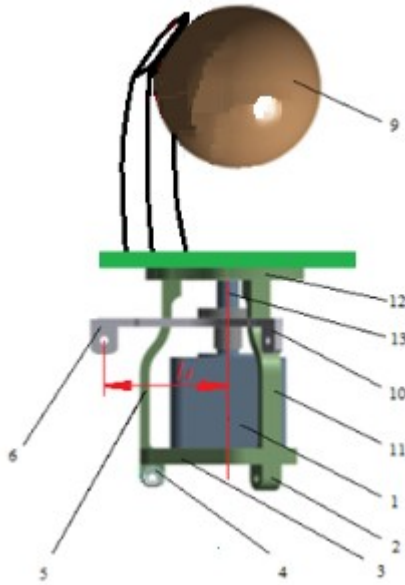


**Figure 2:** Schematic representation of structural elements of the gripper of an object of undefined shape

The gripper design Figure 2 provides for quick change by analogy with the patent [2] and its analogues. All such designs contain a flange 1 for quick disconnection. In addition, the flange 1 contains means for fastening an electric motor 2 with a gearbox and a mechanism for connecting and tensioning cable rods 3. Gripper fingers are fixed to the flange 1 using racks 5 and 17. The number of such fingers can vary depending on the tasks. In the design shown in Figure 2, three of them are used. The basis for fastening each of the three fingers are the bars 4, 6 and 16. The cables 15, as shown, for example for the right and left fingers, pull the upper bar 11 to the lower bars 4, 6, 16 for all three fingers. The latter deforms the elastic elements 7, 9, 10 and tilts the gripper fingers to the side in the direction towards each other. At the same time, stretching the springs 8 of each of the three fingers. An adapter for fastening 12 is installed on the end phalanx of each of the fingers. One upper edge of the elastic element 13 is fixed to each of the gripper fingers. The section of the elements 13 in the side view has a trapezoidal shape. The upper edge of the elastic elements 14 is attached to the bar 11, the lower edge is attached to the lower bars 4, 6, 16. On the front surface of the adapter 12, either the elastic element 13 or the contact force and sliding force sensors 14 or both are installed.

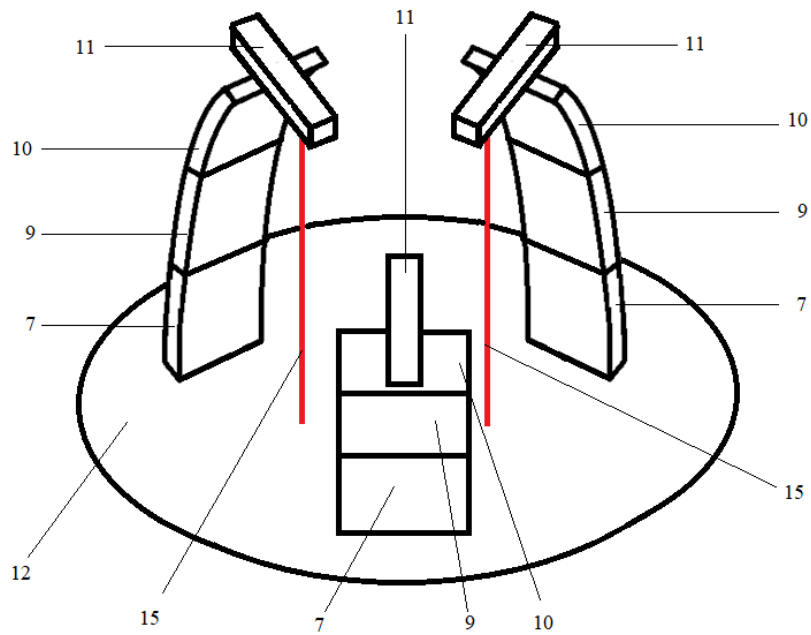
#### **4.2. Development of a mathematical model of the finger drive for the control system in the structure of the gripper of a mobile robot**

To form a mathematical model of the finger drive control in the structure of the manipulator gripper, one of the possible implementation options for the gripper finger drive was identified and displayed. Figure 3 shows a fragment of a generalized gripper. The fragment includes an electric drive 1 and an elastic element of one of the gripper fingers, the complete generalized diagram of which is given in Figure 2.



