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CONSIDERATIONS ABOUT MATRIX EXPONENTIALS IN GEOMETRICAL MODELING OF THE ROBOTS

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Abstract: *In specialized literature, there are many approaches to the mathematical modeling of robots. Thus, different algorithms for geometric modeling are consecrated. Most approaches require the use of reference systems, which can lead to errors in computing. The geometrical study of any mechanical robot structure can be realized by matrix exponential, having essential advantages besides the classical approaches. As a result, within this paper, there will be presented an example of mathematical modeling, concerning the matrix exponentials applied in the geometrical modeling of serial robots.*

Key words: *robotics, geometry, matrix exponentials, control functions.*

1. INTRODUCTION

According to dedicated literature, there are multiple methods to establish the expressions that modeling the geometrical behavior for any mechanical structure. In the first part of paper, will be presented mathematical considerations for geometric control, based on matrix exponentials. In the second part, on the basis of previous section presented expressions, by applying matrix methods based on matrix exponentials, will be determined the direct geometry equations, which express the position and orientation of the characteristic point of the end effector with respect to the fixed reference system attached to robot base.

2. ESTABLISHING OF LOCATING MATRICES BY USING OF MATRIX EXPONENTIALS ALGORITHM

The matrix transfer equations for any kinematical chain, with *(R)-rotation* or *(T)-prismatic* driving joints, corresponding to a *mechanical robot structure* , can be established by means of new concepts in advanced mechanics, with the matrix exponentials [1].

The matrix exponentials and their associated transformations are included in the algorithm of matrix exponentials devoted to direct geometry equations, according to [1] - [6]. The main steps of the algorithm are presented in the following.

The matrix of the nominal geometry $M_{vn}^{(0)}$, corresponding to configuration $\overline{\theta}^{(0)}$ is known:

$$M_{vn}^{(0)} = \underset{\left[(n+1)\times 6\right]}{Matrix}\left\{\left[\overline{p}_i^{(0)T} \;\; k_i^{(0)T}\right] i=1\rightarrow n+1\right\}^T .(1)$$

The matrix of the nominal geometry is completed with the screw parameters $\left\{\overline{k}_i^{(0)} \; ; \; \overline{v}_i^{(0)}\right\}$ also named the homogeneous coordinates. where $\overline{k}_i$ *and* $\overline{v}_i$ are the screw parameters or homogeneous coordinates of the driving axis (i), according to [1], which by generalization are equivalent to:

$$\left\{\overline{k}_i = \left\{\overline{x}_i;\overline{y}_i;\overline{z}_i\right\};\; \overline{v}_i = \left(\overline{p}_i\times\right)\cdot\overline{k}_i\cdot\Delta_i + \left(1-\Delta_i\right)\cdot\overline{k}_i\right\} \quad (2)$$

The differential matrix A_i has the same expression for the both configurations $\overline{\theta}^{(0)}$ and $\overline{\theta}$. Considering [2] and [4], this matrix shows as:

$$\left\{\begin{array}{c} A_i = \begin{bmatrix} \left(\overline{k}_i^{(0)}\times\right)\cdot\Delta_i & \overline{v}_i^{(0)} \\ 0\ 0\ 0 & 0 \end{bmatrix} = \\ \begin{bmatrix} \left(\overline{k}_i^{(0)}\times\right)\cdot\Delta_i & \left(\overline{p}_i^{(0)}\times\right)\cdot\overline{k}_i^{(0)}\cdot\Delta_i+\left(1-\Delta_i\right)\cdot\overline{k}_i^{(0)} \\ 0\ 0\ 0 & 0 \end{bmatrix} \end{array}\right\} \quad (3)$$

In keeping with this, the matrix, corresponding to initial conditions, can be determined without establishing any moving frame.

