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Kinematics modeling and trajectory planning of KUKA manipulator based on MATLAB

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ABSTRACT: For the purpose of engraving, KUKA KR60 mechanical arm was used in the laboratory for research and analysis.Firstly, the improved D-H parameter method was used to establish the D-H coordinate system of the manipulator, and the kinematic equation of the manipulator was obtained by calculating the homogeneous transformation matrix.Secondly, mathematical modeling was carried out with MATLAB Robbtics Toolbox, and the forward and inverse kinematics problems were analyzed and demonstrated to verify the correctness of the kinematic model of the mechanical arm. Thirdly, Monte Carlo method was used to calculate the movement Angle of the mechanical arm joint to reach the working area. Finally, trajectory planning was adopted.The variation curves of Angle, angular velocity and angular acceleration were obtained, and the rationality of its trajectory planning was verified by simulation analysis, which provided a research basis for the next step of carving trajectory path optimization.

1.Introduction

Robot arm often replaces people to solve some high-precision and dangerous work, and the work efficiency is high and the quality is good. Nowadays, robot technology has been widely applied in many fields, such as medicine, military, industry, etc., especially in the field of industrial production. For the proposal of industry 4.0, the development of robot technology has freed human beings from the tedious labor force, making the development of robot technology advance to the newer field[1].

ABB and CLOOS robots in Europe, OTC and MOTOMAN robots in Japan and other foreign robots have been quite mature in assembly line production and development and application. In terms of engraving, Gotlih et al. found the optimal placement area of each part through genetic search algorithm [2]. Chen et al. used the distribution law of NSPI to calculate the optimal feed direction of the cutter for the robot milling plane [3], Xiong et al. proposed an optimization method to obtain the optimal pose to improve production efficiency and quality [4], and Julian et al. used a virtual computer platform to optimize the path stiffness [5]. Compared with the domestic robot industry, shenyang Siasong and Harbin Boshi and other large enterprises have realized modular management production, and more small enterprises have realized the state of small batch production and research and development. For robot applications and carving, improve the precision and stability of the robot operations are particularly important, there are many domestic experts for the profound research, Liu Meng, Liu Yanlin [6] to use five axis robot sculpture processing, according to different structure of the machine, using five dof serial robots are more suitable for application in the arts and crafts sculpture processing, flexible way it works, The motion space is wide, and then the kinematics and dynamics analysis is carried out to determine the control system and method. Zhai Jingmei et al. [7] invented an adaptive fuzzy control algorithm and its controller, which has a faster speed to track and the system can output quickly in time. Kong Lingfu et al. [8] set up a monitoring platform for visual information processing, which is highly intelligent for robot motion path calculation, obstacle avoidance and multi-point movement. Zhang Mingshan et al. [9] designed the kinematics model of a new engraving robot, optimized the control algorithm, and observed the changes in joint torques to obtain the optimal control effect.

KUKA robot was used to analyze its kinematics and simulation in the laboratory, and Robotic Toolbox in MATLAB was used for modeling and simulation research. Firstly, D-H [10] parameters were calculated to solve the kinematics problem, and then the relationship between the Angle of each joint and the position and pose of the end was obtained. Secondly, mathematical models were established. The forward and inverse kinematics problems were analyzed to verify the correctness of the model. Then, the monte Carlo method was used to obtain the robot terminal workspace within the range of each joint activity. Finally, trajectory planning was carried out through simulation to obtain the velocity, displacement and acceleration changes of the manipulator, which provided the basis for the next research.

2.Kinetic analysis and modeling of KUKA KR60 KUKA KR60 manipulator

2.1.Improved D-H method

The improved D-H method is improved on the standard D-H method. The use of standard type after the robot arm is combined with the carving knife is more cumbersome, the calculation is complex. The improved D-H method is used to calculate the operating coordinate system transformation between the end of the robot arm and the end of the engraving knife, the biggest difference in them is that the standard D-H method uses the joint coordinate system after the linkage as the solid-link coordinate system, the improved D-H method uses the previous joint coordinate system of the linkage as a solid-link coordinate system, The D-H parameter calculated using the improved D-H method contains four kinetic parameters for each linkage :linkage length a_{i-1} , linkage twist α_{i-1} ,linkage setover d_i and joint angle θ_i .