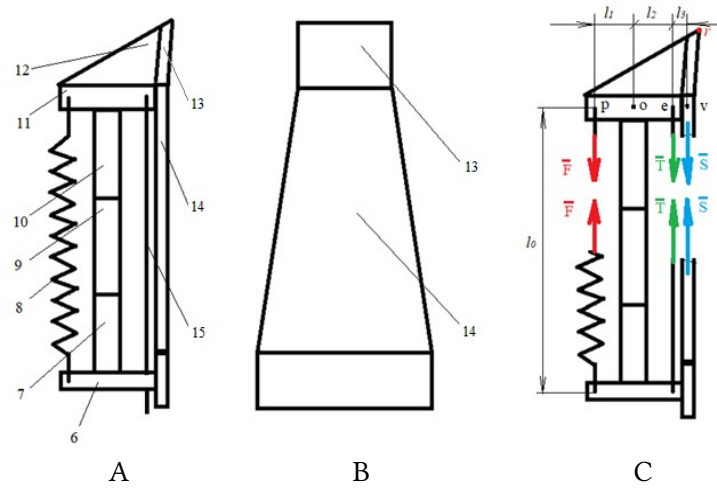
**Figure 3:** Schematic representation of the drive of the elastic element of the gripper finger.

This drive 1 in Figure 3, as in most low-power drives, is made in a single housing with a gearbox. It is fixed to the housing 2, which in turn provides fastening elements 2 and 4 and frame racks 5 and 11, which are connected to the disk 12. The output shaft 13 is installed in the support-thrust unit of the disk 12, which reduces the play from the load, and therefore improves the operating conditions of the engine and gearbox 1. The rods 6 and 10 contain holes for fastening cables for deformation of the elastic elements of the fingers. Figure 3 shows only the elastic element of one finger 8, which is fixed on the bar 7. As a result of the movement of the rod 6, the elastic element of the finger 8 is deformed. All elastic elements are deformed identically and are pressed against the body 9, which needs to be clamped. Thus, to build a mathematical model for the finger drive control system in the structure of the gripper of a mobile robot, the task was set to link the movement of the point of the elastic element with the angle of rotation of the motor shaft, which in turn is determined by the law of change of the voltage applied to the motor windings.



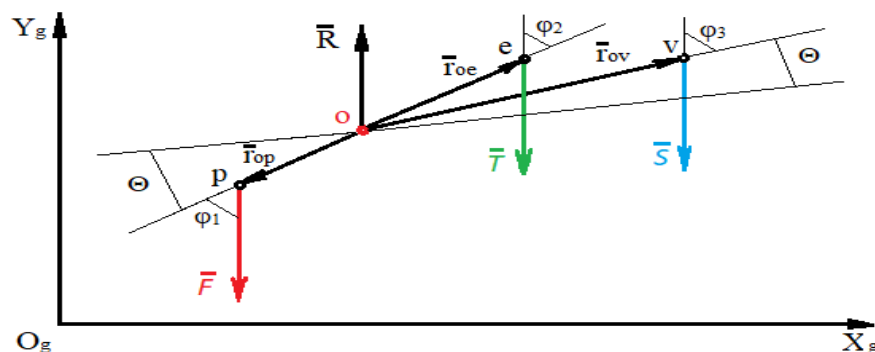
**Figure 4:** Schematic representation of the drive of the elastic element of the gripping finger.

Figure 4 shows the elastic elements 7, 9, 10 of the three fingers fixed on the disk 12. The adapter and elastic elements 13 and 14 of each finger are conditionally not shown or in other words: removed. To simplify the process of building the mathematical model, the problem was divided into several sub-problems. The first one will be formed as a sub-problem about the deformation of an elastic plate of arbitrary shape, made of elastomeric material with a nonlinear dependence of mechanical stress on relative deformation. The second one will be set as a sub-problem about the movement of the cable at a given deformation of the elastic element. The third one about the magnitude of the force that caused the given deformation. The fourth one about the relationship between the linear movement of the point of attachment of the cable to the elastic element and the angle of rotation of the motor shaft. To build a calculation scheme and create a mathematical model based on it, we will isolate a separate finger. Figure 5 shows a side view and a view directly onto the contact surface with the gripping object of such a finger.



