Using weight values of generalized velocities to handle deadlocks in the synthesis of anthropomorphic robot arm movement

F N Pritykin and V I Nebritov
Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
E-mail: pritykin@mail.ru

Abstract. When controlling the movement of an anthropomorphic robot arm mechanism in an organized space with forbidden regions, there is a possibility of deadlocks. The paper studies the motion synthesis using weight coefficients of generalized velocities in order to prevent deadlocks. As a result an algorithm for the motion synthesis using weight coefficients in the virtual simulation of the anthropomorphic robot arm movements is developed.

1. Introduction
In automated control of the anthropomorphic robot arm movement in an organized environment using the motion synthesis along the velocity vector, deadlocks often occur [1-5]. In this case, as a rule, the values of the weight coefficients are assumed being equal to one. In deadlocks, the algorithm cannot provide the calculation of the next configuration in the direction to the specified target point under the specified conditions for the positional relationship of the manipulator mechanism and forbidden regions. To prevent deadlocks, a method for changing the weight coefficient values of generalized velocities is developed. The method rests on the assessment of the effect of each generalized coordinate on the distance from the arm mechanism to the approaching forbidden region. Having assessed the effect, the generalized coordinates that make the greatest contribution to reducing the specified distance are calculated using the weight coefficients of generalized velocities, these coefficients decreasing their values. This permits the calculation of other intermediate configurations with a different location relative to the forbidden regions and, eventually, the mechanism of escaping deadlocks.

2. Problem Statement
Let the executive mechanism of the anthropomorphic robot arm with eight generalized coordinates be specified (Fig. 1). It is required to build automatically intermediate configurations that provide the motion of the output link (OL) center from the initial to the target point (Fig. 2). The point \(A^H (A_1^H, A_2^H, A_3^H)\) indicates the start of the movement trajectory; the point \(A^K (A_1^K, A_2^K, A_3^K)\) denotes the end of the trajectory. Motion synthesis allows the manipulation object to be placed on the rack \(P\). In this case, the rack acts as a forbidden region, which should be taken into account in the virtual simulation of motion. The table specifies the values of arrays used for setting the kinematic chain model of the arm and the position of the current configuration. The position of the nodal points \(O_1-O_{13}\) of the arm mechanism in a fixed space determines the set of matrices \(M_{0,1}, M_{0,2}, ..., M_{0,nm}\) of dimension 4×4 [6-9]. The \(n_m\) parameter defines the number of systems \(O_1, O_2, ..., O_{nm}\) used for setting the geometric model of the anthropomorphic robot arm mechanism (Fig. 1). For this example, \(n_m \neq n\) and \(n_m = 13\), where \(n\) specifies the number of generalized coordinates of the manipulator mechanism.
The matrices $M_{0,k}$ are defined by the product of the matrices $M_{l+k}$ [6, 8, 9]. The arrays $q_i$, $l_{sm}$ and $n_{kod}$ are used to calculate elements of matrices $M_{l+k}$ [3, 6]. These arrays specify, respectively, the values of the generalized coordinates $q_i$, displacement along coordinate axes $l_{sm}$, fixed with the mechanism links, and coordinate system transformation codes $n_{kod}$. The dimension of the $q_i$, $l_{sm}$, $n_{kod}$ arrays is the same and determined by the value of the $n_m$ parameter. When synthesizing the motion along the trajectory of the OL center specified by the points $A_1^H(A_1^H, A_2^H, A_3^H)$ and $A_1^K(A_1^K, A_2^K, A_3^K)$, prevention of deadlocks when calculating intermediate configurations is necessary (Fig. 2). Note that each subsequent configuration allows bringing the OL closer to the specified target position.
Table 1. Values of the parameters determining the geometric model of the arm mechanism.