2.2.KUKA KR60 manipulator link parameters

The KUKA KR60 manipulator is a six-degree-of-freedom robotic arm that belongs to the tandem joint robot, all six joints are rotating joints. Establishes the D-H parameter coordinate system shown in Figure 1, modeling guidelines: the z-axis follows the joint axis, the x-axis follows the joint-link male-hanging line, and the y-axis is determined according to the right-hand rules and applied to the transformation of the previously stated coordinate system. The process is: Solid-connected coordinate system 0 pans 815mm along the axis Z_0 transforms to coordinate system 1. Coordinate system 1 translates 350mm along the axis X_1, rotates 90 degrees around the axis X_1 and then rotates around the axis Z_1 to transforms it into coordinate system 2. Coordinate system 2 pans 850mm along the axis X_2 transforms to coordinate system 3. Coordinate system 3 pans 820mm along axis Y_3, pans 145mm along axis X_3, rotates 90 degrees around the axis X_3 transforms to coordinate system 4. Coordinate system 4 is rotated 90 degrees around axis X_4 in the opposite direction and transformed into coordinate system 5. Coordinate system 5 pans 170mm along axis Z_5, rotates 180 degrees around the axis X_5, and then rotates θ_6 around the axis Z_5 transforms to coordinate system 6.

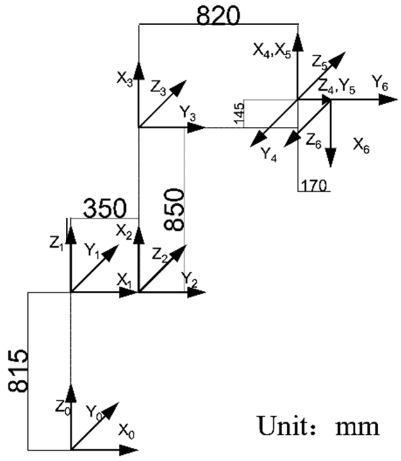

Figure 1: KUKA KR60 manipulator D-H coordinate system

According to the KUKA KR60 robot D-H coordinate system, and four parameters of the criteria, measured KUKA KR60 manipulator D-H parameter as table1.

Table 1: KUKA KR60 manipulator D-H parameter

Joint	a_{i-1} **(mm)**	α_{i-1} **(°)**	d_i **(mm)**	θ_i **(°)**	Joint range
1	0	0	815	θ_1	-90°~90°
2	350	90	0	θ_2	-135°~45°
3	850	0	0	θ_3	-120°~160°
4	145	90	820	θ_4	-350°~350°
5	0	-90	0	θ_5	-120°~120°
6	0	180	170	θ_6	-350°~350°

2.3.Forward kinematics of manipulator

Forward kinematics is the known joint variables θ_i to calculate the terminal posture matrix, according to the D-H definition, combined with the KUKA manipulator D-H coordinate system translation and rotation transformation, by describing the posture matrix, it is not difficult to obtain the general formula between the connecting rod transformation.

$$
{}^{i-1}_{i}T=\begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} & -d_i\sin\alpha_{i-1} \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i\cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
$$

In combination with Formula (1), assuming that each joint variable is $q=[0,45°,135°,0,0,0]$,substitute the parameters in the D-H parameter table to obtain the transformation matrix of each link:

$$
{}^{0}_{1}T=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.815 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{1}_{2}T=\begin{bmatrix} \sqrt{2}/2 & -\sqrt{2}/2 & 0 & 0.350 \\ 0 & 0 & -1 & 0.815 \\ \sqrt{2}/2 & \sqrt{2}/2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{2}_{3}T=\begin{bmatrix} \sqrt{2}/2 & -\sqrt{2}/2 & 0 & 0.850 \\ \sqrt{2}/2 & \sqrt{2}/2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{3}_{4}T=\begin{bmatrix} 1 & 0 & 0 & 0.145 \\ 0 & 0 & -1 & -0.820 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{4}_{5}T=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{5}_{6}T=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -0.170 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}
$$

The total change matrix can be obtained by multiplying the transformation matrix of each link above, that is, the pose matrix of the manipulator from the base coordinate system to the end coordinate system:

$$
{}_6^0T = {}_1^0T \bullet {}_2^1T \bullet {}_3^2T \bullet {}_4^3T \bullet {}_5^4T \bullet {}_6^5T = \begin{bmatrix} 0 & 0 & 1 & 1.941 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 1.561 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}
$$