**Figure 5:** Schematic representation of a separate gripping finger and calculation scheme: A – side view of a separate gripping finger; B – front view of the gripping finger; C – calculation scheme.

Let us break the spring 8, the cable 15 and the elastomer element 14. We will replace the action of the torn parts with the corresponding force vectors, which will be denoted by  $\bar{F}$ ,  $\bar{T}$ ,  $\bar{S}$  and the support reaction  $\bar{R}$ . If in the initial state the grip is opened, then the force  $\bar{F}$  stretches the elastomer element 14, the cable tension force  $\bar{T}$  is minimal or equal to zero, and the elastomer is stretched and the force  $\bar{S}$  will be oriented against the  $O_g Y_g$  axis. It should be noted that the sign of each of the three forces determines the sign of the force  $\bar{T}$  and the conditions of equilibrium of forces and moments of forces relative to the point  $o$  and the deformed state of the spring 8 and the elastomer 14. Thus, the force  $\bar{F}$  is opposite to it in direction, and the force is opposite to the sign of the deformation of the elastomer 14.



**Figure 6:** Calculation scheme for determining the equilibrium condition of an individual finger.

Figure 6 shows a calculation scheme for determining the equilibrium condition of a separate finger in the basic coordinate system  $O_g X_g Y_g$ . Let us also denote  $\Theta$  - the angle of rotation around the point  $o$ , which the bar 11 performs as a result of the action of the traction force  $\bar{T}$ , which develops the cable 15. Let us assume that the bar 11 is absolutely solid and does not deform, then both of its ends rotate by the same angle  $\Theta$ . Let us also denote  $\varphi_1, \varphi_2, \varphi_3$ , respectively, the angles between the force vectors  $\bar{F}, \bar{T}, \bar{S}$  and the radius vectors  $\bar{r}_{op}, \bar{r}_{oe}, \bar{r}_{ov}$ , which determine the positions of the points of application of the forces relative to the point  $o$ . Based on such notations and assumptions, we will formulate the condition for the equilibrium of the moments of forces and write it in scalar form:

$$F l_1 \sin \varphi_1 - T l_2 \sin \varphi_2 - S (l_2 + l_3) \sin \varphi_3 = 0.$$

If we denote the stiffness of the spring 8  $k_1$ , then allow it so that it does not change. Also, we denote the stiffness of the elastomer element 14 as  $k_2(\varepsilon)$  and means that it is the function of the relative deformation  $\varepsilon = \Delta l_v / l_0$  and is repeatable and the function is immutable. For describing of it, may be useful as the most effective form of the structure of empirical models - polynomial and exponential sum [20]. Then we will rewrite the equilibrium condition of moments of force and find out the traction force  $\bar{T}$ :

$$\begin{aligned} -\theta k_1 l_1^2 \sin \varphi_1 + T l_2 \sin \varphi_2 - k_2 (l_2 + l_3)^2 \sin \varphi_3 &= 0; \\ k_2(\varepsilon) &= a_0 + a_1 \varepsilon + a_2 \exp(a_3 + a_4 \varepsilon); \\ T &= \frac{\theta (k_1 l_1^2 \sin \varphi_1 + k_2 (l_2 + l_3)^2 \sin \varphi_3)}{l_2 \sin \varphi_2}. \end{aligned} \quad (1)$$

In addition, the point  $v$  will rotate relative to the point  $o$  by the value  $\Theta$  - the angle of rotation of the bar 11

$$\theta = \frac{T l_2 \sin \varphi_2}{k_1 l_1^2 \sin \varphi_1 + k_2 (l_2 + l_3)^2 \sin \varphi_3} \quad (2)$$

The position of point  $e$ , which is the point of attachment of cable 15 and is located at a distance  $l_2$  from point  $o$  - the center of rotation, will shift by the value  $\Delta l_2$ , which is calculated by the expression:

$$\Delta l_2 = \theta l_2 = \frac{T l_2^2 \sin \varphi_2}{k_1 l_1^2 \sin \varphi_1 + k_2 (l_2 + l_3)^2 \sin \varphi_3} \quad (3)$$

