Method of Formation of Reference Control Signals for Redundant Manipulators

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Abstract. The paper is devoted to preservation of dynamic control accuracy of working tools of multilink manipulators when they move along arbitrary spatial trajectories, taking into account the design limits in all degrees of freedom and special cases of position of their links. Preservation of control accuracy is proposed to be ensured by eliminating reach of all degrees of freedom of the manipulators to the limits and to indicated special positions, characterized by ambiguity in solving the inverse kinematic problems of the manipulators, as well as excluding the reach of their working tools to boundaries of working area due to use of a redundant degree of freedom when approaching indicated undesirable positions. The performed simulation has confirmed efficiency of the proposed method.

1. Introduction

Currently, use of multilink manipulators (MM) for performing various technological operations in automatic mode is often significantly complicated by the fact that even when their working tools (WT) moves inside the working area, some degrees of freedom (DoF) can reach design constraints. If this happens, a controller immediately stops the MM with an appropriate error message. In addition, the MM can enter one of the special (singular) positions characterized by ambiguity in the solution of the inverse kinematics problem (IKP). As a result, when the WT continues to move along spatial trajectories, unexpected reversals may occur in the corresponding MM DoF. In this case, decrease in the WT velocity, collisions with processed objects, tool breakage and other emergency situations are occurring. In addition, when working with extended objects, a part of the WT trajectory may be outside the MM working area. It will require additional reinstallation of these objects.

To expand the MM working area, it is possible to provide it with an additional linear DoF in a horizontal plane [1]. In this case, it’s necessary to obtain new solution of IKP for a specific MM [2, 3]. As a result, using the well-known IKP solution for specific MM and providing a linear displacement its base near an object of work, it was possible to quickly calculate generalized coordinates of the MM in specified ranges and significantly expand its working area. It requires a new solution of the IKP.

In particular, the analytical approach was used in [4], and combination of the analytical approach with fuzzy logic was used in [5] for solving the IKP for 7-DoF manipulator. The use of these solutions
makes it possible to exclude the reach of all DoF to their limits, but a possibility of appearance of reverse in certain DoF is not excluded.

In [6–8], methods for iterative numerical solution of the IKP for kinematically redundant manipulators are presented, and their implementation is considered using an example of 7-DoF MM. The application of the methods described in [6, 7] makes it possible to exclude their entry into singular positions and WT – on the border of the working area. And the application of the method described in [8] makes it possible to exclude the entry of all generalized coordinates and velocities of the MM into their limits. A common disadvantage of these methods is need for laborious calculations at each step of pseudoinverse Jacobi matrices.

In [9–11], methods for solving IKP using neural networks and genetic algorithms are presented. The disadvantage of these systems is also the laboriousness of process of tuning the MM control system.

2. Task definition
The purpose of this work is to create a new method for automatic movement of the MM WT along arbitrary spatial trajectories without reducing the dynamic control accuracy. This is ensured by eliminating the reach of all DoF to limits, the MM – to singular positions, and the WT – to the boundaries of the working area by using the redundant DoF of the MM when approaching these undesirable positions.

3. Description of singular positions of the manipulator and indicators signaling its approach to them
The specified task is solved for MM with PUMA kinematic scheme, installed on a movable horizontal base (see figure 1). In this figure, the following designations are introduced: Ox′y′z′ is CS associated with the movable MM base, located at point O′; q_i is generalized coordinate of the i-th DoF of the MM (i = 1,6); e_i are unit vectors coinciding with joint axes of the i-th DoF of the MM (i = 1,6); a′ = [a′_x, a′_y, a′_z]ᵀ and b′ = [b′_x, b′_y, b′_z]ᵀ are unit vectors located in the gripper plane and determining its orientation in the CS Ox′y′z′; R′ = [R′_x, R′_y, R′_z]ᵀ and r′ = [r′_x, r′_y, r′_z]ᵀ are position vectors of the characteristic point of the axis of fifth joint and tool-center-point (TCP) MM in the CS Ox′y′z′; R′ and r′ are points coinciding with ends of the vectors R′ and r′; W(W′_x; W′_y; W′_z) are coordinates of the characteristic point of axis of third joint in the CS Ox′y′z′; L_j is length of the j-th link of the MM (j = 1,3); L_4 is distance between the points R′ and r′; q_7 is displacement value of the CS Ox′y′z′ along the axis Ox.

![Figure 1. Kinematic scheme of 6-DoF MM installed on movable base.](image-url)
Generalized coordinates \( q_1 \)-\( q_6 \) of this MM can vary in the range \([-\pi; \pi]\). When solving the IKP of the specified MM, it is necessary to take into account its four special positions, in which an ambiguous solution of the IKP arises and therefore unpredictable reversals appear in advance in some DoF.