The exponential of rotation matrix is:

$$\left\{\begin{array}{l} \exp\left\{\left(\overline{k}_i^{(0)}\times\right)\cdot q_i\cdot\Delta_i\right\}\equiv R\left(\overline{k}_i\ ;\ q_i\cdot\Delta_i\right)\equiv \\ \equiv\left\{I_3\cdot\cos\left(q_i\cdot\Delta_i\right)+\left(\overline{k}_i^{(0)}\times\right)\cdot\sin\left(q_i\cdot\Delta_i\right)+\right. \\ \left.+\ \overline{k}_i^{(0)}\cdot\overline{k}_i^{(0)T}\left[1-\cos\left(q_i\cdot\Delta_i\right)\right]\right\}\equiv {}^{i-1}_{\ \ i}[R] \end{array}\right\} . \quad (4)$$

The defining expression for the column vector $\overline{b}_i$, is established with the following:

$$\left\{\begin{array}{l} \overline{b}_i=\left\{I_3\cdot q_i+\left(\overline{k}_i^{(0)}\times\right)\cdot\left[1-\cos\left(q_i\cdot\Delta_i\right)\right]+\right. \\ \left.+\overline{k}_i^{(0)}\cdot\overline{k}_i^{(0)T}\cdot\left[q_i-\sin\left(q_i\cdot\Delta_i\right)\right]\right\}\cdot\overline{v}_i^{(0)} \end{array}\right\} . \quad (5)$$

Another matrix exponential, having a great significance for locating transformation, shows as:

$$\left\{\begin{array}{l} e^{A_i\cdot q_i} = \exp\left(\begin{bmatrix} \left(\overline{k}_i^{(0)}\times\right) & \overline{v}_i^{(0)} \\ 0\quad 0\quad 0 & 0 \end{bmatrix} q_i\right)= \\ =\begin{bmatrix} \exp\left\{\left(\overline{k}_i^{(0)}\times\right)\cdot q_i\cdot\Delta_i\right\} & \overline{b}_i \\ 0\quad 0\quad 0 & 1 \end{bmatrix} \end{array}\right\} ; \quad (6)$$

and:

$$\exp\left\{\sum_{j=0}^{i} A_j\cdot q_j\right\}=\begin{bmatrix} \exp\{R\} & \exp\{p\} \\ 0\ 0\ 0 & 1 \end{bmatrix}; \quad (7)$$

where, the significance of the term is:

$$\begin{array}{l} \exp\{R\}=\prod_{j=0}^{i}\exp\left\{\left(\overline{k}_i^{(0)}\times\right) q_j\cdot\Delta_j\right\}; \\ \exp\{p\}=\sum_{j=0}^{i}\left\{\prod_{k=0}^{i}\exp\left\{\left(\overline{k}_k^{(0)}\times\right)\cdot q_k\cdot\Delta_k\right\}\right\}\cdot\overline{b}_{j+1}. \end{array} \quad (8)$$

In direct geometry, the matrix exponentials algorithm contains in an external loop of iterations from $(i=1\rightarrow n)$. Taking into account the initial conditions is established T_{x0}, according to mechanical structure. The obtained results are included in the resulting of rotating matrix of frame $\{n\}$ beside $\{0\}$ frame. The exponentials expressions for the locating matrices, which define the position and orientation of the $\{n\}$ and $\{n+1\}$ with respect to fixed frame $\{0\}$, are obtained as follows:

$$\left\{\begin{array}{l} T_{x0}=\prod_{i=1}^{x} T_{ii-1}=\begin{bmatrix} R_{x0} & \overline{p} \\ 0\ 0\ 0 & 1 \end{bmatrix} \\ where \quad x=\{n\,;n+1\} \end{array}\right\}; \quad (9)$$

$$T_{x0}=\prod_{i=1}^{n}\left(e^{A_i\cdot q_i}\right)\cdot T_{x0}^{(0)}=\exp\left\{\sum_{i=1}^{n}A_i\cdot q_i\right\}\cdot T_{x0}^{(0)}; \quad (10)$$

where:

- $$R_{x0}=\exp\left\{\sum_{i=1}^{n}\left(\overline{k}_i^{(0)}\times\right)\cdot q_i\cdot\Delta_i\right\}\cdot R_{x0}^{(0)}\ , \quad (11)$$

represents a resultant rotation matrix, and:

- $$\left\{\begin{array}{l} \overline{p}=\sum_{i=1}^{n}\left[\exp\left(\sum_{j=0}^{i-1}\overline{k}_j^{(0)}\times q_j\cdot\Delta_j\right)\right]\cdot\overline{b}_i+ \\ +\exp\left(\sum_{i=1}^{n}\overline{k}_i^{(0)}\times q_i\cdot\Delta_i\right)\cdot\overline{p}^{(0)}\cdot\delta_x \end{array}\right\} \quad (12)$$

is the position vector of the characteristic point, and $\delta_x=\{(0,x=n);(1,x=n+1)\}$.

