The method of the quasioptimal per energy efficiency design of the motion path for the anthropomorphic manipulator in a real time operation mode

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Abstract

The method of the quasioptimal per energy efficiency design of the motion of triple-section anthropomorphic manipulator with seven degrees of mobility approximated in the form of sphere with hindrance in working area in a real time operation mode is provided in this article. Developed method is based on the iterative piecewise-line generation of the anthropomorphic manipulator motion path. This method has rather low computational complexity that allows working in the real time operation mode and gives it the flexibility which adapts it for difference commands. The task of quasioptimal for energy saving motion path of anthropomorphic manipulator the adaptation of iterative piecewise-line generation is method performed in order.

1 Introduction

The required trends of robotics technology development are stipulated by the need to replace the human labour in similar operation performance or during work in potentially dangerous fields which can cause the risk to human health.

The subject of the research is limited by such a variety of robotic product as a manipulator. The manipulators for similar operations implementation are generally presented by the industrial manipulators with centralized power and program control. The industrial manipulators fillfull the similar operations of installation, welding and painting. The power consumption during these operations is a very important question in the process of final product manufacturing because it determines their self-cost. The methods effective for the optimization of the target energy saving but cost-intensive in computational complexity can be applied while the manipulator

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is at work. The optimization of the manipulator movements is carried out only once and its results are used in the control program. The situation is different with the anthropomorphic manipulator which applied for work in the potentially dangerous condition for human like underwater, spaceward and radiation area. While performing rescue works, serving nuclear industry entity and accomplishing the technical maintenance service of technics in space the manipulator movement have low frequency. The operation value due to the energy efficiency is defined by the amortized cost of electric power elements but not by the cost of electric power as against the industrial manipulators with centralized power network. These power elements have the limited amount of charge-discharge cycles. As well, their replacements connected with the complexity of isolated work areas demands extra costs. The hardware and software methods for decreasing energy consumption could be used under these conditions. The hardware-based are expressed by the usage of easer materials, engines with higher efficiency and etc. Hardware methods increase the manipulator cost in spite of their apparent advantages. Program methods use more efficiency algorithm of manipulator motion control. There are a lot of efficient but computationally complex methods of the motion path design. There are two approaches of the motion path design in literature. They are the approach based on the diagram theory and the approach of spline interpolation. The First approach is characterised by computational complexity and the second one is characterised by the complex choice of supporting points, the presence of redundant motions at few points and calculation complexity at many points.

The motion path design at redundant manipulators movement based on the evolutionary approach is considered in the researches [Kam07, Qi14, Qi14, Xid18].

Design methods of the manipulator movement based on the natural movement of a manipulator are presented in works [Liu16, Ren15].

The Numerical methods of design problems solution are presented in works [How14, Che17].

The Manipulator control under the above mentioned extreme conditions is realised in a real time operation mode. So the limitations, which keep out the use of the above mentioned algorithm of the motion path design to optimise the manipulator movement for energy saving are laid on the algorithm computational complexity. However this method do not allow to solve the task how to plan the motion path of the anthropomorphic manipulator with hindrance.

The aim of the research is to work out the motion path design method for the anthropomorphic manipulator on the basis of iterative piecewise-line generation in order to solve the task how to design the quasi-optimal, energy-efficient method in extensional space with hindrance at a real time operation mode. The Quasi-optimality of the suggested method is stipulated by the application of the "greedy method" that do not guarantee the global optimality of the above-mentioned method.

2 Setting the Task

The kinematic diagram of the considered anthropomorphic manipulator with 7-degrees of mobility is shown in Figure 1(a). This kinematic diagram is used in robots of series AR-600, SAR-400, FEDOR manufactured by "AO NPO "Android Technique"" [NPO18]. The following indices are used in this Figure: B_{1-4} shoulder, elbow radoiocarpal key parts and working terminal, correspondently; A_{1-7} manipulator 7-degrees of mobility, A_8 manipulator working terminal.

The design task is to find set of intermediate positions for the manipulator movement in order to go from start to final position while it rounds hindrance

Thus, the following initial data are required on the bases of the above mentioned task.

θ_S - the numerical vector of the manipulator generalised coordinates in starting position (index of s, i-type points at that it is generalised coordinate in starting position); $B_{4,F}$ − the coordinates of the working final position B4 in the global Decartes coordinate system.

O− the coordinates of hindrance center set in global Decartes System and its radius R.

Further the following variables are used.

