

Kinematics Analysis and Simulation of 6-DOF Industrial Robot

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Abstract: The KR 210 R2700 extra type manipulator is selected as the research object. The kinematics mathematical model is established by the standard D-H parameter method, and the forward and inverse kinematics problems are solved. The 3D model established by Solidworks is imported into the multi-body dynamics software ADAMS to establish a virtual prototype model. With the help of the point drive in ADAMS, the end of the robot arm can be moved according to the predetermined trajectory, and the inverse kinematics solution is solved. The SPLINE tool of the processing module implements a positive kinematics simulation. The simulation results show that the method can accurately complete the working conditions of the MARKER point of the end of the manipulator according to the preset trajectory, and the kinetic data obtained at the same time provides a theoretical basis for the selection of the motor and the production of the physical prototype.

Key words: ADAMS, kinematics simulation, general point drive, SPINE driver function

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I. INTRODUCTION

With the development of computer technology, robot technology has entered a peak period of development[1-2], especially for industrial robots used in manufacturing, which is expected to become the second largest industry after the automobile industry. More and more manufacturers are beginning to introduce industrial robots. Instead of manpower, this will greatly improve production efficiency and reduce labor costs. Industrial robots have a relatively fixed working environment and are used to complete a specific task for a long time[3]. Therefore, trajectory planning has become a key technology. In this paper, the KR 210 R2700 extra type manipulator is used as the research object. The kinematics model is established by DH parameter method[4]. The forward and inverse kinematics problems are analyzed. The virtual prototype model is established by multi-body dynamics software ADAMS[5]. The kinematics simulation achieves the goal of the mechanical arm to complete a certain preset condition, and obtains relevant dynamic data, which lays a foundation for further research.

II. KR ROBOT KINEMATICS ANALYSIS

Robot kinematics includes forward kinematics and inverse kinematics. Kinematics analysis is the basis for dynamic analysis, workspace solving, singularity analysis, and trajectory planning. In this paper, the D-H (Denavit-Hartenberg) parameter method is used to establish the kinematics model, and the forward kinematics equation is obtained[2], and the inverse kinematics is solved.

2.1 Establishing the D-H coordinate system

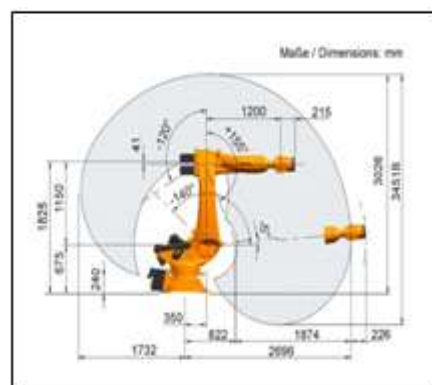
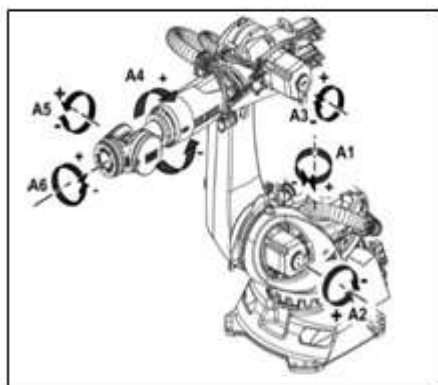


Fig.1.The outline drawing of 6-DOF KR robot **Fig. 2** Structural parameters of the manipulator

This article uses the KR 210 R2700 EXTRA type manipulator as the analysis object. This is a six-degree-of-freedom series robot with six rotating shafts and six links. Its structure is shown in Figure 1. The

standard rear coordinate system is used. The method establishes the link coordinate system , and the coordinate system is shown in Fig. 3.