The obtained expressions (1) - (3) open the possibility of determining the displacement of the edge of the finger, which is designated by the point  $r$  (Fig. 5.B), as a function of  $T$  - the tensile force of the cable 15. To write the model in the form of coordinate increment, we will supplement the equation of the cable tension force (1) and the angle of rotation (2) and the modulus of the vector of displacement of the point  $r$  of the end of the gripper finger relative to the point  $o$ . The projections of the increment of the vector  $or$  on the gripper axis  $\Delta x$  and orthogonal to it  $\Delta y$  will be written:

$$\begin{aligned} \Delta x &= l_{or} \cos(\alpha_1 - \theta) - l_{or} \cos \alpha_1; \\ \Delta y &= l_{or} \sin(\alpha_1 - \theta) - l_{or} \sin \alpha_1, \end{aligned} \quad (4)$$

where  $\alpha_1$  is the angle between the rays  $ov$  and  $or$ , and  $l_{or}$  is the length of the segment  $or$ . The modeling data of the influence of the relative sizes of objects on the parameters of the grippers are presented in Table 1.

**Table 1**

Influence of the relative sizes of objects on the parameters of the grippers

$\Delta l_3/l_0$	$\Theta$ , radians	$\mathcal{E}$	$k_2, N/m$	$T, N$
0,01	0,066568	0,111111	33246,51	2,041092
0,015	0,099669	0,166667	44771,36	3,077574
0,02	0,132552	0,222222	56327,2	4,121689
0,025	0,165149	0,277778	679163,4	5,171229
0,03	0,197396	0,333333	79541,28	6,224041
0,035	0,229232	0,388889	91204,71	7,278061

The column 1 of the table shows the value of the relative deformation  $\Delta l_3/l_0$  of the gripper finger. Its value determines the minimum and maximum size of the object that the gripper with the length of the finger can grasp  $l_0$ . Column 2 shows the angle of rotation of the last phalanx of finger  $\theta$ , columns 3 and 4 show the relative deformation of the elastomer  $\mathcal{E}$  and its stiffness  $k_2$ . Column five shows the tensile force  $T$  of the cable 15, which must be provided by the drive 1 (Fig. 3) for reliable grasping of an object of a given size  $l_0 - \Delta l_3$ .

Thus, the model (1)-(4) is constructed, which determines the relationship between the tension force, the angle of rotation of the bar and the movement of the gripper finger. Its combined application with the model of the drive motion 1 and the models of the movement of the rods 6 and 10 will close the system of description of the gripper drive.

#### 4.3. Construction of a generalized model of the finger drive and the transfer function

Due to the fact that the vast majority of industrial and anthropomorphic robots are classified as ultra-light, light and medium in terms of load capacity, they are oriented towards electromechanical drives of the links. The latter led to the choice of an electromechanical gripper drive (Fig. 3). For such needs, it is enough to choose a low-power electric motor. Next, a brushless DC motor was chosen to form the model, the rotor of which is made in the form of permanent magnets. The model in the form of a system of equations. The first of them, as a single one for all fingers, will be written for the stator winding contour using Kirchhoff's second rule. The second will be constructed for the motor rotor using the main law of mechanics for the rotational motion of the motor rotor of the articulated output shaft together with an adapter or reducer coupling. The third equation is the moment of force due to the interaction of the rotor's magnetic field and the magnetic field of the stator coils with current. Thus, the dynamics of such an engine, to a first approximation, is described by a system of equations:

$$\begin{cases} u(t) = L \frac{di}{dt} + iR + K_{\omega} \dot{\alpha}(t); \\ M_g = J \ddot{\alpha}(t) + \frac{\rho C_m S_i R_i^{n+1}}{2} \dot{\alpha}^n(t) + M_{306} + M_{cme\pi}; \\ M_g = K_M i(t), \end{cases} \quad (5)$$

