Kinematics Analysis and Simulation of Six - DOF Industrial Robot

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Abstract *— This passage takes ABB IRB4600-60 industrial robot as the object of study, using the D-H rule to establish the kinematics coordinate system of robot, then deduce the kinematics equation and the positive and inverse solutions of the robot are obtained by combining the structural parameters of the robot. The kinematics of robot is modelled and simulated by using MATLAB Robotics Toolbox. It provides a reliable theoretical basis for the development of robot off-line programming system.*

Keywords — *industrial robot, D-H rule, kinematics simulation*

I. Introduction

With the rapid development of industrial level in the world today, the application of industrial robots is more and more extensive and has gradually penetrated into the manufacturing, construction, mining, medical, health, life, services and other industries. The stable and reliable operation of industrial robots has brought great benefits to the repetitive work of enterprises. Therefore, the research and development of industrial robots has drawn more and more attention in today's society. Study on the kinematics of the robot is the basis of the robot system, which is of great significance to the development of the robot control system and the off-line programming system.

In this paper, the ABB IRB4600-60 industrial robot is taken as the object of study, and the robotic kinematics is analyzed by using the D-H rule. The robot is simulated and analyzed by using MATLAB Robotics Toolbox to verify the correctness of robotic kinematics, which provides a theoretical basis for further study.

II. Establishment of D-H coordinate system

At present, most industrial robots adopt D-H rule for kinematic modelling. The D-H rule was originally proposed by Denavit and Hartenberg in a paper, and then became a standard method of robotic modelling. The D-H rule is used to analyze the kinematics of the robot. It is necessary to establish a coordinate system for each joint axis of the robot and obtain the homogeneous coordinate transformation matrix of the adjacent two links. Then according to the recursive method, the kinematic equations of the robot are deduced, and the positive and inverse solutions are obtained by combining the relative structural parameters of the robot.

The D-H coordinate system is constructed as follows:(1) Let the coordinate origin of the coordinate system $\{i\}$ be the intersection of the axis of the joint i and the axis of the joint axis i and $i+1$ or be the intersection of the two axis.(2) Let the direction of the Z_i axis is the same as the joint axis .(3) Let the direction of the X_i axis is coincident with the common vertical of the joint axis i and $i+1$ and the direction is from i to $i+1$.(4) The direction of the Y_i axis is determined by the right hand rule based on the X_i and Z_i axes.

In this paper, the ABB IRB4600-60 industrial robot is taken as the object of study, according to the rules above to establish the coordinates of the system, as shown in Figure 1:

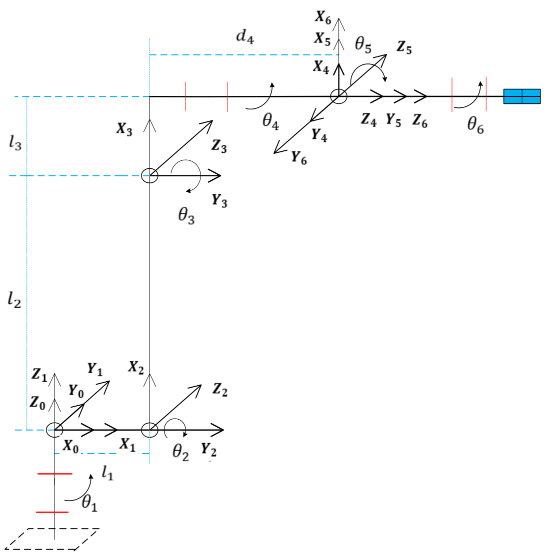

Fig. 1 kinematic coordinate system of ABB robot

The length of the link l_i is the distance between the common vertical line of the joint axes i and $i+1$, torsion angle of connecting rod α_i is the angle between the joint axes i and $i+1$, the distance between two connecting rods d_i is the distance between the two vertical lines l_i and l_{i-1}, that is, the distance between X_i and X_{i-1},the joint angle θ_i is the angle between l_i and l_{i-1}, that is, the angle between X_i and X_{i-1}.