2.2 D-H parameter table and coordinate system transformation

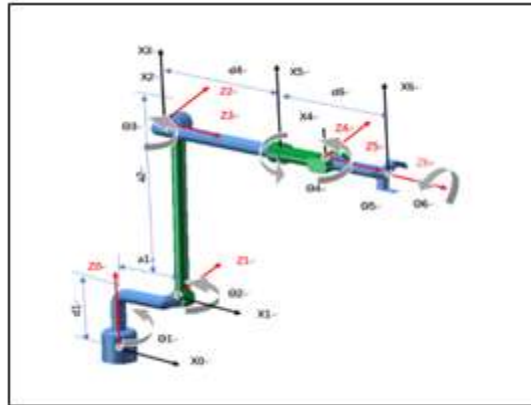


Fig.3.The link coordinate system

In 1955, the DH notation was proposed by Denavit and Hartenberg and has now become the standard method for modeling robot kinematics, which assigns a reference coordinate system to each joint and then transforms from one joint to the next. After the two adjacent coordinate systems are determined, the transformations are combined in order, and the total transformation matrix of the robot is obtained. The DH parameter table of Table 1. can be obtained from the linkage parameters of the robot arm of FIG.2

Table 1. D-H parameter table of the robot arm

Link	$\theta_i/(\text{°})$	$d_i/(\text{mm})$	$a_i/(\text{mm})$	$\alpha_i/(\text{°})$	Range of motion /(°)	structural parameters
0-1	θ_1	d_1	a_1	-90°	$\pm 185^\circ$	$d_1 = 435$
1-2	$-90^\circ + \theta_2$	0	a_2	0	-5° to -140°	$d_4 = 1200$
2-3	θ_3	0	0	-90°	$+155^\circ$ to -120°	$d_6 = 415$
3-4	θ_4	d_4	0	90°	$\pm 350^\circ$	$a_1 = 350$
4-5	θ_5	0	0	-90°	$\pm 125^\circ$	$a_2 = 1150$
5-6	θ_6	d_6	0	0	$\pm 350^\circ$	unit /(mm)

Note: If the robot pose is zero in the state shown in Figure 2, then $\theta_2 = -90^\circ$, $\theta_1 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = 0^\circ$. The coordinate transformation between adjacent two-link coordinate systems is realized by the transformation of the order of four elements. The 4-step standard transformation steps according to the standard D-H method are:

- ① Rotate θ_{n+1} around the z_n axis
- ② Translated d_{n+1} along the z_n axis
- ③ Translate a_{n+1} along the x_n axis that has been rotated
- ④ Rotate the z_n axis around the x_{n+1} axis α_{n+1}

From the above four steps, the relationship of the links n to n+1 can be right-multiplied by the transformation matrix representing the rotation and translation of the relative pose of the coordinate system to obtain the following matrix transformation.

$${}_{n+1}^n T = A_{n+1} = \text{Rot}(z, \theta_{n+1}) \times \text{Trans}(0, 0, d_{n+1}) \times \text{Trans}(a_{n+1}, 0, 0) \times \text{Rot}(x, \alpha_{n+1})$$

$$= \begin{bmatrix} C\theta_{n+1} & -S\theta_{n+1} & 0 & 0 \\ S\theta_{n+1} & C\theta_{n+1} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & a_{n+1} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\alpha_{n+1} & -S\alpha_{n+1} & 0 \\ 0 & S\alpha_{n+1} & C\alpha_{n+1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2-1)$$

among them : $C\theta_{n+1} = \text{Cos}\theta_{n+1}$, $S\theta_{n+1} = \text{Sin}\theta_{n+1}$, $C\alpha_{n+1} = \text{Cos}\alpha_{n+1}$, $S\alpha_{n+1} = \text{sin}\alpha_{n+1}$

The transformation matrix after the above simplification is as follows (2-2)

$$A_{n+1} = \begin{bmatrix} C\theta_{n+1} & -S\theta_{n+1}C\alpha_{n+1} & S\theta_{n+1}S\alpha_{n+1} & a_{n+1}C\theta_{n+1} \\ S\theta_{n+1} & C\theta_{n+1}C\alpha_{n+1} & -C\theta_{n+1}S\alpha_{n+1} & a_{n+1}S\theta_{n+1} \\ 0 & S\alpha_{n+1} & C\alpha_{n+1} & d_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2-2)$$

