Method of optimization synthesis of parameters of actuating system of anthropomorphic gripper with adaptive control

Yu I Zhdanova* and V V Moshkin

MIREA - Russian Technological University, 78 Vernadsky av., Moscow 119454, Russia

*musrosjk@gmail.com

Abstract. Gripper is a basic component of any robot. Its functionality is determined by realized number of degrees of freedom and control system. Anthropomorphic robots (AR) possess the biggest number of mobilities. Usage of group drive with adaptive control of mobile links is developing way of AR construction. This method allows to grasp and hold arbitrary shape objects when the motors number is less than mobilities number. Method of parametric synthesis of actuating system (AS) of AG made by two subsystems: the main kinematic chain (MKC) and motion transmission system (MTS) is represented in the article. MKC including two output links connected with each other and gripper base by rotational pairs with parallel axes is considered. MTS is parallel leverage mechanism. Subsystems are connected with each other by additional functional connection. The connection provides moving torque in MKC kinematic pairs. The presented approach is based on choosing MTS parameters that provide producing maximum torque in MKC kinematic pairs of its links end positions. The obtained equations of connection reflect the specificity of AS construction. The optimality criterion is defined and formalized by revealed equations of connection. The presented method allows to choose MTS parameters providing rational functioning of anthropomorphic gripper AS.

1. Introduction

Robotic complexes capable to function as an equal to humans have become an essential part of modern technology level. The extension of their application field is based on technical and social necessity [1, 2]. This is encouraged by development of element base: sensory, new materials, electronic circuits. Robotic complexes are actively developed and introduced in medicine [3], EMERCOM subdivisions [4], underwater research [5], space performance [6-7]. It is necessary to emphasize robots initially oriented to functioning with human infrastructure — anthropomorphic robots [8-9]. Performance of assignment tasks is provided by robot gripping device. Ideally, the AR gripper must have the same kinematic and force parameters as a human hand.

20 degrees of freedom are realized in a hand. Even apart from rarely used mobilities such as distal phalanges, little finger, the number of active mobilities equals to 10-13 units. Anthropomorphic gripper (AG) used in ‘Robonaut 2’ has 24 degrees of freedom provided by 16 drives [10]. A large number of drives leads to reduction of its generating capacity and decrease of force parameters of a gripper.

AG that possesses enough potential at minimum number of links and degrees of freedom has three actuating systems (AS) with two or three degrees of freedom in each of them [11-13]. AS is formed by two mobile links connected with each other and the base of a gripper by rotational pairs with parallel
axes of rotation. To provide fine motor skills proximal links may have additional mobilities around the axes perpendicular to the first two [14]. In this variation the gripper has 8-9 degrees of freedom. It is possible to decrease the number of mobilities by means of introduction of rotation of the gripper base [15]. In this case functionality is provided by seven degrees of freedom. Besides, six drives are allocated on the gripper base.

Further increase of generating capacity of motors without increase of gripper dimensions can be accomplished by means of group drive with adaptive control of links. In this case three drives installed on the gripper base can be used.

2. Design solutions applied in AS construction of AG

Nowadays there have been developed many constructions that realize the idea of group drive with adaptive control. The presence of two subsystems is the universal factor of all AS constructions [16]. The first one is nonclosed main kinematic chain (MKC) whose links are all output. The second one is motion transmission system (MTS). MTS is located in parallel to MKC and has kinematic connection with output links of MKC. Due to this connection the transmission of motion to MKC links from proximal to distal is performed. Such sequence is determined by two factors: introduction of additional connections in the form of springs and interaction between output links and external object (EO).

Interaction between AS and EO is realized by two stages: grasping and holding. In grasping process the output control parameters are relative rotation angles of MKC links. The stage is finished when the proximal link reaches EO or limit position [16]. At the holding stage the relative motion of links is absent. The force from the output links side to EO is made by drive.

According to the way of arrangement of functional connections all AS should be divided in two types. The first type is the AS’s which have their connections arranged between links of one subsystem – MKC (figure 1, a) [17-19]. According to the second type the connections are realized between the links of subsystems MKC and MTS (figure 1, b) [16, 20-21].

![Figure 1. Options of kinematic schemes of AS.](image)

AS’s presented in figure 1 have output links 1 and 2. The motion of links is provided by leverage MTS which includes links 3, 4. Link 3 is the leading link of the drive. Each AS has one extra mobility

\[ W^I = 3n - 2p_5 - p_4 - t, \]

where \( n \) is the number of mobile links, \( n = 4 \),

\( p_5 \) – the number of kinematic pairs of V class, \( p_5 = 5 \),

\( p_4 \) – the number of kinematic pairs of IV class, \( p_4 = 0 \),

\( t \) – the number of drives, \( t = 1 \).

\[ W^I = 1 \] for AS presented in figure 1. Exclusion of extra mobility is achieved by inclusion of one functional connection as a spring 5 (figure 1, a) or spring 6 (figure 1, b). Springs 5 and 6 differ according to impact on mobile links 1 and 2. This is determined by the way of their installation. Spring 5 is the internal connection of MKC. Spring 6 provides connection between 2 subsystems: MKC and MTS.
Motions of output links in both options of AS construction are identical. At the first stage of grasping, the cooperative motion of MTS and MKC links in a kinematic pair $A$ is provided by means of rotation of a guide link 3. Relative rotation of mobile links is absent. When link 1 reaches EO it stops and the second stage of grasping is realized. By means of motion of MTS links the rotation of link 2 is performed in a kinematic pair $B$ until it reaches the EO surface.