From the parameters above and the structural parameters of the target robot itself, the D-H parameter list of the ABB IRB4600-60 industrial robot can be listed as shown in table 1:

TABLE I
ABB IRB4600-60 robot D-H parameter table

Joint i	θ_i (°)	l_{i-1} (mm)	d_i (mm)	α_{i-1} (°)	Range (°)
1	θ_1	0	0	0	−180~180
2	θ_2	l_1=175	0	−90	−90~150
3	θ_3	l_2=900	0	0	−180~75
4	θ_4	l_3=175	d_4=960	−90	−400~400
5	θ_5	0	0	90	−125~120
6	θ_6	0	0	−90	−400~400

III. KINEMATICS ANALYSIS OF THE ROBOT.

A. *Forward kinematics analysis*

The problem of forward kinematics is to determine the position and attitude of the end effector in terms of the values of the given robot joint variables. The homogeneous coordinate transformation matrix of the coordinate system $\{i\}$ to the coordinate system $\{i+1\}$ can be represented by A_i .The general formula of robot linkage coordinate transformation can be obtained by the rules above, as shown below:

$$A_i = \begin{bmatrix} cos\theta_i & -sin\theta_i & 0 & l_{i-1} \\ sin\theta_i cos\alpha_{i-1} & cos\theta_i cos\alpha_{i-1} & -sin\alpha_{i-1} & -sin\alpha_{i-1} d_i \\ sin\theta_i sin\alpha_{i-1} & cos\theta_i sin\alpha_{i-1} & cos\alpha_{i-1} & cos\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation matrix of each joint axis can be obtained by substituting the D-H parameter of the target robot into the general formula, as shown below:

$$A_1 = \begin{bmatrix} cos\theta_1 & -sin\theta_1 & 0 & 0 \\ sin\theta_1 & cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} cos\theta_2 & -sin\theta_2 & 0 & l_1 \\ 0 & 0 & 1 & 0 \\ -sin\theta_2 & -cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} cos\theta_3 & -sin\theta_3 & 0 & l_2 \\ sin\theta_3 & cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_4 = \begin{bmatrix} cos\theta_4 & -sin\theta_4 & 0 & l_3 \\ 0 & 0 & 1 & d_4 \\ -sin\theta_4 & -cos\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_5 = \begin{bmatrix} cos\theta_5 & -sin\theta_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ sin\theta_5 & cos\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_6 = \begin{bmatrix} cos\theta_6 & -sin\theta_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -sin\theta_6 & -cos\theta_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The result of the equation of the forward kinematics of the robot is:

$$^0_6T = A_1A_2A_3A_4A_5A_6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Calculated by MATLAB can be obtained:

$$\begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = \begin{bmatrix} c_1[c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5c_6] + s_1(s_4c_5c_6 + c_4s_6) \\ s_1[c_{23}(c_4c_5c_6 - s_4s_6) - s_{23}s_5c_6] - c_1(s_4c_5c_6 + c_4s_6) \\ -s_{23}(c_4c_5c_6 - s_4s_6) - c_{23}s_5c_6 \end{bmatrix}$$

$$\begin{bmatrix} o_x \\ o_y \\ o_z \end{bmatrix} = \begin{bmatrix} c_1[c_{23}(-c_4c_5c_6 - s_4s_6) + s_{23}s_5c_6] - s_1(s_6c_5s_4 - c_4c_6) \\ s_1[-c_{23}(c_4c_5s_6 + s_4c_6) + s_{23}s_5s_6 + c_1(s_6c_5s_4 - c_4c_6)] \\ s_{23}(c_4c_5s_6 + s_4c_6) + c_{23}s_5s_6 \end{bmatrix}$$

$$\begin{bmatrix} a_z \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} c_1(-c_{23}c_4s_5 - s_{23}c_5) - s_1s_4s_5 \\ -s_1(c_{23}c_4s_5 + s_{23}c_5) + c_1s_4s_5 \\ s_{23}c_4s_5 - c_{23}c_5 \end{bmatrix}$$

$$\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} c_1(l_3c_{23} - d_4s_{23} + l_2c_2 + l_1) \\ s_1(l_3c_{23} - d_4s_{23} + l_2c_2 + l_1) \\ -l_3s_{23} - d_4c_{23} - l_2s_2 \end{bmatrix}$$

In the equation, $c_i = cos\theta_i$,$s_i = sin\theta_i$, $c_{23} = \cos(\theta_2 + \theta_3)$, $s_{23} = \sin(\theta_2 + \theta_3)$.

B. *Inverse kinematic analysis*

The problem of inverse kinematics is based on the position and attitude of the end effector to determine the values of the robot joint variables. The inverse kinematics is usually solved by algebraic method, geometric method and iterative method. The last two kinds of methods currently only stay in the theoretical stage because of the precision of the result is not high. In this paper, the algebraic inverse method is used to solve the inverse kinematics. Although the process is complex, we can find a high precision closed solution.