2.1 Positive kinematics

Forward kinematics, that is, given the joint variables $(\theta_1, \theta_2, \dots, \theta_6)$ of the robot, calculate the position and attitude of the robot end, and the six transformation matrices obtained by the above formula (2-2) are: 0_1T 、 1_2T 、 2_3T 、 3_4T 、 4_5T 、 5_6T .

$${}^0_1T = \begin{bmatrix} C_1 & 0 & -S_1 & a_1C_1 \\ S_1 & 0 & C_1 & a_1S_1 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^1_2T = \begin{bmatrix} S_2 & -C_2 & 0 & a_2S_2 \\ -C_2 & S_2 & 0 & -a_2C_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^2_3T = \begin{bmatrix} C_3 & 0 & -S_3 & 0 \\ S_3 & 0 & C_3 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^3_4T = \begin{bmatrix} C_4 & 0 & S_4 & 0 \\ S_4 & 0 & -C_4 & 0 \\ 0 & 1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^4_5T = \begin{bmatrix} C_5 & 0 & -S_5 & 0 \\ S_5 & 0 & C_5 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^5_6T = \begin{bmatrix} C_6 & -S_6 & 0 & 0 \\ S_6 & C_6 & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Then, the homogeneous pose transformation matrix of the end effector of the arm about the base coordinate system is:

$${}^0_6T = {}^0_1T {}^1_2T {}^2_3T {}^3_4T {}^4_5T {}^5_6T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2-3)$$

In the above formula, to simplify the calculation $C_i = \text{Cos}\theta_i$, $S_i = \text{Sin}\theta_i$; $C_iC_j - S_iS_j = C_{ij}$, $S_iC_j + C_iS_j = S_{ij}$.among them :

$$n_x = C_6(C_5S_1S_4 + C_{23}C_1S_5 + C_1C_4C_5S_{23}) - S_6(C_1S_4S_{23} - S_1C_4)$$

$$n_y = -C_6(C_1S_4S_{23} - C_4S_1) - S_6(C_5S_1S_4 + C_{23}C_1S_5 + C_1C_4C_5S_{23})$$

$$n_z = C_{23}C_1C_5 - S_5(S_1S_4 + C_1C_4S_{23})$$

$$o_x = C_6(C_{23}S_1S_5 - C_1C_5S_4 + C_4C_5S_1S_{23}) - S_6(C_4C_1 + S_1S_4S_{23})$$

$$o_y = -C_6(S_1S_4S_{23} + C_4C_1) - S_6(C_{23}S_1S_5 - C_5C_1S_4 + S_1C_4C_5S_{23})$$

$$o_z = C_{23}S_1C_5 - S_5(S_1C_4S_{23} - C_1S_4)$$

$$a_x = -C_6(S_5S_{23} - C_{23}C_4C_5) - C_{23}S_4S_6$$

$$a_y = S_6(S_{23}S_5 - C_{23}C_4C_5) - S_4C_6C_{23}$$

$$a_z = -S_{23}C_5 - C_{23}C_4S_5$$

$$p_x = a_1C_1 + a_2C_1S_2 + d_4C_1C_{23} - d_6(S_1S_4S_5 - C_1C_5C_{23} + C_1C_4S_5S_{23})$$

$$p_y = a_1S_1 + a_2S_1S_2 + d_4S_1C_{23} + d_6(C_1S_4S_5 + S_1C_5C_{23} - S_1C_4S_5S_{23})$$

$$p_z = d_1 + a_2C_2 - d_4S_{23} - d_6(C_5S_{23} + S_5C_4C_{23})$$

In order to verify the correctness of the kinematics equation, the following two sets of joint variables under special conditions can be selected.