$I_{B1-B2}, I_{B1-B2}, I_{B1-B2}$− the length of shoulder , elbow and hand elements of the manipulator.

k the numerical vector of energy intensity coefficients for engines which rotation degree corresponds to generalised coordinates with relevant indices. These coefficients are required for energy consumption.

According to the above mentioned motion path design task the result of the applied method is to achieve the arranged set of the numerical vectors for the generalised coordinates describing the position that should be gone by the manipulator from the starting position in order to achieve aim point under condition of going round the hindrance. This arranged set is defined as the path $L = \theta_S, \theta_1, ..., \theta_F$ where, θ_S − the numerical vector of the manipulator generalised coordinates in starting position, θ_F – the numerical vector of the manipulator generalised coordinates in final position.

3 Method Development

Let's introduce the following notions used further in the article. Global Starting (GS) and global final (GF) positions are starting and final position of the motion under which the path design is accomplished. The in-line motion paths are considered during the design of the manipulator motion path by the suggested method. Starting, intermediate and final positions for every path are indicated as local starting (LS) local intermediate (LI) and local final (LF) positions.

Let's use Denavite-Khartenberg presentation to develop the transform matrix between different system of coordinates connected with a manipulator elements. The Connected systems of coordinates are shown in Figure 1(b).

The rotation angles of the anthropomorphic manipulator connections are considered to be generalised coordinates to this manipulator of the circular type - θ. Developed method algorithm of movement path design shown on Figures 2(a) and 2(b). Let's describe every step.

Step 1. Input Data. As it was described earlier, the input data are the numerical vector of the manipulator generalised coordinates in starting position θ_S; the coordinates of the working final position $B_{4,F}$; the coordinates of hindrance center O and radius R; length of elements $I_{B1-B2}, I_{B1-B2}, I_{B1-B2}$; the numerical vector of energy intensity coefficients for engines K.

Step 2. Inclusion GS position. As the manipulator movement starts from GS position, the numerical vector of the manipulator generalised coordinates, first of all, must be added to movement path L, which is presented as a sorted list.

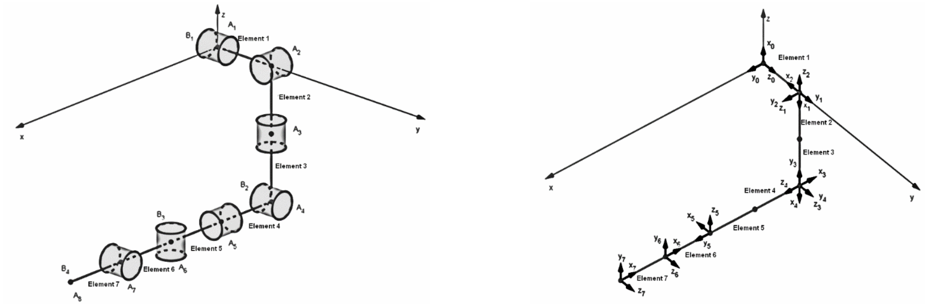
Step 3. Calculation GF position. We must solve the kinematic inversed problem to control the manipulator as we know only the point of GF in which the effector should be. We can use the approach suggested in [Pet18]. This approach allows to optimise the manipulator final position thus, that at the in-line movement from start to final position the power consumption is minimal, if the effector reaches the target final point.

It can be considered that engine energy consumption linearly depends on the change absolute value of the corresponding rotation angles at the manipulator connections while moving between two positions. Thus aimed function is equal to total energy consumption of all the engines while moving from start to final position, and can be written as follows:

$$f(\theta_S, \theta_F, k) = k|\theta_F - \theta_S| \tag{1}$$

where θ_F – the numerical vector of the generalised coordinates in final position.

$|\theta_F - \theta_S|$ – elementwise diminution manipulation and module taking; The following limitation is put on the numerical vector of the generalised coordinates in final position – effector B_4 is set to be in point $B_{4,F}$.