2.4.Inverse kinematics of manipulator

Inverse kinematics is the inverse calculation of the joint variables θ_i corresponding to the known end pose, I used algebra to find equations by comparing matrices with the same equal sign. Take solving the terminal pose matrix above as an example combined with the D-H parameter table joint Angle range, I have multiple sets of solutions, one of which is shown below: combine the ${}_1^0T^{-1} \bullet {}_6^0T = {}_2^1T \bullet {}_3^2T \bullet {}_4^3T \bullet {}_5^4T \bullet {}_6^5T$ and the ${}^0T_1^{-1} g\, {}^0T_6\, g\, {}_6^5T^{-1} = {}_2^1T\, g\, {}_3^2T\, g\, {}_4^3T\, g\, {}_5^4T$ to calculate the θ_1, then get the θ_2 and the θ_3: $\theta_1 = 0° or -90°, \theta_3 = 45° or 135°, \theta_2 = 45°$

Assuming that $\theta_1 = 0$, $\theta_2 = 45°$, $\theta_3 = 45°$ we can get that $\theta_5 = 0°$, $\theta_4 = 0°$, $\theta_6 = 0°$.

2.5.Kinematics simulation model of manipulator

Using MATLAB R2018a and Robbtics Toolbox for MATLAB version 10.4, according to d-H table parameters, run the code to establish the simulation model of KUKA KR60 mechanical arm as shown in the figure 2.

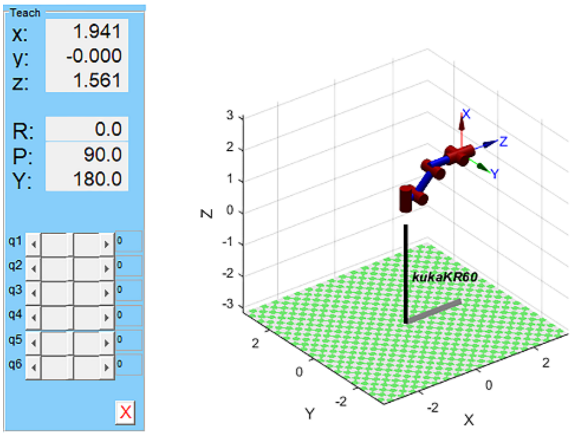

Figure 2: Three-dimensional simulation model of KUKA KR60 manipulator

On the left side of figure 2, position coordinates X, Y, Z and attitude coordinates R, P, Y can be seen from top to bottom. In particular, teach() function can be used to adjust the Angle of each joint q1, q2, q3, q4, q5, q6. Drag the position of the slider or input a specific Angle on the right end, and the 3D graph can be rotated accordingly to intuitively display the terminal state.

2.6.Forward and inverse kinematics simulation verification of the manipulator

For multi-link robots, forward and inverse kinematics can be solved by algebraic method, variable separation method, geometric method, iterative method, etc., but manual calculation is impractical due to the huge amount of computation[11].On the basis of the establishment of the 3D simulation model, forward kinematics verification was carried out first. fkine() function in MATLAB Robbtics Toolbox was used for calculation, joint variables were set, and fkine() function was used to obtain the following pose matrix, as shown in Figure 3.

$$T = \begin{bmatrix} 0 & 0 & 1.000 & 1.941 \\ 0 & -1.000 & 0 & 0 \\ 1.000 & 0 & 0 & 1.561 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

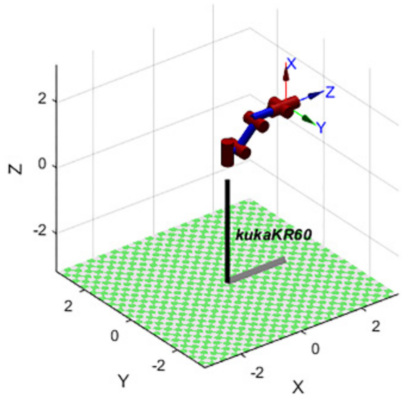

Figure 3: Schematic diagram of forward and inverse kinematics verification

Therefore, the forward kinematics analysis was verified to be correct, and the correctness of the modeling of the modified mechanical arm model was verified, which provided a basic theoretical research model for further study of the sculpting path and path planning.