- ① variable 1 (zero status) : $\theta_2 = -90^\circ$, $\theta_1 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = 0^\circ$
- ② Variable 2 : $\theta_3 = \theta_2 = -90^\circ$, $\theta_1 = \theta_4 = \theta_5 = \theta_6 = 0^\circ$

Bring in (2-3), because the calculation is cumbersome and complicated, you can use MATLAB robotictoolbox to program, as follows:

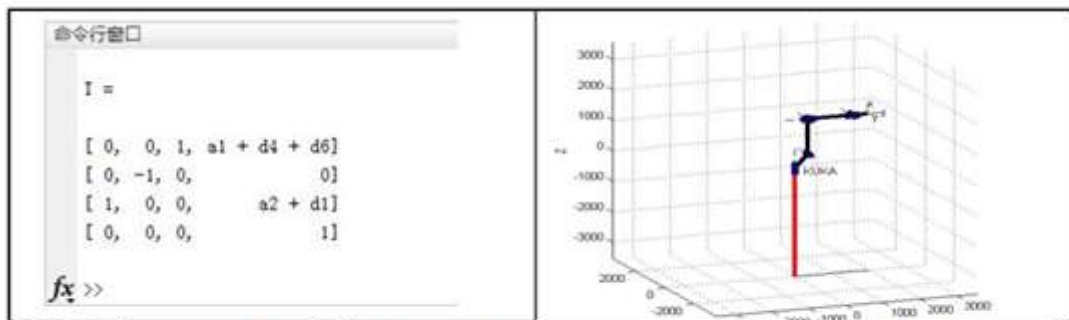


Fig. 4. Calculation result of variable 1 Fig.6.Pose corresponding to variable 1 Fig.5.Calculation result of variable 2

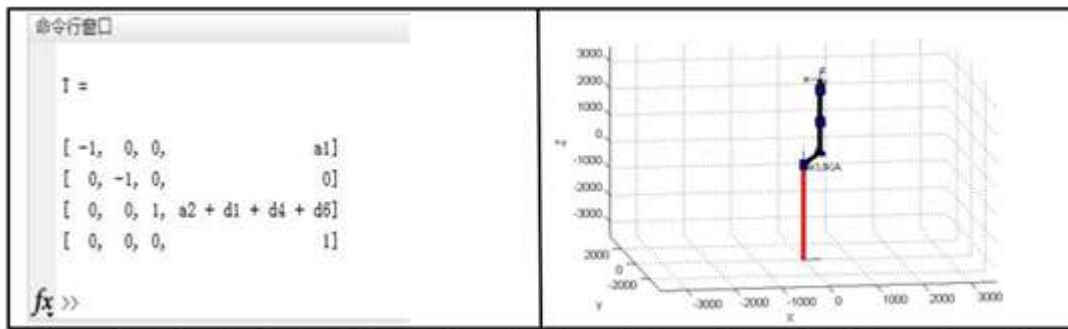


Fig. 7.Pose corresponding to variable 2

Observing the program calculation results of Fig. 4 and Fig. 5, it can be found that the three-dimensional shape of the robot arm (Fig. 6, 7) is consistent, and thus the correctness of the above kinematic model is verified.

2.2 Inverse kinematics problem

Inverse analysis, the process of knowing the position and orientation of the operating space, and solving the joint space variables. The inverse kinematics problem is the most difficult part of kinematics analysis and the basis for further trajectory planning and kinematics control.

The inverse kinematics solution can be mainly divided into analytical methods and numerical methods. The mathematical derivation process of the analytical method is very cumbersome. It is the process of obtaining the closed solution by decoupling the variables, and then obtaining the values of the six joint variables. Whether or not a closed solution can be obtained can be judged according to the piepercriterion. Pieper The guidelines have two conditions:

- a. Three adjacent joint axes intersect at a point
- b. 3 adjacent joint axes are parallel to each other. The robot's joint configuration satisfies one of them to obtain a closed solution, and most commercial robotic arms, including the robotic arm selected herein, meet this criterion.