Remark: *The MEG Algorithm*, due to computational advantages and independent of the reference can be applied for any robot structure. Another important advantage in using of matrix exponential is the lack of reference frames.

3. THE GEOMETRY EQUATIONS BASED ON MATRIX EXPONENTIALS FOR A SERIAL ROBOT STRUCTURE

In this section, it will be presented the geometry equations for a serial structure, by using the matrix exponentials used for determining he is locating matrices, according to [1]- [4]. It's considered a kinematical structure of RTT-type robot, presented within of the Figure 1.

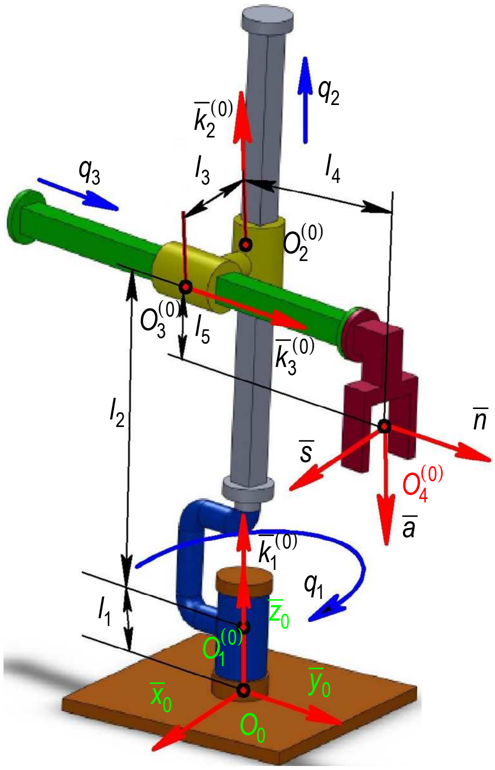

Fig. 1 The R2T serial structure

According to the Figure 1, the mechanical structure, is a cylindrical structure which can perform a rotation around O_0z_0 axis and two translations; one along O_0z_0 axis, the other along O_0y_0 axis [7]. Applying the Algorithm of Matrix Exponentials [8], presented in previous section, will be determined the direct geometry equations (position and orientation) of the end effector.

The matrix of the nominal geometry $M_{vn}^{(0)}$, corresponding to configuration $\overline{\theta}^{(0)}$ of the serial robot structure from Figure 1, [7] is presented in Table 1, as:

The table of nominal geometry $M_{vn}^{(0)}$ *Table 1*

Element $i=1\to4$	Joint type $\{R;T\}$	$\overline{p}_i^{(0)T}$			$\overline{k}_i^{(0)T}$		
		$x_i^{(0)}$	$y_i^{(0)}$	$z_i^{(0)}$	$x_i^{(0)}$	$y_i^{(0)}$	$z_i^{(0)}$
1	R	0	0	l_1	0	0	1
2	T	0	0	l_1+l_2	0	0	1
3	T	l_3	0	l_1+l_2	0	1	0
4	-	0	l_4	$l_1+l_2-l_5$	1	0	0

According to (2), the matrix of the nominal geometry is completed with are the screw parameters as:

The table of nominal geometry ${}^{*}M_{vn}^{(0)}$ *Table 2*

$1\to4$	Joint type	$\overline{k}_i^{(0)T}$			$\overline{v}_i^{(0)T}$		
1	R	0	0	1	0	0	0
2	T	0	0	1	0	0	1
3	T	0	1	0	0	1	0
4	-	1	0	0	-	-	-

In keeping with the algorithm and the mechanical structure of the robot, it's opened an external loop from $i=1\to3$.