(a) The Kinematic Diagram

(b) Joint System of Coordinates

Figure 1: Diagram of the Anthropomorphic Manipulator with 7-Degrees of Mobility

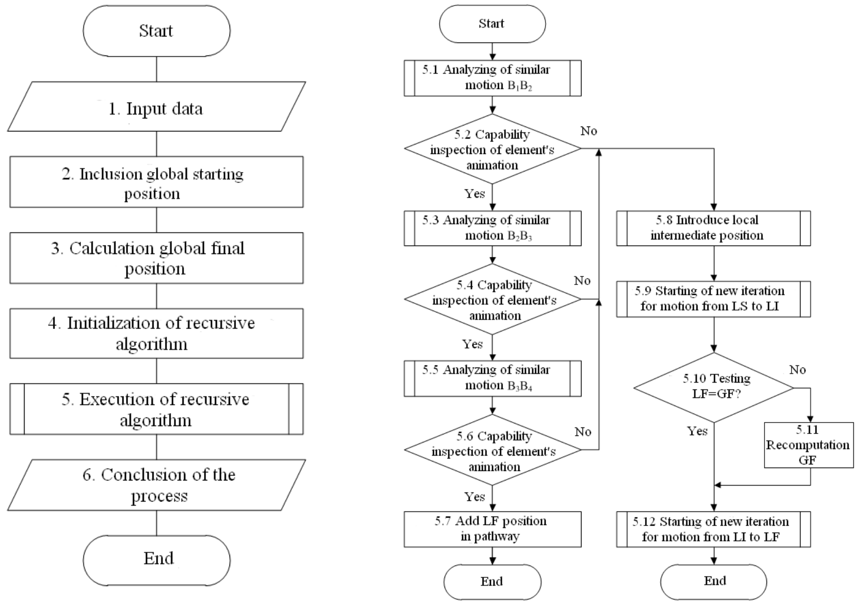
The effector final position for the generalised coordinates could be find with Deneavit-Khartenberg presentation. Thus, the mathematical notation of this requisition is:

$${}^0T_8(\theta_{F,1}, \theta_{F,2}, \theta_{F,3}, \theta_{F,4}, \theta_{F,5}, \theta_{F,6}, \theta_{F,7}) * (0, 0, 0, 1)^T = B_{4,F} \tag{2}$$

where ${}^0T_8$ – the transformation matrix from 8-th coordinate system in 0-th .

The method of generalized reduced gradient could be used for the purpose of this 7-dimensional optimization with three limitation-equality (2) task [Pet18].

Step 4. Recursive Algorithm Initialization. The following recursive algorithm allows to analyse the possibility of in-line motion in generalised coordinates between two positions. The intermediate position is introduced by “pushing out” the nearest motion path point to the center of the hindrance if the in-line motion is impossible because the path crosses the hindrance.



(a) The Scheme of the Movement Path Design Algorithm

(b) Recursive Algorithm Scheme

Figure 2: Algorithm for the Anthropomorphic Manipulator

Thus, the following data as required to be sent during the first iteration of the recursion if the recursive algorithm is initialized: generalised coordinates in starting θ_S and final θ_F positions; logical type variable g, which informs us if the final position is global or not (for this situation – yes); hindrance characteristics O and R; the numerical vector of energy coefficients k; length of elements $I_{B1-B2}, I_{B1-B3}, I_{B3-B4}$; The motion path formed for the current period L (this motion path includes only the numerical vector of the generalised coordinates in the global starting position for the first iteration)

Step 5. Recursive Algorithm. The reported positions are conceded as the local starting and the local final inside the recursive algorithm. The inside input variable indicates if the local final position is also the global final. The following steps are performed at every iteration of recursive algorithm.

Step 5.1. Assay in-line Motion of element B_1B_2. The objective of the assay applied to the in-line movement for B_1B_2. is to find the “worst” intermediate position of this element at the in-line movement from the local starting to the local final position. If all the generalised coordinates depend on time linearly and reach the final value simultaneously, the movement is in-line. The following function can describe this time dependence:

$$\theta(t) = \theta_S + t(\theta_F - \theta_S) \tag{3}$$

where t – the normalized time changing from 0 to 1. 1 is complied to the time in a total scale required for the movement in the slowest connection. If a distance from the element B_1B_2 to the center of hindrance O is minimal in intermediate position, this position is called the “worst”

Step 5.2 Element B_1B_2 in-line Motion Capability Check. It is necessary to accomplish the following inequation to supply the possibility of the element B_1B_2 in-line motion:

$$d_1(\mathbf{Y}_1(\theta(t^*))) > R \tag{4}$$

The physical sence of this inequation is following: the time when the distance from the element B_1B_2 to the center of the hindrance is minimal the distance should increase the hindrance radius.

The assay of the in-line motion for the elements B_2B_3 and B_3B_4 as well as the check of their possibility in steps 5.3-5.6 are carried out if the inequation (4) is accomplished. This operations are similar to steps 5.1, 5.2.

The Local final position is added to the motion path L on step 5.7 and the output from the current iteration of the recursive algorithm is performed if all the in-line motions are possible.