In the first special position, the projection of the characteristic point of the axis of the fifth hinge \( R'(R'_5; R'_7) \) onto the horizontal plane \( O'x'y' \) coincides with the origin of coordinates \( O' \), in which the MM base is located. In this position many different values of the angle \( q_3 \) are possible, which will correspond to different \( q_4 \}-q_6 \). In the second special position, the origin of coordinates \( O' \), as well as points \( R' \) and TCP \( r' \) lie on the same vertical line, and it is possible that there are many pairs \( q_1 \) and \( q_6 \).

In the third (see figure 1), the origin of coordinates \( O' \), the characteristic point of the axis of the third hinge \( W' \) and the point \( R' \) lie on the same vertical line, and the coordinates \( q_4 \) and \( q_5 \) are not uniquely determined. In the fourth special position, the last links of the MM, \( q_5 = 0 \), lie on one straight line, and the coordinates \( q_4 \) and \( q_6 \) are undefined.

In addition, when working with large objects, it is possible for WT, which retain the given spatial orientations, to reach the boundary of the MM working area, where the continuation of technological operation is impossible.

The appearance of the described singular positions and MM entrances to the constraints can be prevented by introducing an additional (redundant) linear DoF \( q_7 \). A system for forming the reference signal for controlling this redundant DoF is presented below. For its implementation, several special indicator functions are introduced, the current values of which should indicate the approach of the MM to its special (critical) positions [12].

The value of the first indicator \( J_1 \) tends to 1 when any of the generalized coordinates \( q \) approaches its limits \( \pm \pi \), and equals 0 when all DoF are in their average positions. As a result, the following expression can be used as the first indicator

\[
J_1 = \max_{i=1,6} \{|q_i|/\pi \}. \tag{1}
\]

The value of the second indicator \( J_2 \) tends to 1 when the MM approaches the first three special positions, in which point \( R' \) is located on the \( O'z' \) axis associated with the base of MM. Expression for calculating it:

\[
J_2 = 1 - \sqrt{R_x^2 + R_y^2}/(L_2 + L_3) \tag{2}
\]

The third indicator \( J_3 \) indicates the approach of the MM to its fourth special position, in which \( q_5 = 0 \). Its value can be calculated as

\[
J_3 = 1 - |q_3|/\pi. \tag{3}
\]

The value of the fourth indicator \( J_4 \) is equal to 1 if the WT approaches the border of the working area, where \( q_3 = 0 \). Its value can be calculated as

\[
J_4 = 1 - |q_3|/\pi. \tag{4}
\]

During operation of the MM, changes in these indicators (1–4) are monitored. If any of these indicators signals the approach of the MM to undesirable positions, then due to the redundant movement of the base along the coordinate \( q_7 \), the exclusion of the above MM positions is ensured.

5. Description of the system for formation reference signals

Figure 2 shows a generalized scheme of device that provides the formation of all main reference signals \( q_1 \)-\( q_6 \) and an additional displacement of the MM base according to its redundant DoF. In this figure, the following designations are introduced: PD is program device generating the current reference values of the TCP coordinates (elements of the vector \( r = [r_x, r_y, r_z] \)\(^T\), equal to \( r'_x + q_7, r'_y, r'_z \), respectively), the values of elements of orientation vectors \( \mathbf{a} \) and \( \mathbf{b} \) in CS \( Oxyz \) (equal to vectors \( \mathbf{a}' \) and \( \mathbf{b}' \), as well as vector \( \mathbf{K} \), whose elements uniquely determine a current (one of many possible)
configuration of the MM; S is position sensor measuring the current value \( q_7 \); G is generator of constant signal \( \Delta q_7 > 0 \); IKP are blocks for solving the MM IKP, which form vectors of generalized coordinates \( \mathbf{q} = [q_1, q_2, ..., q_7]^T \) and \( \mathbf{q}_0 \), respectively, for two different positions of the MM base \( -q_7 \) and \( q_7 + \Delta q_7 \); C are controllers that calculate the current values of all four indicators \((1–4)\) and select the largest \( J \) and \( J_c \) from them, respectively, for two different positions of the MM base \( -q_7 \) and \( q_7 + \Delta q_7 \); \( I \) is relay element that determines the magnitude and sign of constant speed \( \dot{q}_7 \); \( 2 \) is a relay providing connection of output of the relay element 1 to input of the electric drive controlling the coordinate \( q_7 \); \( 3 \) is adder that generates the \( J-J_{th} \) signal (its input from the block G has a gain \( J_{th}/\Delta q_7 \)).

Before the MM movement starting, the reference values of elements of the vectors \( \mathbf{r}, \mathbf{a}, \mathbf{b} \) and \( \mathbf{K} \) are formed at the output of the PD (see figure 2). Taking these signals into account, the initial vector \( \mathbf{q} \) is formed at output of the IKP, and the corresponding signal \( J = \) at the output C, which is received at entrance of the PD. The manipulator work begins, and it takes the initial configuration (taking into account the value of output signal of the sensor \( S = \mathbf{q}_7 \)), moving the WT to beginning of its reference trajectory.

