Parametric synthesis of system of transmission of motion to links of anthropomorphic gripper of variable structure

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Abstract. The article is dedicated to issues of designing an anthropomorphic gripper (AG) made from actuating link groups (ALG) possessing kinematics similar to human fingers kinematics. The ALG option with the number of output links exceeding the number of motors is being considered. The general drive of links using motion transmission system (MTS) of variable structure is realized. The accepted method of MTS construction provides development of a new feature that is adaptability of the location of links to the profile of the grasped object surface. MTS may be constructed using leverage, rope and combined mechanisms. The transmission of high force is realized by leverage mechanisms. Its special feature is significant number of projected parameters. It determines the necessity of solving a problem of MTS parametric synthesis in optimization performance. The maximal force on the ALG output links at the end positions is proposed to be used as an optimality criterion. The restrictions placed on an optimality criterion and terms of similarity to finger phalanges motion are determined.

1. Introduction
The amount of work executed by robotic systems (RS) under extreme conditions is being expanded permanently [1]. The application of RS in outer space [2-5], under water [6], in emergency zones [7] is the most advanced. All objects of the RS interaction are initially adapted according to parameters and capacities of a human hand.

The Robonaut 2 reproduces astronaut activities on International Space Station [8]. Russian analogue FEDOR is preparing to perform similar functions [9]. Flight missions of space-performed robots correspond to the tasks performed by cosmonauts in full measure.

RS interacts with external objects adapted to kinematic and force capacities of a human hand. This fact determined a new direction of designing gripper devices that are anthropomorphic grippers (AG). AG realizes kinematics similar to a human hand. The gripper includes no less than three independent actuating link groups (ALG). To provide the required kinematics ALG must include three output links and possess three degrees of freedom with parallel axes of rotation. In the general case AG has from 9 to 15 degrees of freedom. According to the classic scheme with providing motion along each degree of freedom from individual motor the technical problems with their placement may appear [10].

Usage of group drive makes it possible to decrease the total number of motors in three times [11, 12]. However, the availability of kinematic dependence of motion of output links leads to decrease of reliability of keeping objects. It caused by the fact that only one or two links contact with object.
Usage of conceptually new approaches of MTS construction in a group drive makes it possible to eliminate that disadvantage. Transmission of motion from a motor to output links is performed by mechanism of variable structure. In this case the adaptability principle of location of links to object surface profile is realized. The basics of construction of ALG of variable structure are represented in previously performed works [13, 14].

2. Scheme of ALG of variable structure of MTS

2.1 Work of system of transmission of motion to the ALG links of variable structure

According to technical decision [12] MTS provides the rotation of three ALG output links from one motor. The peculiarity of the developed MTS is introduction of two additional connections of functioning that provide variability of structural scheme of the whole ALG [13] into a structural scheme. This makes it possible to receive a new feature that is adaptability of the location of ALG output links 1-3 to the object surface (figure 1).

![Figure 1](image_url)

*Figure 1.* The general kinematic scheme of ALG and its parameters determining the lengths of MTS links $x_1 = l_{AF}$, $x_2 = l_{AD}$, $x_3 = l_{DE}$, $x_4 = l_{EF}$, $x_5 = l_{FB}$, $x_6 = l_{FE}$, $x_7 = l_{EG}$, $x_8 = l_{BG}$, $x_9 = l_{BC}$, $x_{10} = l_{GJ}$, $x_{11} = l_{CH}$, angles of the initial installation $x_{12} –$ balancing lever $AD$.

MTS is made as a double-lever mechanism. The output link of the drive is connected with the balancing lever $AD$. The additional connections of functioning are realized through springs $a$ and $b$ (figure 1). The spring $a$ is installed between the first output link $AB$ and balancing lever $AD$. The second spring $b$ is installed between the second output link $BC$ and balancing lever $BG$.

Three types of structural scheme are realized in the process of ALG working. In case of absence of interaction with external object the motion only in kinematic pair $A$ is provided – that is the first type. The motion in pairs $B$ and $C$ is blocked by additional connections of functioning $a$ and $b$ (figure 2, a). When the link 1 reaches the object surface it stops (figure 2, b) and the second type of the ALG structural scheme is realized. The link 2 is output and the motion in kinematic pair $B$ is provided (figure 2, b). When it reaches the object surface the third type of the ALG structural scheme is realized. The link 3 is output and the motion in kinematic pair $C$ is provided (figure 2, c).
2.2 Projected parameters
Independent projected parameters are lengths of MTS links $x_i$ ($i = 1 \ldots 11$) and angle $x_{12}$ of installation of a balancing lever $AD$ (figure 1). This set of parameters determines the location of links definitely.

The number of projected parameters makes twelve units. To calculate projected parameters, it is necessary to have the same number of equations of constraints. If this condition is not fulfilled it is necessary to solve a problem of parametric synthesis in optimization performance.