Thus the output from the recursion after the first iteration will be performed if the in-line motion from the global starting position to the global final position is possible.

If one of the element can not move directly transition to the step 5.8 introducing the intermediate position is performed.

Step 5.8. Intermediate Position Introduction. The intermediate Position is introduced if the worst position from 1 of the manipulator element to the center of the hindrance is less than its radius. To do this the manipulator is pushed out from the center of the hindrance with a some margin h subsequently starting the shoulder element.

If the in inquality is not performed is indicates that any element goes across the hindrance (4).

The pushing out procedure of any manipulator element is the following.

Let's analyze any element B_iB_{i+1} with known started $B_i\,(x_{Bi},\ y_{Bi},\ z_{Bi})$ and final $B_{i+1}\,(x_{Bi+1},\ y_{Bi+1},\ z_{Bi+1})$ points.

Let's introduce the new circle with the center in point O and with radius $R+h$ where h is some magian that is necessary to protect the pushed-out manipulator touching the hindrance. Then, the element position in hand coordinates after pushing out will coincide with the tangency that is the closest to the circle started from the point B_i .

It is necessary to find both of the tangency and the points of tangence K_1 and K_2 coordinates to find the nearest tangency. These points lie in the crossing points of the sphere with (the center in point O and the radius $R+h$), the sphere with (the center in point B_i and the radius $r = B_iK_1$) and also the subspace crossing the sphere center and the element B_iB_{i+1}. The system of equations for this points is:

$$\begin{cases} (x-x_O)^2+(y-y_O)^2+(z-z_O)^2=(R+h)^2, \\ (x-x_{Bi})^2+(y-y_{Bi})^2+(z-z_{Bi})^2=r^2, \\ N_0x+N_1y+N_2z+D=0, \end{cases} \tag{5}$$

where, $R^2 = min\left[B_iB_{i+1}{}^2; B_iO^2-(R+h)^2\right]$; $\mathbf{N} = \{N_0; N_1; N_2\} = \mathbf{B_iO}\times\mathbf{B_iB_{i+1}}$ – the tangence vector to the drawing subspace. $D = -N_0x - N_1y - N_2z$.

To find the nearest tangency to the element B_iB_{i+1} we must choose those tangency which directional single vector has the bigger scalar module multiplication with the element vector:

$$K = \begin{cases} K_1, if\,\frac{|\mathbf{B_iK_1B_iB_{i+1}}|}{B_iK_1} \geq \frac{|\mathbf{B_iK_2B_iB_{i+1}}|}{B_iK_2}, \\ K_2, if\,\frac{|\mathbf{B_iK_1B_iB_{i+1}}|}{B_iK_1} < \frac{|\mathbf{B_iK_2B_iB_{i+1}}|}{B_iK_2}. \end{cases} \tag{6}$$

After that, the segment of length BB should be laid out along the chosen tangency B_iB_{i+1} from the point B_i:

$$\mathbf{B_iB_{i+1}}' = \frac{\mathbf{B_iK}B_iB_{i+1}}{B_iK} \tag{7}$$

where, $\mathbf{B_iB_{i+1}}'$ – is the expected vector of the deflect position.

The following should be concided at the moment of elements pushing-out. After the shoulder element pushing-out the change of hand coordinates of elbow and hand ends is happening as they depend on shoulder element position. Similar, after the elbow pushing-out it is necessary to recalculate the end of hand element coordinates.

For that in the algorithm after pushing-out every element, the recalculation of generalized coordinates, which describe its position, is performed. Further, the recalculation of hand coordinates for all the previous elements is performed with Denavit-Khartenberg presentation.

The values of the generalised coordinates in pushing-out position can be find with help of the specific solution with the help of inverse kinematic solution.

Let's define the value of the generalised coordinates for the manipulator in position indicated in Figure 1(b), as $\Theta = \{\Theta_1, \Theta_2, \Theta_3, \Theta_4, \Theta_5, \Theta_6, \Theta_7\}$.