The analytical solution to the inverse kinematics problem of the manipulator is to multiply the inverse of the two sides of the equation by the inverse of the matrix, so that the corresponding elements of the equal matrix at both ends are equal, and select a suitable pair of elements, through the trigonometric function method, Find the value of each variable. The kinematic equation of the manipulator is as follows:

$${}^0_6T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^0_1T {}^1_2T {}^2_3T {}^3_4T {}^4_5T {}^5_6T \quad (2-4)$$

Note: When inverting the solution, the variables in the above formula are known.

Equation (2-4) is multiplied on both sides $({}^0_1T)^{-1}$.

$$({}^0_1T)^{-1} {}^0_6T = {}^1_2T {}^2_3T {}^3_4T {}^4_5T {}^5_6T \quad (2-5)$$

which is
$$\begin{bmatrix} C_1 & S_1 & 0 & -a_1 \\ 0 & 0 & -1 & d_1 \\ -S_1 & C_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^1_2T {}^2_3T {}^3_4T {}^4_5T {}^5_6T \quad (2-6)$$

The two sides of the above formula are equal, similar, can be obtained $({}^1_2T)^{-1} ({}^0_1T)^{-1} {}^0_6T = {}^2_3T {}^3_4T {}^4_5T {}^5_6T$

$$\begin{aligned} ({}^2_3T)^{-1} ({}^1_2T)^{-1} ({}^0_1T)^{-1} {}^0_6T &= {}^3_4T {}^4_5T {}^5_6T \\ ({}^3_4T)^{-1} ({}^2_3T)^{-1} ({}^1_2T)^{-1} ({}^0_1T)^{-1} {}^0_6T &= {}^4_5T {}^5_6T \\ ({}^4_5T)^{-1} ({}^3_4T)^{-1} ({}^2_3T)^{-1} ({}^1_2T)^{-1} ({}^0_1T)^{-1} {}^0_6T &= {}^5_6T \end{aligned}$$

The above-mentioned equations can be solved by trigonometric functions, and the joint angles $(\theta_1, \theta_2, \dots, \theta_6)$ can be solved, and the inverse solution of kinematics is completed.

III. ADAMS-BASED MOTION SIMULATION

The solution of the inverse kinematics problem of the manipulator consumes a lot of computational resources. The ADAMS solver can be used to realize the inverse solution of the position[6], and the end marker points can be operated according to the desired route, and the position solution of the six rotation pairs of the joint space can be solved. And complete the simulation of forward and inverse kinematics and the motion planning aiming at the task purpose[7]. At the same time, the kinetic parameters of the six joints were also obtained, providing data support for further production of physical prototypes.

3.1 Establishment of virtual prototype model

The advantage of ADAMS lies in multi-body dynamics analysis, and the modeling ability is limited. To this end, the 3D model of the KR210 2700 robotic arm (Fig. 8) established in Solidworks can be imported into ADAMS, and the following simulation environment settings are completed: a Add gravity, contact force b. Add motion pair c to set material properties. The virtual prototype model built is shown in Figure 9.



Fig.8. Build the three-dimensional model Fig.9. Virtual prototype model

3.2 Method of implementing kinematics control using ADAMS

Using ADAMS to achieve motion planning, the general point motion (General Point Motion) is used to make the end effector move according to a given motion trajectory, and the joint angular displacement curve is converted into a spline curve in the post-processing module[8], and then used. The spline curve is driven by each joint to achieve the purpose of kinematics control. The specific operation process is shown in Figure 10.

