Determination of target points approachability by an android robot arm in organized space based on virtual modeling of movements

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Abstract. The paper proposes a method for overcoming deadlocks in implementation of the android arm mechanism movement in an organized space in the vector of velocities. The proposed method is based on the calculation of the allowable positioning accuracy of the output link center in order to change the position of the arm configuration relative to the forbidden zones with a deviation from the specified trajectory. An algorithm based on this method is proposed, and an implementation of a test case confirming the functional check of this algorithm is presented.

1. Introduction
When controlling movements of manipulator mechanisms of autonomously functioning robots, it is essential to solve the problem at the virtual level of the approachability of target points in the presence of forbidden zones [1-4]. One of the ways to solve this problem can be the synthesis of movement in the vector of velocities [5]. When such movement is conducted along a specified trajectory of the output link (OL) center, deadlock situations may occur [5, 6]. In this case, the algorithm is not able to calculate the succeeding configuration, which allows for the displacement of the OL center at a specified speed and positioning accuracy in the subsequent point of the trajectory. If the use of motion to change the type of configuration has not led to further movement along the target trajectory [7], it is necessary to change the position of the trajectory of OL center movement.

2. Description of position of arm mechanism links with respect to forbidden zones in deadlock
Figure 1ab presents a general view and kinematic diagram of the arm mechanism of android robot AR-600E. It is necessary to determine the approachability of a given target point by the robot arm with the use of virtual modeling, taking into account the prescribed geometric dimensions of a manipulation object.
Figure 1. Android robot AR-600E: a - general view of the android robot; b - kinematic diagram of the arm mechanism

Figure 2 shows an example of the position of the last two links and OL of the android arm mechanism with the object of manipulation on the front projection in a deadlock. Points $A_2^s$ and points $B_i$ in figure 2 assign the position of the target point and the contour of the forbidden zone, respectively. Points $A_2^H$, $A_2^{P1}$, $A_2^{P2}$ and $A_2^K$ define initially specified OL center movement trajectory in the form of the line segments. The lower indices of the points of the specified trajectory define their membership in the frontal projection.

Figure 2. Position of the last two links and OL of the arm mechanism in a deadlock on the frontal projection

When the center of the OL coincides with the point $A_2^s$ in the motion synthesis, the deadlock arises. In figure 2, the parameters $l_δ$ and $l_0$ respectively determine the safe distance from the arm mechanism with the manipulation object to the forbidden zone and the length of the manipulation object to be moved. In the figure this object has the notation $P_{ob}$. In this case the width $h$ of the corridor specified by the lines $l_3$ and $l_4$ in which the center of capture can move, is determined by the formula (Fig. 2):

$$h = l - 2(l_δ + l_0 / 2),$$

where $l$ is the size of the free cavity inside the forbidden zone.
3. Algorithm for solving problem of arm mechanism escape from deadlock

If a deadlock arises in the point \( A_3' \), it is essential to perform the motion of the OL center perpendicular to the trajectory specified by the segment \( A_4'^2 A_3'^5 \) in the direction to the line \( l_3 \), with the maximum allowable accuracy of positioning. The line \( l_3 \) is at the same distance from the lines \( l_1 \) and \( l_2 \). In this case with the displacement of the OL from the point \( A_3' \) to the point \( A_3'^3 \in l_1 \) after the deadlock, the maximum value of the positioning accuracy is computed from the relations (in such a case one of the values \( d' \) and \( d'' \) is accepted as the positioning accuracy). The distance \( d'' \) and \( d' \) of the OL center to the front-projecting planes \( \Delta \) and \( \Sigma \), passing through the lines \( l_3 \) and \( l_5 \), is found:

\[
dl'' = (a_{13} \cdot r_0 + D_1)P(a_{13}) \cdot \]
\[
dl' = (a_{14} \cdot r_0 + D_2)P(a_{14})
\]

where \( a_{13}, a_{14} \) are normal unit vectors of the front-projecting planes \( \Delta \) and \( \Sigma \), passing through the lines \( l_3 \) and \( l_5 \), \( r_0 \) is the radius vector of the point \( O_3'^2 \) specifying the OL center; \( D_1, D_2 \) are the distances from the beginning of the fixed coordinate system to the planes \( \Delta \) and \( \Sigma \).