The value of the generalised coordinates in pushing-up position $\theta_{\mathbf{P}}$ can be recalculated as:

$$
\begin{array}{ccc}
\mathrm{B}_2^0 = (\mathrm{T}_0)^{-1}\mathrm{B}_2; & \theta_1^* = atan2\left(B_{2\ x}^0, B_{2\ y}^0\right); & \theta_1 = \begin{cases} \theta_1^*, \text{ if } \theta_1^* > 90^\circ, \\ \theta_1^* + 2\pi, \text{ if } \theta_1^* < 90^\circ \end{cases}; \\
\mathrm{B}_2^1 = (\mathrm{T}_1)^{-1}\mathrm{B}_2; & \theta_2 = \Theta_2 + atan2\left(B_{2\ x}^1, B_{2\ y}^1\right); & \mathrm{B}_3^2\mathrm{B}_2^2 = (\mathrm{T}_2)^{-1}\mathrm{B}_2 - (\mathrm{T}_2)^{-1}\mathrm{B}_3; \\
\theta_3 = atan2\left(B_3^2B_{2\ x}^2, B_3^2B_{2\ y}^2\right); & \mathrm{B}_3^3 = (\mathrm{T}_3)^{-1}\mathrm{B}_3; & \theta_4 = \Theta_4 + atan2\left(-B_{3\ x}^2, -B_{3\ y}^2\right); \\
\mathrm{N}^4 = (\mathrm{T}_4)^{-1}\mathrm{N}; & \theta_5 = atan2\left(\mathrm{N}_x^4, \mathrm{N}_y^4\right); & \mathrm{N}^5 = (\mathrm{T}_5)^{-1}\mathrm{N}; \\
\theta_6 = \Theta_6 + atan2\left(\mathrm{N}_x^5, \mathrm{N}_y^5\right); & \mathrm{B}_4^6 = (\mathrm{T}_6)^{-1}\mathrm{B}_4; & \theta_7 = atan2\left(-B_{4\ x}^6, -B_{4\ \mathrm{y}}^6\right),
\end{array}
\tag{8}
$$

where ${}^iT_j$ – the homogeneous transforming matrix from j- to i- coordinate system, $i < j$, composed in accordance with Denavit-Khartenberg presentation. (if transforming into the global coordinates system, the left index will be taken out; $atan2\,(x, y)$ – anti-tangent function from two argument considering the quadrant of the angle argument:

Step 5.9. Start the New Iteration for Moving from LS in LI. The new iteration for movement from LS in LI is performed after all the manipulator elements are pushed out and the generalised coordinates of LI position are calculated.

Step 5.10. Checking LF Conjunction with GF. If LF position is global too, the determined generalised coordinates GF are not optimal as they were calculated to find the motion from GS or other LI. So, it is necessary to recalculate GF on step 5.11.

Step 5.11. GF Recalculation. Input data for this calculation are the same as for step 3, but starting position now is LI.

Step 5.12. Start the New Iteration for Moving from LI in LF. Similar to step 5.9. the design of the motion path from LI to LF fullfield.

Step 6. Position List Output. After the calculations the list of positions is derived for the following using.

Let's explain the effect of the h characteristic on the trajectory energy efficiency and computational complexity. If its value is increased, the manipulator motion becomes more angular due to the number of intermediate positions is decreased. This alteration decreases the calculation spends but increases the energy consumption. If the characteristic h is decreased, the energy consumption is also decreased but the calculation spends are increasing as the number of intermediate positions is increased and the movement becomes more plain.

According to the analysis in of temporary computational complexity [NPO18] , the time of algorithm accomplishment for the designed method while using the parallel computations is similar to the time of accomplishing the following number of operations:

$$
N \approx n\log_2\left(\frac{1}{\varepsilon}\right)\left[\log_2\left(\frac{\pi}{2\arccos\left(\frac{r}{r+h}\right)}\right) + 1\right],
\tag{9}
$$

where, N – number of operations; n – the coefficient depending on the definite program realisation (for authors this coefficient is $42 * 10^3$); r – the hindrance radius; h – the setting characteristic of the motion path algorithm; ε – the setting precision of one-dimensional optimization process.

Thus, for the following example: $n = 42 * 10^3,\ \varepsilon = 0,01,\ r = 50\text{cm},\ h = 1\text{cm}$, the number of operations for the worst case is $N \approx 1,1 * 10^6$. More than, the design of the motion path for the anthropomorphic manipulator can be done so that the motion can start before the total calculations are completed.