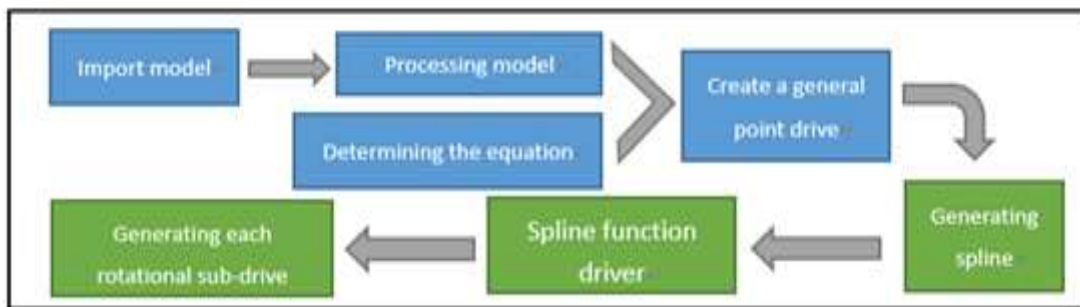


Fig. 10. Kinematics inverse solution flow chart

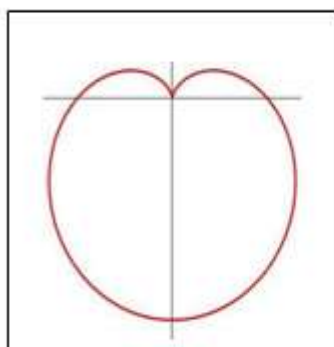



Fig.11. heart-shaped line Fig.12. General point driver creation

Inverse kinematics solution using general point drive .Mission goal: The end point should follow the heart-shaped line as shown in Figure 11, and the trajectory of the heart-shaped line is the parametric equation of equation (3-1).

$$\begin{cases} x=a*(2*\cos(t)-\cos(2*t)) \\ y=a*(2*\sin(t)-\sin(2*t)) \end{cases} \quad (3-1)$$

a. Create a general point drive

b. In the driver creation toolbar, select the  icon and pop up the setting tab shown in Figure 12 to set the position equations of X and Y respectively.

After the setup is completed, the simulation is performed. The position equation along the X direction is $X = -520 \cdot \cos(\text{time}) - \cos(2 \cdot \text{time})$, $Y = -640 \cdot \sin(\text{time}) - \sin(2 \cdot \text{time})$, the simulation time is set to 6.4s, and the step size is set. After the simulation is run, the six joints Joint1-Joint6 are measured, and the angular displacement as shown in Fig. 13 is obtained.

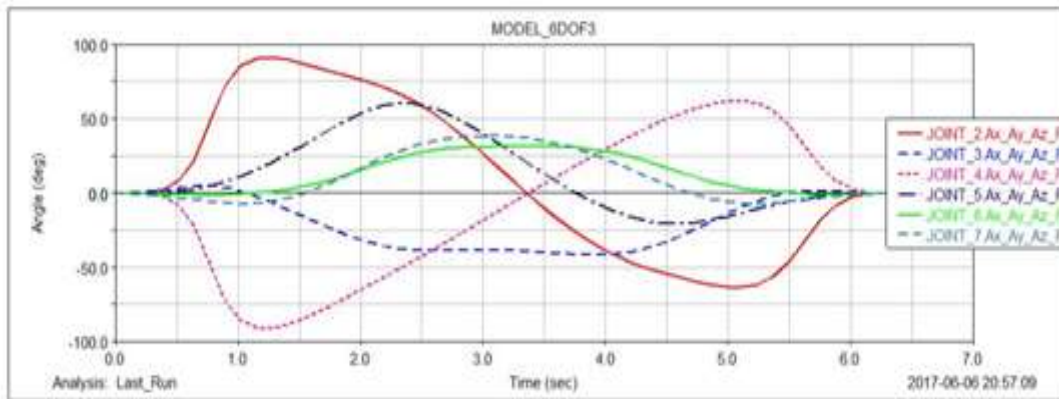


Fig. 13. Curve of each joint rotation angle with time

Looking at the displacement curves of Fig. 13, it can be found that both are continuous and smooth, and there is no mutation. The above six curves can be extracted as SPLINE curves using the spline tool. The above process obtains the angular displacement variation law of each driving joint by means similar to the robot teaching, and is used for the driving of each rotating pair in the next step. In fact, the inverse kinematics solution of the robot is completed by using ADAMS.