The latter will be supplemented taking into account the installed gearbox with a gear ratio  $i_g$  and efficiency  $\eta_g$  and the mechanism of three rods, cables 15 of three rods:

$$M_g = K_M i(t) = 3T(t) l_4 \eta_g i_g \quad (6)$$

Let us introduce the notation with a wavy line above the value of the image of the infinite Laplace transform. Let us consider the viscous friction of the rotor of an electric motor, then the model, taking into account the application of the Laplace transform to the equations of the system (5), we write:

$$\begin{cases} \tilde{u} = Lp\tilde{i} + R\tilde{i} + K_{\omega} p\tilde{\alpha}; \\ K_M \tilde{i} = J p^2 \tilde{\alpha} + K_{cme\pi} p\tilde{\alpha} + \tilde{M}_{306} + \tilde{M}_{cme\pi}. \end{cases} \quad (7)$$

The latter allows us to determine the transfer function analytically:

$$\begin{aligned} W(p) = \frac{\tilde{\alpha}}{\tilde{u}} &= \frac{K_M \tilde{i}(t) - \tilde{M}_{306} - \tilde{M}_{cme\pi}}{(J p^2 + K_{cme\pi} p)(Lp\tilde{i}(t) + R\tilde{i}(t) + K_{\omega} p\tilde{\alpha}(t))} = \\ &= \frac{(K_M \tilde{i}(t) - \tilde{M}_{306} - \tilde{M}_{cme\pi})(J p + K_{cme\pi})}{(J p^2 + K_{cme\pi} p) \left\{ (J p + K_{cme\pi}) [Lp\tilde{i}(t) + R\tilde{i}(t)] + K_{\omega} [K_M \tilde{i}(t) - \tilde{M}_{306} - \tilde{M}_{cme\pi}] \right\}} = \\ &= \frac{(K_M \tilde{i}(t) - \tilde{M}_{306} - \tilde{M}_{cme\pi})}{p \left\{ (J p + K_{cme\pi}) [Lp\tilde{i}(t) + R\tilde{i}(t)] + K_{\omega} [K_M \tilde{i}(t) - \tilde{M}_{306} - \tilde{M}_{cme\pi}] \right\}}. \end{aligned} \quad (8)$$

Algebraic transformations of the denominator (8):

$$\begin{aligned} &\left\{ (Jp + K_{cme\pi}) [Lp\tilde{i}(t) + R\tilde{i}(t)] + K_{\omega} [K_M \tilde{i}(t) - \tilde{M}_{306} - \tilde{M}_{cme\pi}] \right\} = \\ &= \left\{ \left[ JL p^2 + (K_{cme\pi} L + JR) p \right] \tilde{i}(t) + K_{cme\pi} R \tilde{i}(t) + K_{\omega} K_M \tilde{i}(t) - K_{\omega} (\tilde{M}_{306} + \tilde{M}_{cme\pi}) \right\} = \\ &= JL \left\{ \left[ p^2 + \left( \frac{K_{cme\pi} L + JR}{JL} \right) p \right] \tilde{i}(t) + \frac{K_{cme\pi} R + K_{\omega} K_M}{JL} \tilde{i}(t) - \frac{K_{\omega}}{JL} (\tilde{M}_{306} + \tilde{M}_{cme\pi}) \right\} \end{aligned} \quad (9)$$

and the designation of the constants and roots  $p_1$  and  $p_2$  of the quadratic trinomial:

$$\begin{aligned} D &= \frac{K_M U_0}{JL}; \beta = \frac{K_{cme\pi} L + JR}{2JL}; C = \frac{K_{cme\pi} R + K_{\omega} K_M}{JL}; \\ p_1 &= -\beta + \sqrt{\beta^2 - C}; p_2 = -\beta - \sqrt{\beta^2 - C}; \end{aligned} \quad (10)$$

under the conditions  $\tilde{M}_{306} = \tilde{M}_{cmp} = 0$  simplifies the transfer function:

$$\begin{aligned}
 W(p) &= \frac{(K_M \tilde{i}(t) - \tilde{M}_{306} - \tilde{M}_{cmp})}{p \left\{ (Jp + K_{\text{emep}}) [Lp \tilde{i}(t) + R \tilde{i}(t)] + K_{\omega} [K_M \tilde{i}(t) - \tilde{M}_{306} - \tilde{M}_{cmp}] \right\}} = & (11) \\
 &= \frac{K_M}{JLp \left[ p^2 + \frac{(K_{\text{emep}}L + JR)}{JL} p + \frac{K_{\text{emep}}R + K_{\omega}K_M}{JL} \right]} = \frac{K_M}{JLp [p^2 + 2\beta p + C]} = \\
 &= \frac{K_M}{JLp(p - p_1)(p - p_2)}.
 \end{aligned}$$