- Hence, for $(i=1)$, specific to the first element of the robot, according to the Table 2, and in concordance with (3)-(7), there are determined the following terms:

- $$A_1=\left[\begin{array}{c:c}\left(\overline{k}_1^{(0)}\times\right) & \overline{v}_1^{(0)}\\ \hdashline 0\;0\;0 & 0\end{array}\right]=\left[\begin{array}{ccc:c}0 & -1 & 0 & 0\\ 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ \hdashline 0 & 0 & 0 & 0\end{array}\right] \quad (13)$$

$$e^{\left(\overline{k}_1^{(0)}\times\right)\cdot q_1\cdot\Delta_1}=\exp\left\{\left(\overline{k}_1^{(0)}\times\right)\cdot q_1\right\}= \quad (14)$$
$$=I_3+\left(\overline{k}_1^{(0)}\times\right)\sin q_1+\left(\overline{k}_1^{(0)}\times\right)^2(1-\cos q_1)$$

$$e^{\left(\overline{k}_1^{(0)}\times\right)\cdot q_1\cdot\Delta_1}=\begin{bmatrix}\cos q_1 & -\sin q_1 & 0\\ \sin q_1 & \cos q_1 & 0\\ 0 & 0 & 1\end{bmatrix} \quad (15)$$

$$\overline{b}_1=\Big[I_3\cdot q_1+\left(\overline{k}_1^{(0)}\times\right)\cdot(1-\cos q_1)+$$
$$+\left(\overline{k}_1^{(0)}\times\right)^2\cdot(q_1-\sin q_1)\Big]\cdot\overline{v}_1^{(0)}=[0\;0\;0]^T \quad ;(16)$$

$$e^{A_1\cdot q_1}\equiv\exp\left(\left[\begin{array}{c:c}\left(\overline{k}_1^{(0)}\times\right) & \overline{v}_1^{(0)}\\ \hdashline 0\;0\;0 & 0\end{array}\right]\cdot q_1\right)=$$
$$=\left[\begin{array}{ccc:c} & R\left(\overline{k}_1^{(0)};\,q_1\right) & & \overline{b}_1\\ \hdashline 0 & 0 & 0 & 1\end{array}\right]=\left[\begin{array}{ccc:c}\cos q_1 & -\sin q_1 & 0 & 0\\ \sin q_1 & \cos q_1 & 0 & 0\\ 0 & 0 & 1 & 0\\ \hdashline 0 & 0 & 0 & 1\end{array}\right] \quad (17)$$

• For $(i=2)$, specific to the second kinetic element, according to (3)-(7) there are obtained the following expressions:

$$A_2=\left[\begin{array}{c|c}(\overline{0}\times) & \overline{v}_2^{(0)}\\ \hline 0\ 0\ 0 & 0\end{array}\right]=\left[\begin{array}{ccc|c}0&0&0&0\\0&0&0&0\\0&0&0&1\\ \hline 0&0&0&0\end{array}\right]; \quad (18)$$

$$e^{\left(\overline{k}_2^{(0)}\times\right)\cdot q_2\cdot\Delta_2}=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}=I_3; \quad (19)$$

$$\overline{b}_2=I_3\cdot q_2\cdot\overline{v}_2^{(0)}=\begin{bmatrix}0\\0\\q_2\end{bmatrix}; \quad (20)$$

$$e^{A_2\cdot q_2}=\left[\begin{array}{ccc|c}\multicolumn{3}{c|}{e^{\left(\overline{k}_2^{(0)}\times\right)\cdot q_2\cdot\Delta_2}} & \overline{b}_2\\ \hline 0&0&0&1\end{array}\right]=\left[\begin{array}{ccc|c}1&0&0&0\\0&1&0&0\\0&0&1&q_2\\ \hline 0&0&0&1\end{array}\right] \quad (21)$$

• The third step corresponding to the last kinetic element $(i=3)$ it's characterized by:

$$A_3=\left[\begin{array}{c|c}\left(\overline{k}_3^{(0)}\times\right) & \overline{v}_3^{(0)}\\ \hline 0\ 0\ 0 & 0\end{array}\right]=\left[\begin{array}{ccc|c}0&0&0&0\\0&0&0&1\\0&0&0&0\\ \hline 0&0&0&0\end{array}\right] \quad (22)$$

$$e^{\left(\overline{k}_3^{(0)}\times\right)\cdot q_3\cdot\Delta_3}\equiv\exp\left\{\left(\overline{k}_3^{(0)}\times\right)\cdot q_3\right\}\equiv$$
$$\equiv I_3\cdot\cos q_3+\left(\overline{k}_3^{(0)}\times\right)\cdot\sin q_3+ \quad (23)$$
$$+\overline{k}_3^{(0)}\cdot\overline{k}_3^{(0)T}\cdot(1-cosq_3)=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}=I_3$$