(2) Implementation of kinematics control driven by SPLINE function

a. Use of spline function

A spline fit is an interpolation method that finds an intermediate point between known points on a given curve or surface. A smooth curve approximating the data points can be formed by the spline fitting function during the simulation. The spline function is more general in the following cases: a. using the test test data to drive the model; b. using the test test data to define the driving force; c. drawing a smooth curve through the data points.

ADAMS/View allows three interpolation methods, namely: 1. Cubic spline curve fitting 2. B spline curve fitting 3. Akima fitting method, their corresponding functions are CUBSPL, CURVE, AKISPL, three splines The format of the driver function is:

- 1.CUBSPL(1st_Indep_Var , 2nd_Indep_Var , Spline_Name , Deriv_Order)
- 2.CURVE(Indep_Var , Deriv_Order , Direction , Curve_Name)
- 3.AKISPL(1st_Indep_Var , 2nd_Indep_Var , Spline_Name , Deriv_Order)

For example, using the AKISPL function, 1st_Indep_Var is the first argument in the spline, which can be a function of time time or distance. 2nd_Indep_Var is the second argument in spline must be 0, and Spline Name is the name of the data unit spline. Derivative Order (optional) is the differential order of the interpolation point. Generally, 0 is used, and 1 means 1 derivation.

b. Create a spline function driver

The point drive is disabled, and the rotation drive is added for the six rotation pairs, and then the drive parameters are modified; in the previous section, the SPLINE curve is obtained corresponding to each joint as the spline drive function of the joint. For example, the rotational drive of the joint 2 can be set to AKISPL (time, 0, JOINT2, 0), and the remaining joints are analogous.

After the rotation drive settings are completed, the forward kinematics simulation can be performed. The effect of the current operation according to the predetermined heart-shaped line is shown in Figure 3.6. The displacement curve of the reference point of the end effector obtained by the post-processing module is shown in Fig. 3.7; the torque variation curve of each joint can be obtained, as shown in Fig. 14.

Fig.14. Implementation of positive kinematics simulation

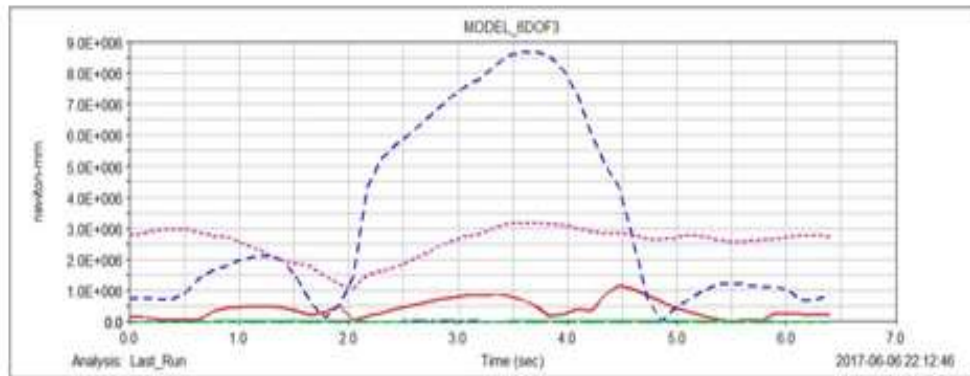
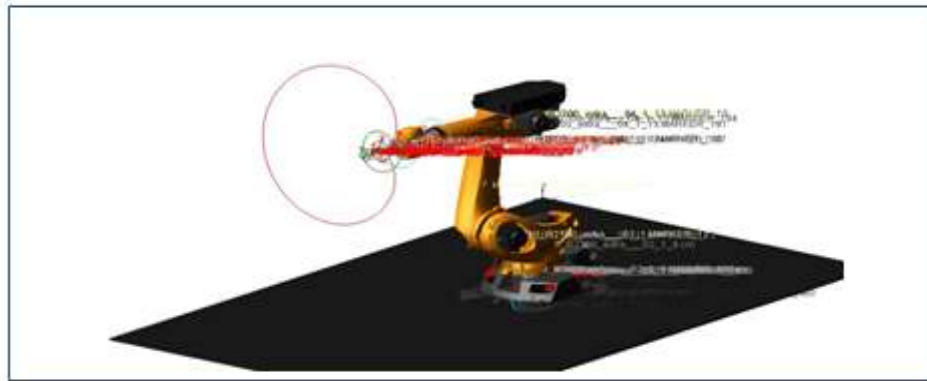