According $^0_6T = A_1A_2A_3A_4A_5A_6$ to $A_1^{-1}(\theta_1)\,^0_6T = A_2A_3A_4A_5A_6$,By the corresponding element of the matrix is equal on both sides can be obtained θ_1. In the same way, we can find out θ_2 θ_3 θ_4 θ_5 θ_6.

In addition, additional four sets of solutions may be present due to the reversal of the joint axis, as shown below:

$$\theta_4^* = \theta_4 + 180^\circ$$
$$\theta_5^* = -\theta_5$$
$$\theta_6^* = \theta_6 + 180^\circ$$

The inverse solutions of six axis industrial robots are generally no more than 16 groups. But if the six-axis industrial robot meets the Pieper criterion, that is, when the three adjacent joints of the robot intersect at one point or three axes are parallel, there are 8 sets of inverse solutions, and closed solutions can be obtained. There are 8 sets of inverse solutions and closed solutions can be obtained. The ABB IRB4600-60 robot exactly meets the Pieper criterion, so there are 8 sets of inverse solutions. Although there are 8 sets of inverse solutions, they do not satisfy the motion range of the robot. Therefore, in the case of satisfying the motion range of the robot, we need to select a set of optimal solutions. There is no uniform standard for the selection of the optimal solution. In the practical application of the process, we can choose a solution closest to the position of the manipulator according to the range of motion, collision and machining requirements of the robotic joint axis. Generally, in the case of collision avoidance, the optimal solution of the robot is selected according to the "shortest travel" criterion.

IV. KINEMATICS SIMULATION OF THE ROBOT

MATLAB is a powerful, highly efficient simulation software, including matrix operations, array operations, numerical analysis and other functions. In addition, it also contains a wealth of library and function commands as well as dozens of tool kits, such as Robotics Toolbox, which is widely used in the field of industrial robot kinematics verification and simulation.

A. The establishment of robot kinematics model

The kinematics model of ABB IRB4600-60 industrial robot is created by using Link function and Robot function in Robotics Toolbox. In the MATLAB environment, a model diagram of the ABB IRB4600-60 industrial robot was created, as shown in Figure 2:

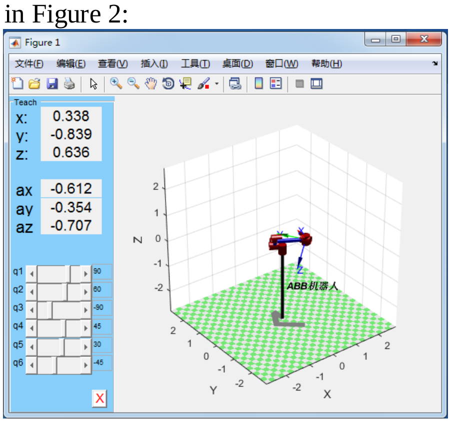

Fig.2 the model of the ABB robot

B. Verification of robot kinematics model

The 6 sliders in Figure 2 represent the 6 joint angles of the robot. By adjusting each slider to set the robotic joint angles to obtain the corresponding robot end actuator position and posture. By adjusting the sliderq_1、q_2、q_3, you can change the position of the robot end effector. By adjusting the slider q_4、q_5、q_6, you can change the posture of the robot end effector. Figure 2 is a robot model with joint angles of $q_1 = 90^{\circ}$, $q_2 = 60^{\circ}$, $q_3 = -90^{\circ}$, $q_4 = 45^{\circ}$, $q_5 = 30^{\circ}$, $q_6 = 45^{\circ}$.

From Fig. 2, given the angle of the joint, we can intuitively read the position and posture of the robot end actuator. The given joint angle and robot related parameters are substituted into the kinematics equations and a matrix representing the position and posture of the robotic end effector can be obtained by MATLAB calculation, as shown in figure 3,the values of the them is very close and the correctness of ABB - IRB4600 robot kinematics model can be verified.

```
p0 =

   -0.6124   -0.5000   -0.6124    0.3382
   -0.3536    0.8660   -0.3536   -0.8392
    0.7071   -0.0000   -0.7071    0.6364
         0         0         0    1.0000
```

Fig. 3 matrix representation of robot position and attitude

V. CONCLUSIONS

This paper takes ABB IRB4600-60 industrial robot as the object of study. The kinematics modelling is carried out by D-H rule and the positive and negative solutions of the robot are obtained. The model of robotic is created and the correctness of the kinematics model of robot is verified by MATLAB Robotics Toolbox, which laid a reliable theoretical foundation for the research of off-line programming system.

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