The simulation of robot inverse kinematics is to analyze the correctness of the inverse solution of various joint variables from the robot end pose, that is, whether the robot end can reach the given positioning pose [12]. Then, the inverse solution function Ikine() is used to calculate the corresponding joint variable value, and the result is $q_2 = [0.000, 0.7854, 0.7854, 0.000, 0.000, -0.000]$. When converted to the angle system is $q_1 = q_2 = [0, 45°, 45°, 0, 0, 0]$, thus the inverse kinematics of the manipulator is verified.

3.Workspace for the KUKA KR60 manipulator

Monte Carlo method is a numerical method for solving mathematical problems by random sampling [13]. To put it simply, the values of all joint variables are as random as possible within the limited range, and the range displayed is the set of random value positions of the end points of the manipulator. Based on the previously established 3D model and according to the range of each joint in the D-H table, MATLAB programming is used to calculate the Monte Carlo method, in which rand() function is used to generate a series of random values at each joint Angle, showing the range of image representation as shown in Figure 4.

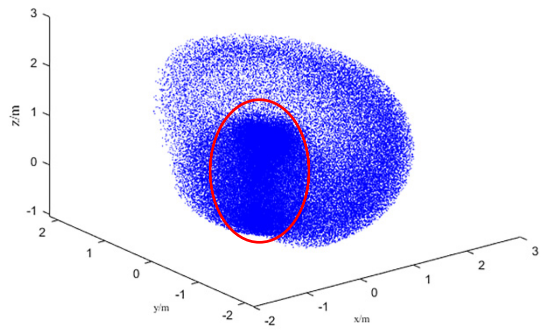

Figure 4: Working range of KUKA KR60 manipulator

The enclosed part of the space is a dense place, which is the most suitable for the design of experimental platform for sculpture research.

4.Trajectory planning of KUKA KR60 manipulator

The main content of robot trajectory planning is to make the robot move along path points or trajectory under certain constraints, including acceleration and deceleration planning and smooth transition planning of trajectory [14]. In the aspect of engraving, the stability of the running track of the mechanical arm directly affects the precision of engraving. Usually, the interpolation equation of the starting point to the end point of each joint is determined, so that the movement speed and acceleration change continuously without jumping, so as to achieve the smoothness of engraving. General trajectory planning of robots mainly includes two forms: trajectory planning for point-to-point motion and trajectory planning for continuous point motion [15]. Point-to-point motion is concerned with the starting point and end point of the robot's terminal movement, and there is no requirement for the position and posture of the running process. Continuous point motion is based on point-to-point motion, and the motion of each joint needs to be linked. The robot can be guaranteed to move repeatedly in a certain range according to the desired trajectory through linear or arc trajectory interpolation operation between adjacent two points that meets the accuracy requirements [16]. In cartesian coordinate system, the most direct way to use is linear and circular interpolation for terminal trajectory planning.

The trajectory planning of KUKA KR60 manipulator was studied by point-to-point programming, and the images of displacement, velocity and acceleration of each joint were obtained. Finally, the simulation of linear trajectory was verified. First, the end starting point and end point are established, and the joint Angle of the starting point is set as $q_1 = [0, 45°, 45°, 0, 0, 0]$, the joint Angle of the end point is set as $q_3 = [90°, -60°, -45°, -60°, 36°, 30°]$. The position and pose matrices are obtained by formula of the forward motion equation, as shown below.

$$T_1 = \begin{bmatrix} 0 & 0 & 1 & 1.941 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 1.561 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2 = \begin{bmatrix} -0.3568 & 0.7833 & -0.5090 & -0.0865 \\ 0.2890 & -0.4256 & -0.8575 & -0.2004 \\ -0.8884 & -0.4530 & -0.0745 & 0.1384 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The robot arm takes 100 steps from to and runs 100s. A large matrix of fitting approximation is solved by jtran() function, and images of Angle, angular velocity and angular acceleration of each joint are drawn by plot() function, as shown in Figure 5,6 and 7.