Fig. 15. The driving torque curve of the six rotating shafts

Observing the driving torque variation curve of each rotating shaft, it can be seen from fig. 15 that there is no turning point where the torque variation is obviously severe, and the torque data can be used for the driving control of the physical prototype.

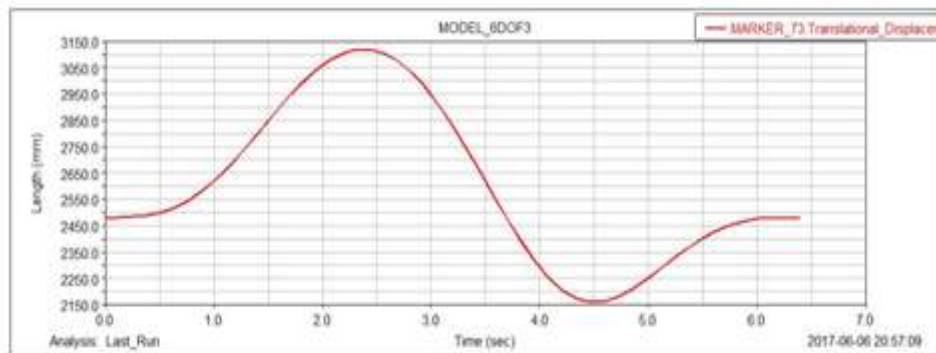


Fig. 16. Displacement curve of the end reference point

Finally, comparing the displacement curves of the end reference points of the forward and backward kinematics of the manipulator, it can be seen from fig. 16 that almost coincident, the error can be neglected, and the correctness of the acquired inverse kinematics data is also verified.

IV. CONCLUSION

The kinematics model of the KUKA six-degree-of-freedom manipulator is established by the standard DH parameter method. The correctness of the established forward kinematics equation is verified by MATLAB programming. The solution of the closed solution of the inverse kinematics equation is explained. The derivation method is realized. The kinematics control based on the operation space is realized by ADAMS, and the angular displacement curves of the six joints are obtained. The inverse solution of the position from the operation space to the joint space is realized, and the dynamic data of the six joints are obtained. It laid the foundation for the selection of motors and the production of physical prototypes.

REFERENCES

- [1]. Yuan An-fu, XueJin-ji. Performance analysis and simulation of joint robot based on ADAMS [J]. Manufacturing Automation, 2011 (8) : 85-89.
- [2]. Zhang Mei, Qiu Zhao-peng, Zhu Gang. Robotics [M]. Beijing: Machinery Industry Press, 2011.
- [3]. Cai Zi-xin. The Basis of the Robotics [M]. Beijing: Machinery Industry Press, 2009.
- [4]. Chen Liping. Kinematics Analysis and ADAMS Application for Mechanical System [M]. Tsinghua University Press, Beijing, China, 2005.
- [5]. Wu, Z.B., Wang, Z.J.; Industrial Robot. Huangzhong University of Science and Technology Press, Wuhan (2006)
- [6]. Duan, J.M., Liu, L. Kinematics simulation of six degrees of freedom platform based on virtual prototyping technology. Machinery Design & Manufacture 1, 81-82 (2011)
- [7]. Zhan , X.L., Xin, H.B., Hans, P.L. Kinematics Simulation of MoToman-HP3 Robot Based on Virtual Reality. China Mechanical Engineering 16, 1953-1954 (2010)
- [8]. Zeng, J., ET AL.: Kinematics analysis and simulation for 6-rotation joint spraying robot. Machinery Design & Manufacture 6, 145-146 (2010)

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