Then the holding stage is realized (figure 2). The force impact of output links 1 and 2 on EO is made by means of a torque on a guide link.

![Figure 2. Interaction of MKC links with EO at holding stage.](image)

In this case principal difference between ways of installation of springs 5 and 6 comes out. Spring 5 decreases the load on EO from the link’s 2 side, and spring 6 provides additional force impact of link 2 on EO. As a consequence, $R_{2b}$ exceeds $R_{2a}$, and what is more important $R_{1b} > R_{1a}$. AS constructed with addition of functional connections between subsystems provides more rational scheme of force interaction between output links and EO.

Correspondence of forces $R_{1b}$ and $R_{2b}$ is determined by geometric parameters MTS and spring’s 6 rate. The synthesis of MTS parameters should be performed for realization of optimized force impact of MKC links on EO.

3. Formalization of the objective of AS parametric synthesis

3.1. Initial parameters

According to AR purpose and probable set of EOs the parameters that characterizes MKC: lengths of links $l_1, l_2$, limit rotation angles $\phi_1, \phi_2$ are determined at the previous level of designing. Allowable forces of force impact on OE that are $[R_{1b}]$ and $[R_{2b}]$ are set due to EO strength characteristics. In general case $[R_{1b}] = [R_{2b}]$.

3.2. Projected parameters

The dimensions that determine MTS refer to projected parameters. Linear: $x_1 = l_{AG}, x_2 = l_{GD}, x_3 = l_{BD}$, angular: $x_4 = \gamma_{GAY} -$ determines initial position of the guide link of drive 3, $x_5 = \gamma_{DBY} -$ parameter of link 2 (figure 3,a).
3.3. Conditions of connection

Condition of connection must reflect permanence of AS structure in the functioning process. This condition is formalized in a form of correspondence of \( q \) – rotation angle of guide link 3, through the rotation angle of output link 2 - \( \varphi_2 \) and MTS parameters:

\[
q = F(\varphi_2, x_i) \quad (1)
\]

It should be noted, that when rotation angle \( \varphi_1 \) changes, the relative motion of MTS links is absent. In this regard only the second phase of grasping stage should be considered further.

AS is a double-lever mechanism with driven link smaller than a guide link. Correspondence (1) can be obtained from the closure condition of vector contour AGDB formed by links 1–4. In turn its closure determines closure of triangles AGB and BGD. By writing these conditions in projections on the axes \( x \) and \( z \) we obtain 4 equations enabling to gain the final correspondence through auxiliary angles \( t_1, t_2, g \) and distance \( l_{GD} \)

\[
q = \pi - \left( x_2^2 + x_1^2 - l_1^2 - x_3^2 + 2 x_1 x_3 \cos \varphi_2 \right) / \left( 2 x_1 \left( \left( l_1^2 + x_3^2 - 2 l_1 x_3 \cos \varphi_2 \right)^{0.5} \right) + \arctan \left( x_3 \sin \varphi_2 / \left( x_3 \cos \varphi_2 - l_1 \right) \right) \right) \quad (2)
\]

Correspondence (2) enables to determine mutual position of AS links as a function of projected parameters and realized angle \( \varphi_2 \). The corresponding value \( q_H \) and \( q_K \) is calculated by substitution of angle \( \varphi_2 = \varphi_{2H} \) and \( \varphi_2 = \varphi_{2K} \) in expression (2).

3.4. Optimality criterion

In MTS maximum force \( R_{2b} \) is provided with angle \( \beta = \pi/2 \) for the same torque on a guide link. The combination of projected parameters is the most effective from power point when condition of minimal difference \( \pi/2 - \beta \), while \( \varphi_2 = \varphi_{2H}, \varphi_2 = \varphi_{2K} \) is performed. In this case optimality criterion is the following:

\[
F = \min \left( k_1 \mid \pi/2 - \beta_H \right) + k_2 \mid \pi/2 - \beta_K \right) \quad (3)
\]

where \( k_1 \) and \( k_2 \) are weighted coefficients that reflect the most preferable working area of the angle of link 2 rotation;
β_H, β_K – correspondingly is an angle made by links 4 and 5 with \(φ_2 = φ_{2H}\) and \(φ_2 = φ_{2K}\).

Correspondence of angle \(β\) by projected parameters is easily expressed by consideration of triangles AGB and BGD:

\[
β = \arccos \left( \frac{-l_{GB}^2 + x_2^2 + x_3^2}{2x_2 x_3} \right)
\]  

(4)

\[
l_{GB}^2 = x_2^2 + l_1^2 - 2x_2 l_1 \cos q
\]

Angles \(β_H\) and \(β_K\) are calculated correspondingly by substitution of values \(q_H\) and \(q_K\) in expression (4).

Seeking if extremum of function \(F\) can be performed by any program product realizing direct search method. In this case direct constraints are \(a_i < x_i < m_i\), where \(a_i\) and \(m_i\) are initially set constraints on projected parameters.

4. Conclusions

Presented method of formation of optimality criterion enables to calculate MTS parameters reasonably. The achieved analytic form reflects correspondence between projected parameters. In this case the specificity of AS construction including two subsystems connected by functional connection and realizing adaptive control system is represented.

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