The direct restrictions of $d_i \leq x_i \leq e_i$ kind, where $d_i$, $e_i$ are correspondingly min and max accepted values of $x_i$ parameter are imposed upon projected parameters.

2.3 Condition of constraint
Flexibility of a finger interacting with external objects is provided by limit angles of relative rotation of phalanges: 90° for proximal, 135° for medial, 45° for distal. Anthropopathy of grasping determines kinematics of ALG that is similar to the human finger kinematics. In this regard the limit angels of relative rotation of output links must be provided as $\varphi_1 = 90^\circ$, $\varphi_2 = 135^\circ$, $\varphi_3 = 45^\circ$. The rotation of output links by the given angles is provided by projected parameters that is represented by equations of constraint

\begin{align*}
\varphi_2 &= f_1 (x_i) = 135^\circ \\
\varphi_3 &= f_2 (x_i) = 45^\circ
\end{align*}

where $x_i$ ($i = 1 \ldots 12$).

Besides that, projected parameters must provide the initial position of output links corresponding to the position of phalanges of an open palm $\varphi_2 = \varphi_3 = 0$. This allows to get two more equations of constraint

\begin{align*}
\varphi_2 &= f_3 (x_i) = 0^\circ \\
\varphi_3 &= f_4 (x_i) = 0^\circ
\end{align*}

The rotation of link 1 is provided without MTS links concern. It excepts the presence of equations of constraint between $\varphi_1$ and $x_i$.

The number of functional equations of constraint is less than number of projected parameters. The problem of its determination should be solved in optimization performance.
2.4 Optimality criterion in MTS parametric synthesis

The functioning of ALG of variable structure [14] is characterized by two factors: realized angles of relative rotation of links and generated forces while grasping objects. Both factors should be taken into account in solving a problem of parametric synthesis.

When the link 1 of a kinematic pair \( A \) rotates the first type of structural scheme is realized. The relative motion of the MTS links is absent. The force applied by output links to external object is determined only by a moment made on a balancing lever \( AD \) and does not depend on projected parameters.

When the second type of structural scheme is realized the motion in four-link chains \( ADJF \) and \( FEBG \) takes place. The force made by link 2 is determined by angle \( \beta \) (figure 1, 2). The maximal degree of transmission of force between links \( EG \) and \( GB \) is provided when \( \beta = \pi/2 \). However, the value \( \beta \) changes when angle \( \phi_2 \) changes. The combination of projected parameters wherein the current value \( \beta \) verges towards \( \pi/2 \) within the whole period of existence of the second type structural scheme should be considered as optimal. The achievement of function \( F_1 \) its minimal value corresponds to this requirement

\[
F_1 = \min (k_1 |\pi/2 - \beta_1| + k_2 |\pi/2 - \beta_2|) \tag{5}
\]

\( \beta_1 \) and \( \beta_2 \) are angles of links \( EG \) and \( GB \) correspondingly when \( \phi_1 = 0^\circ \) and \( \phi_2 = 135^\circ \); \( k_1 \) and \( k_2 \) are coefficients determining the degree of priority of making force correspondingly at the beginning of the motion of link 2 (\( \phi_2 = 0^\circ \)) or at the end (\( \phi_2 = 135^\circ \)).

3. Formalization of optimality criterion

The method of closed circuit system [15] is the basis of analytical dependencies.

The final phase of realization of the first type structural scheme (figure 2, a) is represented in equation of constraint (3). The closure condition of the circuit of double-lever mechanisms \( FEBG \) determines the following:

\[
\beta_1 = \arccos \frac{-l_{EB}^2 + x_7^2 + x_8^2}{2 \cdot x_7 \cdot x_8} \tag{6}
\]

where

\[
l_{EB}^2 = x_6^2 + x_5^2 - 2x_6 \cdot x_5 \cos \alpha_1
\]

In its turn angle \( \alpha_1 \) is determined from the closure condition of the circuit \( ADJF \)

\[
\alpha_1 = \arccos \frac{x_3^2 - x_4^2 - l_{DF}^2}{2 \cdot x_4 \cdot l_{DF}} + \arctg \frac{-x_2 \cdot \sin x_{12-1}}{-x_2 \cdot \cos x_{12-1} + x_1} \tag{7}
\]

where \( l_{DF}^2 = x_1^2 + x_2^2 - 2x_1 \cdot x_2 \cos x_{12-1} \).

When the second type of structural system is realized the balancing lever \( GB \) moves together with link 2 (figure 2, b). The change of value of \( GBF \) angle coincides with the rotation angle \( \phi_2 \).