| Arrays | Coordinate system conversion number |
|--------|-------------------------------------|
|        | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|        | $q_i$ (deg.) | $q_1$ | $q_2$ | $q_3$ | $q_4$ | $q_5$ | $q_6$ | $q_7$ | $q_8$ | $q_9$ | $q_{10}$ | $q_{11}$ | $q_{12}$ |
|        | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|        | $s_{mi}$ (mm) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|        | $l_1$ | 103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|        | $l_2$ | -130 | 104 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|        | $l_3$ | 104 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|        | $n_{kod}$ | 4 | 1 | 2 | 12 | 3 | 12 | 1 | 12 | 3 | 12 | 1 | 2 | 12 |

3. Theoretical Basis

If a deadlock occurs, the link specified by the nodes $O_7$, $O_{10}$, locates from the obstacle at a distance less than the specified minimum allowed distance. The specified distance is calculated by the dependence:

$$d = \frac{|a \times (r_o - r_i)|}{|a|},$$

where on the profile plane of projection: $d$ is the distance from the point $F$, belonging to the forbidden region $P$, to the profile projection of the line segment connecting the nodes $O_7$, $O_{10}$ of the manipulator mechanism; $a (a_x, a_z)$ is the unit director vector of the line passing through the points $O_7$, $O_{10}$; $r_o$ is the radius vector of the point $F \in P$; $r_i$ is the radius vector of the point $O_7$.

After a deadlock occurs, the distances (1) are investigated for the set of configurations $N_k$, the number of them is equal to the number of generalized coordinates calculated with the parameter $k_n$, where $k_n$ is the accepted value for the number of iterations before the deadlock, after which movement correction using the weight values of the generalized velocities is required. For example, if $k_n = 10$, then for the configuration $t_p = t_T - 10$ the values of generalized velocities $q_i$ matching the motion volume minimization criterion are defined [1, 3]. $t_T$ is the number of the intermediate configuration at which a deadlock occurs. $t_p$ is the number of the calculated configuration after which the weight coefficients of generalized velocities $a_i$ are used. The values of generalized velocities $q_i$ are calculated by solving a linear system of equations:

$$J_{i1}a_{11}q_i + J_{i2}a_{12}q_i + \ldots + J_{in}a_{1n}q_n = V_x,$$

$$J_{i1}q_i + J_{i2}a_{22}q_i + \ldots + J_{in}a_{2n}q_n = V_y,$$

$$\ldots$$

$$J_{r+1,1}a_{11}q_i + J_{r+1,2}a_{12}q_i + \ldots + J_{r+1,n}a_{1n}q_n = \omega_x,$$

$$J_{r+1,1}q_i + J_{r+1,2}a_{22}q_i + \ldots + J_{r+1,n}a_{2n}q_n = 0,$$

$$J_{r+2,1}q_i + J_{r+2,2}a_{22}q_i + \ldots + J_{r+2,n}a_{2n}q_n = 0,$$

$$\ldots$$

$$J_{r+p,1}q_i + J_{r+p,2}a_{22}q_i + \ldots + J_{r+p,n}a_{2n}q_n = 0,$$

$$\ldots$$
where \( J_{11}, J_{12}, \ldots, J_{r1}, \ldots, J_{rn} \), are the coefficients for the matrix of the angular velocity ratios [3, 5]; \( J_{r+1,1}, J_{r+1,2}, \ldots, J_{rp,1}, \ldots, J_{rp,n} \), are the coefficients calculated using the condition of perpendicular hyperplanes defined by the last equations of the system (2) (the total number of these hyperplanes is equal to the parameter \( p = n - r \)) with the hyperplanes defined by the first \( r \) linear equations (2); \( \dot{q}_i \) are the unknown components of the vector \( \dot{Q}_M \); \( a_i \) are the weight coefficients of generalized velocities. In this case, the condition of hyperplane perpendicularity reflects the equality to zero of the sum of multiplied coefficients at the unknown \( q_i \) of the first \( r \) hyperplane equations (2) and the added \( p \) hyperplane equations (2) [1]. \( \dot{V}_x, \ldots, \omega_x, \ldots \) are the components of the vector \( V \), which defines the velocity of the simplest OL movements.