$$\overline{b}_3=\Big[I_3\cdot q_3+\left(\overline{k}_3^{(0)}\times\right)\ (1-\cos q_3)+$$
$$+\overline{k}_3^{(0)}\cdot\overline{k}_3^{(0)T}\cdot(q_3-\sin q_3)\Big]\cdot\overline{v}_3^{(0)}=\begin{bmatrix}0\\q_3\\0\end{bmatrix};(24)$$

$$e^{A_3\cdot q_3}\equiv\exp\{A_3\cdot q_3\}=$$
$$=\left[\begin{array}{ccc|c}\multicolumn{3}{c|}{e^{\left(\overline{k}_3^{(0)}\times\right)\cdot q_3}=R\left(\overline{k}_3^{(0)};q_3\right)} & \overline{b}_3\\ \hline 0&0&0&1\end{array}\right]=\left[\begin{array}{ccc|c}1&0&0&0\\0&1&0&q_3\\0&0&1&0\\ \hline 0&0&0&1\end{array}\right].(25)$$

• For initial configuration, $\overline{\theta}^{(0)}$ the locating matrix between the links $\{0\}\to\{4\}$ is:

$$T_{40}^{(0)}\equiv\left[\begin{array}{c|c}R_{40}^{(0)} & \overline{p}^{(0)}\\ \hline 0\ 0\ 0 & 1\end{array}\right]=\left[\begin{array}{ccc|c}0&1&0&l_3\\1&0&0&l_4\\0&0&1&l_1+l_2-l_5\\ \hline 0&0&0&1\end{array}\right](26)$$

In keeping with (11), by calculus is obtained the resultant locating matrix and the position vector between the links $\{0\}\to\{4\}$ as:

$${}_4^0[R]=\left(E_{\exp}^1\cdot E_{\exp}^2\cdot E_{\exp}^3\right)\cdot R_{40}^{(0)},; \quad (27)$$

where:

$$E_{\exp}^1=\exp\left\{\left(\overline{k}_1^{(0)}\times\right)\cdot q_1\right\};$$
$$E_{\exp}^2=\exp\left\{\left(\overline{k}_2^{(0)}\times\right)\cdot q_2\right\}=I_3;; \quad (28)$$
$$E_{\exp}^3=\exp\left\{\left(\overline{k}_3^{(0)}\times\right)\cdot q_3\right\}=I_3.$$

Substituting (15) and (28) in (27), results:

$${}_4^0[R]=\left[\begin{pmatrix}n_x\\n_y\\n_z\end{pmatrix}\begin{pmatrix}s_x\\s_y\\s_z\end{pmatrix}\begin{pmatrix}a_x\\a_y\\a_z\end{pmatrix}\right]=\begin{bmatrix}-\sin q_1&\cos q_1&0\\\cos q_1&\sin q_1&0\\0&0&1\end{bmatrix}.(29)$$

According to (12),the position vector of the characteristic point is established as:

$$\overline{p}=\overline{b}_1+e^{\left(\overline{k}_1^{(0)}\times\right)\cdot q_1}\cdot\left(\overline{b}_2+\overline{b}_3\right)+$$
$$+e^{\left(\overline{k}_1^{(0)}\times\right)\cdot q_1}\cdot e^{\left(\overline{k}_3^{(0)}\times\right)\cdot q_3}\cdot\overline{p}^{(0)}= \quad ;(30)$$
$$=\begin{bmatrix}l_3\cdot\cos q_1-\sin q_1\cdot(l_4+q_3)\\l_3\cdot\sin q_1+\cos q_1\cdot(l_4+q_3)\\l_1+l_2-l_5+q_2\end{bmatrix}=\begin{bmatrix}p_x\\p_y\\p_z\end{bmatrix}$$