If the current point \( O_3'^2 \), which prescribes the position of the OL center, is on the line \( l_5 \) \( (O_3'^2 \in l_5) \), then the maximum value of the positioning accuracy is determined by the dependence (provided that the distance to the lower horizontal plane of the level, which specifies the lower boundary of the opening, is greater than the parameter \( d_{\text{max}}^l \)):

\[
dl_{\text{max}}^l = h / 2.
\]

If the center of OL is in the point \( A_3'' \) (derived by the implementation of the values of the generalized velocities vector at the displacement of the OL center from the point \( A_3' \) to the point \( A_3'^3 \) and do not belong to the line segment \( l_5 \)), then it is necessary to determine the distances \( d'' \) and \( d' \) to the planes \( \Delta \) and \( \Sigma \) respectively (2) (Fig. 2).

The value of the vector of generalized velocities is determined by the known dependence [5]:

\[
Q_N = Q_M + \sum_{i=1}^{p} k_i m_i Q_i
\]

where \( Q_M \) is the vector specifying the point \( M^0 \in \Gamma^0 \) conforming to the range of motion minimization criterion. The upper index \( \Gamma^0 \) shows that the point belongs to the space of generalized velocities. The point \( M^0 \) prescribes the check point center connected with the \( p \)-plane \( \Gamma^0 \); \( k_i \) is the coordinates of the point \( N^0 \) in the \( p \)-plane \( \Gamma^0 \) (particular instant of state of the manipulator mechanism corresponds to each point \( N^0 \)); \( m \) is the length of the unit check point segment of the \( p \)-plane \( \Gamma^0 \); \( Q_i \) is unit director vectors of the check point axes; \( p \) is the dimension of the \( p \)-plane \( \Gamma^0 \) (for the considered example \( p = 2 \)).

It is necessary to fulfill the conditions for the construction of the following configuration:

\[
d\delta < d'' < d' \quad \text{if the point } A_3' \text{ is to the left from the line } l_5;
\]

\[
d\delta < d' = d'' \quad \text{if the point } A_3' \text{ is to the right from the line } l_5;
\]

where the \( d \delta \) parameter specifies the linearization error, which is determined by the formula:

\[
d\delta = \left( (x_{012} - m_{012}'n)^2 + (y_{012} - m_{024}'n)^2 + (z_{012} - m_{024}'n)^2 \right)^{1/2}
\]

coordinate values \( x_{012}, y_{012}, z_{012} \) determine the succeeding point on the specified trajectory of the OL center, in such a case the trajectory after the occurrence of a deadlock is the segment \( A_3'A_2'^3 \) which is perpendicular to the originally specified trajectory \( A_3'A_2'^5 \); \( m_{014}'n, m_{24}'n, m_{34}'n \) are the coordinates of the OL center after the implementation of the value of the generalized velocity vector \( Q^N \) (4). These coordinates are calculated by the matrix \( M_{0,n} \) which determines the position of OL [8].

The motion synthesis for the general case in the absence of deadlocks is performed if the deviation from the given subsequent point of the OL trajectory \( dd \) satisfies the positioning accuracy \( dd < \delta \). The parameter \( \delta \) specifies the initial positioning accuracy, which is calculated from the ratios (2) after the
deadlock occurs. The initial value of the positioning accuracy in the calculation of the test task is taken as \( \delta = 10 \text{ mm} \).

After the deadlock under the motion synthesis along an arbitrarily planned trajectory specified by points \( A_2 \) and \( A_2^E \), it is necessary to take into account two values of \( dl^r \) and \( dl^l \) together when calculating the maximum allowable positioning accuracy. In such a case it is important to evaluate which side in relation to the line \( l_5 \) the point \( A_2^" \) is located. This allows the OL center to move perpendicular to the segment \( A_2P_2A_2^E \) with the greatest possible positioning accuracy and to handle deadlock situations. In this regard, it is appropriate to determine other values of \( k_{i_{max}} \) parameters specifying the range of permissible values of the generalized velocity vector in accordance with the new calculated value of the positioning accuracy of \( dl_{max}^r, dl^l \) or \( dl^l \) [9, 10]. After shifting the OL one step out of the deadlock, the direction of the linear velocity vector \( V \) is again calculated by moving to the target point \( A_2^E \). If the deadlock occurs again, then another point \( A_2^P_3 \in l_5 \) and the vector of linear velocities of the OL center \( V \perp l_5 \) are determined. The algorithm scheme of motion synthesis for the prescribed and arbitrary trajectories of the OL center motion with a maximum allowable positioning accuracy is presented in figure 3.