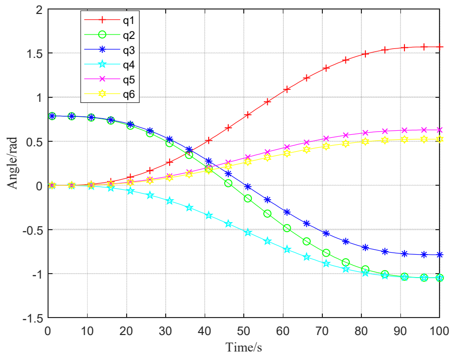

Figure 5: Curve of Angle change of each joint

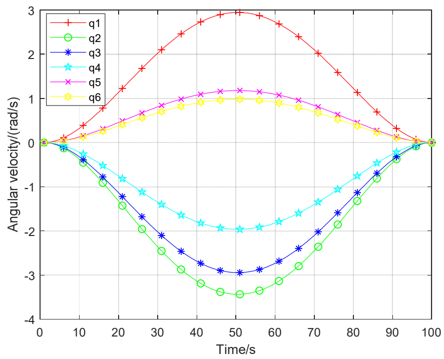

Figure 6: Curve of angular velocity change of each joint

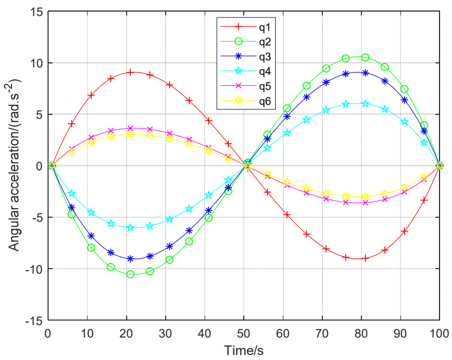

Figure 7: Curve of angular acceleration of each joint

Figure 5,6,7 have six curves, obviously in different speed of each joint coordinate rotation, can clearly see every curve is continuous smooth, no mutation phenomenon, more no singularity occurs, movement is normal, ensure the stability of mechanical arm in carving process, ensure the accuracy of carving, also meet the requirements of path planning, it facilitated further experiments. According to the point-to-point trajectory planning method, the motion posture and position trajectory from the starting point to the end point are shown in Figure 8 and 9. The same results were obtained through the operation test of the laboratory mechanical arm.

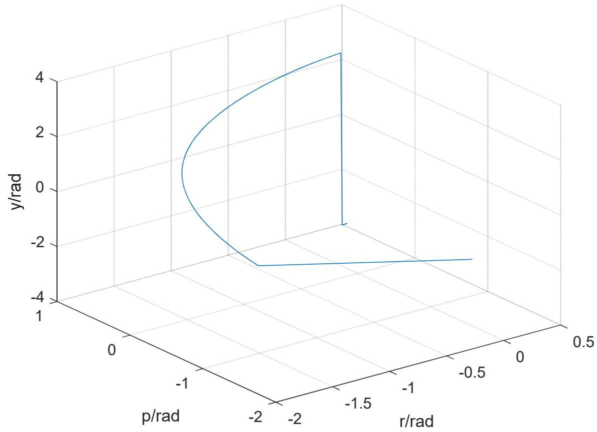

Figure 8: Attitude change curve from T1 to T2

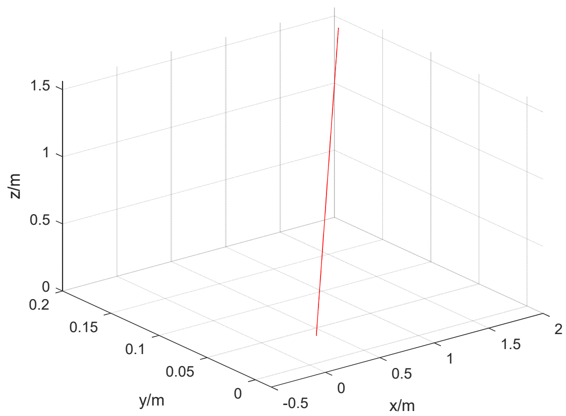

Figure 9: Change of straight line trajectory from T1 to T2

5.Conclusion

The main KUKA KR60 mechanical arm kinematics simulation analysis, through the use of improved D-H modeling method to establish DH coordinate system, solve D-H parameters, the establishment of forward and inverse kinematics equations to solve the operation, then through MATLAB robot toolbox three-dimensional modeling, verify forward and inverse kinematics. Monte Carlo method is used to calculate the working space accessible to the end of the manipulator, which provides a basis for the placement of the experimental platform. Finally, the linear trajectory is run within its working range, and the curves of the Angle, angular velocity and angular acceleration of each joint are obtained, providing a basis for further research.

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