The image of the angle of rotation of the output shaft of the drive as a transient process is obtained for a columnar pulse  $X(p)$  with a time duration  $\tau = t_2 - t_1$ :

$$L(\tilde{\alpha}) = W(p)X(p) = \frac{De^{-pt_1} [1 - e^{-p(t_2-t_1)}]}{p^2(p^2 + 2\beta p + C)} = \frac{De^{-pt_1} [1 - e^{-p(t_2-t_1)}]}{p^2(p - p_1)(p - p_2)}. \quad (12)$$

To find the original of  $L(\alpha)$ , we apply the delay theorem. To do this, we first find the original for the function:

$$\frac{1}{p^2(p - p_1)(p - p_2)} \quad (13)$$

Let us find the original for the auxiliary function (13), which we decompose before into simpler fractions for this purpose

$$\frac{1}{p^2(p^2 + 2\beta p + C)} = \frac{A_1}{p^2} + \frac{B_1}{p - p_1} + \frac{C_1}{p - p_2} \quad (14)$$

where the unknown constants are determined by comparing fractions:

$$A_1 = \frac{1}{p_1 p_2}; B_1 = \frac{1}{p_1^2(p_1 - p_2)}; C_1 = \frac{1}{p_2^2(p_2 - p_1)}. \quad (15)$$

The original from (14) in this arrangement will be presented:

$$A_1 t + B_1 e^{p_1 t} + C_1 e^{p_2 t}, \quad (16)$$

then, according to the delay theorem, we obtain the transient process for the angle of rotation of the motor shaft:

$$\alpha(t) = D(A_1 t + B_1 e^{p_1 t} + C_1 e^{p_2 t}) [\eta(t - \tau_1) - \eta(t - \tau_2)] \quad (17)$$

The analytical model of the transient process for a DC electric motor (17), according to Figure 3 and models (1) – (4), is supplemented with the following equations of the angle of rotation of the bar 11 -  $\Theta$ , the tension force  $T$  of the inextensible cable 15 and the moment of forces developed by the thrusts 6 and 10 with a length of  $l_4$  due to the drive reducer with a gear ratio  $i_g$ :

$$\begin{cases} \theta = \frac{T l_2}{k_1 l_1^2 + k_2 (l_2 + l_3)^2}; & \theta l_2 = \alpha \frac{l_4}{i_g}. \end{cases} \quad (18)$$

Applying the model of mechanisms of identical drives of the gripper fingers taking into account the transient process of the motor rotation angle (17) for the rotation angle  $\Theta$  of the bar 11, the tension force  $T$ , we have the transient process of the bar 11 of each of the gripper fingers:

$$\begin{cases} \theta = \alpha \frac{l_4}{l_2 i_g} = \frac{l_4}{l_2 i_g} D (A t + B_1 e^{p_1 t} + C_1 e^{p_2 t}) [\eta(t - \tau_1) - \eta(t - \tau_2)]; \\ T = \frac{D l_4}{l_2^2 i_g} (k_1 l_1^2 + k_2 (l_2 + l_3)^2) (A t + B_1 e^{p_1 t} + C_1 e^{p_2 t}) [\eta(t - \tau_1) - \eta(t - \tau_2)]. \end{cases} \quad (19)$$

and find the displacement of the gripper finger:

$$\Delta x = l_{or} \cos \left( \alpha_1 - \alpha \frac{l_4}{l_2 i_g} \right) - l_{or} \cos \alpha_1 \approx l_{or} \cos \alpha_1 \left[ 1 - \left( \alpha_1 - \alpha \frac{l_4}{l_2 i_g} \right) \operatorname{tg} \alpha_1 - \frac{1}{2} \left( \alpha_1 - \alpha \frac{l_4}{l_2 i_g} \right)^2 \right] \quad (20)$$

where  $\alpha$  is a function of time and is described by equation (17).