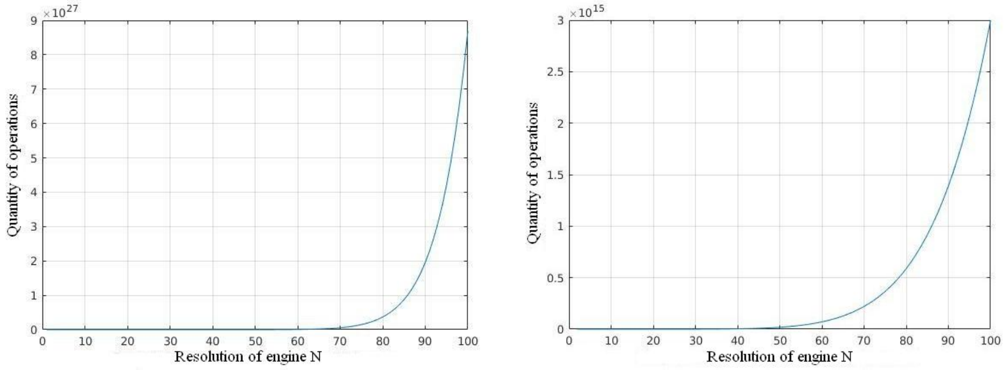
Considering the fact that modern central and graphic processors have the capacity of about 10^{11} FLOPS, the designed method can be applied in a real time operation mode.

In order to compare the designed method with other well-known methods used design the path for the anthropomorphic manipulator, let's compare computational complexity.

Neural network and graphical analytic methods are based on a flow chart. The implementation of Voronoi diagrams [Qi14] is improved variant of graphical analytic methods. According to the data published in [Psh15], the complexity class of the methods based on the compilation of flow charts is $O\left(n^2\right)$, and on the Voronoi diagram is $O\,(n\lg{(n)})$, where, $n-$ the number of elements on the frame.

On the basis of the research we can build the diagram including the number of required operations depending on the resolution power N within constant factor. The results of the numerical simulation are shown in Figures 3(a) and 3(b).

As the diagrams show the number of operations even for the resolution power $N = 100$ (positional accuracy in an engine is about 1°) go beyond the accepted limits in a real time operation mode.



(a) The Number of the Operations for the Methods based on the Voronoi Diagram

(b) The Number of the Operations for the Methods based on the Road Map.

Figure 3: The Number of the Operations

In order to prove this, the further practical implementation of the algorithm considering the abovementioned recommendations be performed. Energy consumption of the anthropomorphic robot manipulator when performing the target operation in the working area with a typical obstacle was reduced by 11.2% without the use of an intermediate solution to the optimization problem of calculating the generalized coordinates in the final position, and by 16.6% with its use. The effectiveness of the proposed solution to the optimization problem of finding generalized coordinates in the final position as a whole, and the proposed objective function in particular indicates by saving of energy consumption on 38%.

It's also planned to measure the operation time and analyze the energy efficiency of the methods during the computing experiment.

4 Discussion

The aim of the article was to work out the design method of motion path for the anthropomorphic manipulator on the basis of the iterative piecewise-line generation in order to solve the design problem of the quasioptimal energy efficient path in extensional space with a hindrance in a real time operation mode.

The algorithm of the adopted method as well as all the required calculations are presented in the article. The designed method allows to round the hindrance – approximated by the sphere and the applied "greedy method" makes it possible to achieve the quasioptimal per energy efficiency path. The computational complexity using this method is equal to $1,1 * 10^6$operations. Modern central and graphic processors have the productivity of about 10 FLOPS. So, the developed method can be applied for designing the motion path of the anthropomorphic manipulator in areal time operation mode.

As the design is considered to be quasioptimal and based on the "greedy method", the software implementation of this method and its comparison to the other methods of energy efficient path design for the anthropomorphic manipulators per the criterion of energy efficiency are to be urgent.

5 Conclusion

The description of the designed methods of quasioptimal per energy efficiency motion path of the anthropomorphic manipulator in a real time operation mode is presented in the article. The methods is based on the numerical approach of the iterative piecewise-line generation of the point motion path function in the space with hindrances and its adaptation to the anthropomorphic manipulator in a view of the design method of the optimal path function in a work area with hindrances. The solution method of the kinematic inversed problem for the triple-section anthropomorphic manipulator with 7-degrees of mobility on the basis of the Denavit-Khartenberg presentation and the solution of the nonlinear optimization task per the criterion of the energy efficiency by the numerical method of the generalized reduced gradient were used to build the starting path. In order to move between the positions of the anthropomorphic manipulator, the formulas of the inversed kinematic approach adopted to this task were developed. The initial data for the suggested methods are start, intermediate and final positions of the manipulator motion path as well as the generalized coordinates used to fulfill established destination operation. The analysis of the computational complexity showing the possibility to perform the mentioned operations in a real time operation mode was conducted.

The software implementation of the developed method and its comparison to the other energy efficient path design methods of the anthropomorphic manipulator motion are considered to be the further tasks.

6 Acknowledgements

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