**Figure 3.** Algorithm scheme for the motion synthesis along an arbitrary trajectory of the OL center

The following notations are taken in figure 3:

1 is setting the initial, target and intermediate points of the OL center trajectory (\( A_5, A_1^P, A_2^P \) and \( A_5^E \)). Setting the forbidden zone by node points \( B_1 \)–\( B_{10} \) (these points determine the positions of the lines \( l_1 \) and \( l_2 \)). Setting the value parameters \( l_0, l_0, \delta \) and \( k_k = 0 \). Calculation of the coefficients of line equations \( x \) \( l_3, l_4, l_5 \) and planes \( \Delta \) \( \Sigma \); 2 is the calculation of the OL center linear velocity vector \( V \) in the direction of the assigned trajectory; 3 is the definition of the matrix for the private gear ratios and generalized velocities vector \( Q (q_1, q_2, ..., q_5) \) corresponding to the range of motion minimization criterion [5, 8]; 4 is the construction of the following configuration \( q_i = q_i + \dot{q}_i \); 5 is the computation of
\( k_i^\text{max} \) in accordance with \( \delta \) or \( dl' \) and \( dl'' \) \cite{9, 10}; 6 is \( kk = 1 \); 7 is the fulfillment of the condition (5); 8 is the definition of the condition (5); 9 is determination of the condition for manipulator mechanism intersection with forbidden zones. Defining the condition of noncompliance with the specified limit values of generalized coordinates \( q_i^{\text{max}}, q_i^{\text{min}} \) and maximum values of velocity in the devices; 10 - The target point is reached; 11 is constructing the succeeding configuration (along the specified trajectory), \( kk = 0 \); 12 is defining the condition \( k_i > k_i^\text{max} \); 13 is calculating the parameters \( k_i = k_i + 1 \) used in the dependence (4); 14 is calculation of the generalized velocity vector with the values \( k_i \) (4) \cite{5}; 15 is calculation \( h(1), dl', dl'' \), \( kk = 0 \); 16 is defining the condition \( kk > 0 \); 17 is checking if the center of OL is to the left of the line \( l_5 \) in case of a deadlock; 18 is \( \delta = dl' \); 19 is \( \delta = dl'' \); 20 is the change in the direction of the velocity vector of the OL center (\( V \perp l_5 \)); 21 - The deadlock cannot be avoided; 22 - The target point is reached, interpolation of intermediate values of generalized coordinates defining the motion of OL to the target point.

4. Calculation data of test case associated with motion synthesis with overcoming deadlock

The values of the geometric parameters in the test case are taken to be equal to the following values \( \delta = 10 \text{ mm}, l = 130 \text{ mm}, l_0 = 40 \text{ mm} \). The values of the point coordinates that define the originally specified movement trajectory of the OL center and the forbidden zone of test case are given in table 1. The values of \( y \) coordinate specified by the fraction in the table for points \( B_1, B_1 \) define two points on the front-projecting lines. Figure 4a presents the synthesis of movement of the OL center in the sections of the trajectory prescribed by the segment \( A^S A^P_1 \) and \( A^P_1 A^P_2 \).

| Coordinate values of points (mm) | \( A_2^S \) | \( A_2^P_1 \) | \( A_2^P_2 \) | \( A_2^E \) | \( B_1 \) | \( B_2 \) | \( B_3 \) |
|---------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| \( x \)                        | 150         | 253         | 396         | 396         | 240         | 240         | 360         |
| \( y \)                        | 6           | 50          | 40          | 3           | 228/72      | 228/72      | 228/72      |
| \( z \)                        | 400         | 452         | 452         | 354         | 259         | 424         | 424         |
| \( \text{Coordi} \text{nate} \) | \( B_4 \)  | \( B_5 \)  | \( B_6 \)  | \( B_7 \)  | \( B_8 \)  | \( B_9 \)  | \( B_{10} \) |
| \( x \)                        | 360         | 490         | 490         | 240         | 240         | 527         | 527         |
| \( y \)                        | 228/72      | 228/72      | 228/72      | 228/72      | 228/72      | 228/72      | 228/72      |
| \( z \)                        | 301         | 301         | 502         | 502         | 538         | 538         | 259         |

The simulation of the arm mechanism movement along an arbitrary trajectory of the OL center (with the specified start and end points \( A_2^P_2 \) and \( A_2^E \)) with overcoming the deadlock is presented in figure 4b. Movement simulation is performed using AutoCAD and programs written in AutoLISP.
Figure 4. Simulation results of the OL center movement of the android robot arm: 

- **a** — along the trajectory on the segment prescribed by the points $A^S, A^{P1}, A^{P2}$;
- **b** — along the arbitrary trajectory on the segment prescribed by the points $A^S, A^E$.

5. Summary and Conclusion
The developed algorithm for the motion synthesis along an arbitrary trajectory of the OL center allows one to determine by an automated method at the virtual level the approachability of target points in the presence of the forbidden zones. In such a case specified geometric dimensions of the forbidden zone and objects of manipulation are taken into account. This algorithm can be used in the development of intelligent control systems of autonomously functioning robots that move objects of manipulation without a human-operator.

6. References
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