In keeping with [1] and [7], the independent angles for orientation, included in the orienting vector $(\overline{\psi})$ are defined according to:

$$R\left(\alpha_x-\beta_y-\gamma_z\right)\equiv R\left(\gamma_z-\beta_y-\alpha_x\right)={}^{0}_{4}[R]$$
$$\begin{bmatrix} A & D & G \\ B & E & H \\ C & F & I \end{bmatrix}=\begin{bmatrix} -\sin q_1 & \cos q_1 & 0 \\ \cos q_1 & \sin q_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (31)$$

where:

$$\begin{aligned}
&A=\cos\beta_y\cdot\cos\gamma_z;\\
&B=\sin\alpha_x\cdot\sin\beta_y\cdot\cos\gamma_z+\cos\alpha_x\cdot\sin\gamma_z;\\
&C=-\cos\alpha_x\cdot\sin\beta_y\cdot\cos\gamma_z+\sin\alpha_x\cdot\sin\gamma_z;\\
&D=-\cos\beta_y\cdot\sin\gamma_z;\\
&E=-\sin\alpha_x\cdot\sin\beta_y\cdot\sin\gamma_z+\cos\alpha_x\cdot\cos\gamma_z; \quad (32)\\
&F=\cos\alpha_x\cdot\sin\beta_y\cdot\sin\gamma_z+\sin\alpha_x\cdot\cos\gamma_z;\\
&G=\sin\beta_y;\\
&H=-\sin\alpha_x\cdot\cos\beta_y;\\
&I=\cos\alpha_x\cdot\cos\beta_y.
\end{aligned}$$

According to expression (31), in order to establish the orientation angles, α_x, β_y, γ_z for exact determination of the values, there is used the trigonometric function $A\tan 2$, defined by:

$$x=A\tan 2(\sin\alpha;\cos\alpha)=$$
$$=\begin{Bmatrix} \{\alpha;[\sin\alpha\geq 0;\cos\alpha>0]\}; \\ \{\pi/2+\alpha;[\sin\alpha>0;\cos\alpha<0]\} \\ \{\pi+\alpha;[\sin\alpha<0;\cos\alpha<0]\}; \\ \{-\pi/2+\alpha;[\sin\alpha<0;\cos\alpha\geq 0]\} \end{Bmatrix} \quad (33)$$

Hence, in keeping with (33), results:

$$\alpha_x=A\tan 2(\sin\alpha_x;\cos\alpha_x)=A\tan 2(0;-1)=\pi \quad (34)$$

$$\gamma_z=\pi/2+q_1,\quad \beta_y=0 \quad (35)$$

and respectively the column vector of operational coordinates is equivalent with:

$${}^{0}\overline{X}=\begin{bmatrix} \overline{p} \\ -- \\ \overline{\psi} \end{bmatrix}=\begin{bmatrix} l_3\cdot\cos q_1-\sin q_1\cdot(l_4+q_3) \\ l_3\cdot\sin q_1+\cos q_1\cdot(l_4+q_3) \\ l_1+l_2-l_5+q_2 \\ \hline \pi \\ 0 \\ \dfrac{\pi}{2}+q_1 \end{bmatrix} \quad (36)$$

The expressions (29) and (30) are representing the resulting orientation matrix, respectively the position vector, included in the resulting locating matrix. All these matrices are included in the expression of column vector of the operational coordinates (36), also known [1] as the equations of direct geometry (DGM).

4. CONCLUSIONS

As can be remarked from previous sections, the equations of forward geometry kinematics (direct model), the position and orientation (locating) parameters, for any mechanical structure can be established by means of matrix exponentials.

The using of the matrix exponentials has a few advantages like the number of mathematical operations, which is lower than in the case of classical algorithms. The using of screw parameters from the matrix of input data, are making the representation of mobile reference frame a nonsense, hence, the geometrical errors owed to reference systems being diminished. Another advantage of the exponentials is that are conducting to a compact representation of the necessary information for defining the direct geometry of a mechanical system with an open or close chain.

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Considerații asupra funcţiilor exponenţiale de matrice în modelarea geometrică a roboților

Rezumat: În literatura de specialitate, există multe abordări pentru modelarea matematică a roboților. Astfel, exista diferiți algoritmi pentru modelarea geometrică consacrați. Cele mai multe abordări necesită utilizarea sistemelor de referință, ceea ce poate duce la erori în calcul. Studiul geometric al oricărei structuri mecanice de robot poate fi realizat prin exponențiale de matrice având avantaje esențiale pe lângă abordările clasice. Drept urmare, în cadrul acestei lucrări, va fi prezentat un exemplu de modelare matematică, bazat pe exponențiale de matrice aplicate în modelarea geometrică a roboților seriali.

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