Generalized velocities calculated from the dependencies determine the first examined configuration \( t_{p1} \) of the set \( N_k \):

\[
\begin{align*}
q_1 &= q_1 + k_n \cdot \dot{q}_1, \\
q_2 &= q_2 + \dot{q}_2, \\
& \hspace{1cm} \ldots \\
q_n &= q_n + \dot{q}_n.
\end{align*}
\]

(3)

For the second configuration \( t_{p2} \) of the set \( N_k \) the generalized coordinate \( q_2 \) in the dependence (3) is calculated using the parameter \( k_n - q_2 = q_2 + k_n \cdot \dot{q}_2 \). The remaining generalized coordinates are calculated by the dependencies \( q_i = q_i + \dot{q}_i \). The OL center of the calculated configurations for the set \( N_k \) in such a case can deviate significantly from the specified trajectory. However, these configurations of the set \( N_k \) are necessary only for evaluating the degree of influence of a generalized coordinate on the distance (1). Next, we determine the configurations and generalized coordinates that make the greatest contribution to reducing distances (1). In this case, a condition is used:

\[
d < \frac{(d_{pl} - d_T)}{2},
\]

(4)

where \( d_{pl} \) is the distance (1) for the configurations of the set \( N_k \); \( d_T \) is the distance (1) for the configuration where a deadlock occurs.

The values of generalized coordinates matching the condition (4) are obtained by using the weight values \( a_i \) of generalized velocities in the linear system of equations (2). This allows defining intermediate configurations where the distance (1) decreases to a lesser extent. Fig. 3 shows the algorithm scheme for handling deadlocks.

**Figure 3.** Algorithm scheme for the manipulator mechanism escape from a deadlock in motion synthesis along the velocity vector

The algorithm scheme has the following notation: 1 is input of array data \( l_i, sm_i, n_{side}, a_i = 1, k_n = 1 \) (defining the geometric model of a kinematic chain), point coordinates \( A_H \) and \( A_K \); 2 is calculation of coordinates for intermediate points \( A_{PL} \) and \( A_{PR} \), assigning the synthesized path of the OL center motion providing the absence of the path and forbidden region intersection \( P_t \) (ensuring the minimum distance to the forbidden region); 3 is the calculation of the generalized velocities vector \( \dot{Q}_M (\dot{q}_{1M}, \dot{q}_{2M}, \ldots, \dot{q}_{JM}) \) and motion synthesis on the motion volume minimization criterion, definition of the
condition for the arm mechanism intersection with the tool rack forbidden region; 4 denotes the
deadlock occurs; 5 is \( q_i = q_i + \dot{q}_i \); 6 signifies the target point is reached; 7 is the definition of the
configuration \( t_p \) and the set of configurations \( N_k \); \( k_n = k_n + 10 \) (3); 8 is calculation of distances (1) for
the set of configurations \( N_k \). Definition of the numbers of generalized coordinates for which condition
(4) is met and definition of the values for the weight coefficients \( a_i \) of generalized velocities; 9 is \( k_n > 10 \); 10 signifies the deadlock cannot be escaped by changing the weight coefficients of generalized
velocities.

4. Experimental results

Fig. 4 shows the position of intermediate configurations generalized by the robot control system. These configurations allow moving the OL from the initial position set by the point \( A^{H}(A^{H}_{1}, A^{H}_{2}) \) to the target position set by the point \( A^{K}(A^{K}_{1}, A^{K}_{2}) \) preventing the deadlock. Projections \( P^1 \), \( P^2 \) and \( P^3 \) indicate the forbidden region in Fig. 4.

![Figure 4. Results of modeling the anthropomorphic robot arm motion escaping the deadlock](image)

5. Conclusion

The use of weight values of generalized velocities and the developed algorithm allows the mechanism
to handle the deadlock in the automated synthesis of motions along the velocity vector.
The developed algorithm for the synthesis of small movements using variable weight values of
generalized velocities can be used for virtual modeling an anthropomorphic robot arm motions in
order to determine the approachability of target points in case of tool rack forbidden regions.

6. References

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