After the completion of transient processes in all electric drives, the MM WT begins to move along the trajectory. For this, the values of vectors \( \mathbf{r}, \mathbf{a}, \mathbf{b} \) are changing at output of the PD according to a program in real time. This leads to a change in the \( \mathbf{q} \) and \( J \) signals at outputs of blocks IKP and C, respectively. If the condition \( J \leq J_{th} \) is satisfied, then the MM base remains motionless and the value of \( q_7 \) does not change. If this inequality is true, then the signal \( J - J_{th} \leq 0 \) at the output of the adder 3 opens the relay 2, and the signal \( \dot{q}_7 \) remains zero. If the inequality \( J - J_{th} > 0 \) becomes true, then the movement of MM base along the \( q_7 \) coordinate begins. To determine the direction of this movement, signals \( \mathbf{q}_7 \) and \( \mathbf{J} \) are generated at the outputs of the second blocks IKP and C, corresponding to the value \( \mathbf{r}_x' \), equal to value of projection of TCP \( r' \) on the axis \( Ox' \) for the MM, the base of which is shifted along the \( Ox \) axis by a distance \( q_7 + \Delta q_7 \). Taking into account the indicated values \( J \) and \( J_c \), a constant speed signal \( \dot{q}_7 \) is generated at the output of relay element 1, the sign of which coincides with the sign of the difference \( J - J_c \) (or equal to 0, if \( J = J_c \)), and key 2 closes, connecting the output of relay element 1 to the system output. The signals \( \mathbf{q} = [q_1, q_2, ..., q_7]^T \) and \( \dot{q}_7 \) are processed by the corresponding servo drives, moving the WT along the trajectory.

If in the process of system operation the condition \( J > J_c \), which is checked in the PD, starts to be fulfilled, then the WT stops and operation of the MM stops. In this case, the signals \( \mathbf{r}, \mathbf{a} \) and \( \mathbf{b} \) at the PD output are fixed in order to avoid emergency situations.

From description of operation of the system (see figure 2) it follows that the signal \( J_c \) is only necessary to determine the sign of velocity \( \dot{q}_7 \) (the motion direction of the MM base along the coordinate \( q_7 \)) when \( J > J_{th} \). If the condition \( J \leq J_{th} \) is satisfied (with fixed MM base), the calculation of the signal \( J_c \) can be omitted, saving computational resource of the system.
Due to the redundant displacement of the MM base along the coordinate $q_7$ near the processed object, the proposed system ensures the elimination of all undesirable positions of the MM described above.

6. Results of simulation
The study of the developed system (see figure 2) for forming reference signals was carried out for the 6-DoF MM (see figure 1). The lengths of the MM links are $L_1 = L_2 = L_3 = 0.5$ m, $L_4 = 0.15$ m. To control this MM, the control system described in [13] was used. Its WT was moving along a smooth spatial trajectory, specified by parametric splines [14], with a fixed speed equal 0.5 m/s, which in the general case can be variable and adjusted according to method described in [15].

The trajectory shape and WT orientation were chosen such that at $q_7 = 0$, when the fixed $Oxyz$ and associated with the MM base $O'x'y'z'$ coordinate systems coincide, the MM successively entered the undesirable positions described above: in two different special positions, three times – the exit of its three DoF to the restrictions and once at the end of the movement – the exit of the WT to the border of the MM working area. Behavior of the reference values of the generalized coordinates $q_1$–$q_6$ in this operating mode are shown in figure 3. Implementation of the presented reverses leads to increase of TCP deviation from the trajectory to unacceptable values of 1.7 mm – 1.5 m.

To prevent these negative situations, the proposed system was used, which ensures the movement of the MM base along the coordinate $q_7$ while its configuration approaches the problem areas. The behavior of generating of reference values $q_1$–$q_6$ by the system, taking into account the real value $q_7$, also changing in time in the process of working out the trajectory, are shown in figure 4. This figure shows that abrupt changes in reference values in all generalized coordinates of the MM are completely excluded. As a result, the deviation of the TCP from the reference trajectory did not exceed 0.65 mm in all its sections and the motion of the WT was fully completed (strictly at the end of the trajectory) without approaching to the border of the working area (when $q_3 = 0$).

7. Conclusion
The paper presents a method for automatic generation of reference signals for all actuators of a typical 6-DoF manipulator with PUMA kinematic scheme, which has an additional redundant DoF for linear displacement of its base in the horizontal plane. This method, by moving the base horizontally near a processed object, makes it possible to exclude the MM entry into singular positions characterized by the ambiguity of the IKP solution, the reach of the WT to the boundaries of its working area, as well as some of its DoF – to limits. As a result, the occurrence of emergency situations, breakage of WT and equipment are completely excluded, and the working area of the MM is expanded.

8. References
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