Thus, a model of the movement of the finger of the fruit and vegetable picker with an electric drive has been built, which allows, taking into account their location and orientation, to predict the fact of the fingers touching the surface of the fruit. However, the control of the touch force and the formation of a decision on the separation of the fruit is significantly simplified if touch force sensors are additionally added to the video camera and proximity sensors [6]. The properties of the analytical model of the design of a multi-finger gripper with elastomeric elements and analytical expressions of the transient processes of the drive together with the transfer function of a brushless DC electric drive allow for analytical modeling and coordination of requirements for all design elements. Table 2 presents the transient data for the complex parameter  $K_w K_M$ , which characterizes the drive and the properties of the gripper fingers with an elastomeric element based on the analytical model.

**Table 2**

The influence of the relative design parameters of the drive on the transient processes of deformation of the gripper finger  $Y(t)$

$K_w K_M$	0,01	0,02	0,03	0,04	0,05	0,06
t, s						
0,1	-0,132349	-0,0518452	-0,0311617	-0,0216827	-0,0162494	-0,0127319
0,2	-0,1146267	-0,0396286	-0,0205658	-0,0120127	-0,0072576	-0,0042991
0,3	-0,0971523	-0,0274815	-0,0106428	-0,0036929	-0,0002717	0,00151879
0,4	-0,0833269	-0,0188243	-0,0048899	-0,000186	0,00139944	0,00167349
0,5	-0,0751513	-0,0154026	-0,0046418	-0,0022472	-0,0023024	-0,0031273

0,6	-0,0734225	-0,0174498	-0,0093481	-0,0084601	-0,0091194	-0,0098858
0,7	-0,0780025	-0,0240895	-0,0172787	-0,0163731	-0,016128	-0,0155024
0,8	-0,0881096	-0,0338294	-0,0263412	-0,0236637	-0,0211857	-0,0183685
0,9	-0,1025931	-0,045028	-0,0347543	-0,028913	-0,0236176	-0,0187377
1	-0,1201674	-0,0562506	-0,0414389	-0,0318357	-0,0240714	-0,0180478

Column 1 of Table 2 presents a fragment of the time of the transient process, and columns 2-7 show the value  $Y(t)$  according to (16), which is a significant factor in both models (14) and (15). As can be seen from the analysis of the data in these columns, the properties of the elastomer ensure the immobilization of the object by the gripper fingers, and their plasticity significantly damps oscillations in the transient process, but this requires increasing  $K_M$ , and therefore increasing the required traction force  $T$ . The latter demonstrates the need to formulate the problem of optimal determination of the parameters of the drive, electric motor, design of elastomer elements and multi-finger gripper as a whole. Only an analytical model will be able to provide its successful solution, expanding the possibilities of modeling and solving problems of constructing optimal solutions.

## 5. Discussion of results

The search for new ways to redistribute the contact clamp forces in grippers was carried out by using elastic elements that are able to grasp the object, which is important for work in the ACS, for example, harvesting. The proposed calculation scheme of the generalized gripper allows building models from the generalized one by specifying the parameters in accordance with the design features of the object. It was demonstrated on the model how such a problem is solved in manipulators with a single type of drive and the complex use of soft and hard rods. Development, research and design based on the generalized scheme of the gripper design, suitable for taking into account the new requirements of the ACS: versatility, automatic variability, the possibility of installing additional sensors - according to the needs of the time. An important direction of further research is the search for constructive solutions that minimize the size of the gripper, using elastomeric materials and a set of sensors to sense it into during the gripping process.

## 6. Conclusions

1. The use of elastic elements to create the structure of a universal gripper provides versatility, automatic variability and dispersion of clamping forces of objects in the grip, which makes grippers of this type suitable for working with objects that require clamping with a controllable force.
2. The analytical models have been developed that allow the use of a single type of drive and modeling static and dynamic that will increase the efficiency of grippers of industrial and anthropomorphic robots by studying their properties in detail during design.

## Declaration on Generative AI

The author during the preparation of this work, used ChatGPT in order to: Grammar and spelling check. After using these tools, the author reviewed and edited the content as needed and take full responsibility for the publication's this content.

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