Angle \( \beta_2 \) is determined according to functional dependence of (6) type but for angle \( \alpha_2 \), which in its turn is determined by angle \( x_{12-2} \). The equation of constraint (1) should be used to determine the angle \( x_{12-2} \). Angle of rotation

\[
\phi_2 = \alpha_1 - \alpha_2 = 135^\circ \tag{8}
\]

The closure condition of four-link chain \( FEBG \) determines the following
\[
\omega_1 = \arccos \frac{x_7^2 - x_8^2 - l_{EB}^2}{2 \cdot x_7 \cdot l_{EB}} + \arctg \frac{-x_8 \cdot \sin \alpha_1}{-x_8 \cdot \cos \alpha + x_9}
\]  

(9)

\omega_2 \text{ is expressed after substituting } \omega_1 \text{ in the dependence } 8, \text{ then angle } x_{12-2} \text{ and } \beta_2 \text{ are expressed.}

Analytic expression of angle \(\beta_2\) has complicated, multilevel form and is not considered in the article. After substitution of the obtained expressions \(\beta_1\) and \(\beta_2\) into the dependence (5) the criterion of optimality is finally formed.

4. Conclusions

The analytical form of representation of functional dependence between MTS projected parameters has been obtained. On its basis the methodology of performance of parametric synthesis providing maximal force transmitted to the output links within operating angle of rotation has been developed.

References

[1] Manko S V, Diane S A K, Lokhin V M and Romanov M P 2015 Models and the software-algorithmic maintenance of multi-agent robotic systems HERALD of MSTU MIREA 8(1) 166-91

[2] Sorokin V G 2017 The variant of content and structural scheme of base block of space-performed anthropomorphic robot Manned Spaceflight scientific periodical 1(22) 68–4

[3] Schiele A, Kruger T, Kimmer S, Aiple M, Rebelo J, Smisek J, den Exter E, Mattheson E, Henandez A and van der Hulst F 2016 Haptics - A system for bilateral control experiments from space to ground via geosynchronous satellites In IEEE Int. Conf. on Systems, Man, and Cybernetics (SMC) 892–7

[4] Bamfaste S 2016 Development of a software layer for the integration of robotic elements into the METERON Infrastructure using Robotic Services, Master Thesis (Luleå University of Technology)

[5] Zhidenko I G, Kutlubaev I M, Bogdanov A A and Sychkov V B 2013 Argumentation of choosing of structural scheme of robots of space performance Conf. Proc. of the 17th. Int. Scientific Conf. devoted to the chief designer of Space-rocket Systems academician M.F. Reshetnev ed Ju Ju Loginov (Siberian State Aerospace University, Krasnoyarsk) 1(17) pp 278-80

[6] Zanin V Yu and Kozhemyakin I V 2016 Manipulator systems for autonomous underwater vehicles New defense order strategy 3(40) 72-4

[7] Kachanov S A, Moshkov V B, Barannik A Yu and Yakutov A V 2016 Adaptation of technologies realized in designing of anthropomorphic robots and robotic complexes for solutions J Civil security technology 13 4(50) 14-8

[8] Badger J, Gooding D, Ensley K, Hambuchen K and Thackston A A Case Study on Robonaut 2 ROS in Space 1 343-73 doi: https://doi.org/10.1007/978-3-319-26054-9

[9] Bogdanov A A, Kutlubaev I M and Permyakov A F 2018 Robot of space application as a component of software Manned spaceflight 3(28) 83-96

[10] Wolf S, Eiberger O and Hirzinger G 2011 The DLR fsj: Energy based design of a variable stiffness joint Robotics and Automation (ICRA) IEEE Int. Conf. pp 5082-9

[11] Bridgewater L B et al 2012 The Robonaut 2 hand-designed to do work with tools Robotics and Automation (ICRA) IEEE Int. Conf. on. IEEE

[12] Bogdanov A A, Permyakov A F and Zhdanova Yu I 2018 Adaptive drive of gripper links group (Moscow: Rospatent) vol 35 patent N 185794

[13] Bogdanov A, Permyakov A and Zhdanova Yu 2018 Synthesis of structural scheme of drive of adaptive multiple-link gripper MATEC Web of Conf. 161 03009 doi: 10.1051/matecconf/201816103009

[14] Bogdanov A, Permyakov A and Zhdanova Yu 2018 Research of kinematics of an actuating
group of an anthropomorphic gripper with a common drive. MATEC Web of Conf. 01029 doi: 10.1051/matecconf/201822401029

[15] Artobolevsky I I 1988 The Theory of Machines and Mechanisms Naukapublisher (Moscow) p 640

[16] Sorokin V G 2017 An option of the configuration and structural scheme of the base unit of the stand-alone humanoid space robot Manned Space Flights 1(22) pp 64-8

[17] Schiele A, Kruger T, Kimmer S, Aiple M, Rebelo J, Smisek J, den Exter E, Mattheson E and Henandez A et al 2016 Haptics-2 – a system for bilateral control experiments from space to ground via geosynchronous satellites In IEEE Int. Conf. on Systems, Man, and Cybernetics (SMC) pp 892–7

[18] Bamfaste S 2016 Development of a software layer for the integration of robotic elements into the METERON infrastructure using robotic services Master Thesis (Luleå University of Technology)