Kinematic simulation and verification based on six-axis tandem robotic arm

Zhiyu An[1,*]
Wuhan University of Technology, Wuhan, China

ABSTRACT

Nowadays, with the continuous development of technology, industrial robots are widely used in the manufacturing industry, where tandem robots are working with increasing capabilities. Robot kinematics aims to study in depth the laws of robot motion in a specific frame of reference and as an important function of time, as well as the correlation between the spatial structure of robot joint variables, robot end-effector positioning and pose, and their internal interactions. It takes into account not only the forces and moments of robot motion, but also the temporal characteristics of robot motion. The purpose of this paper is to study the kinematic characteristics of the robot based on the desktop-level six-axis tandem robot GLUON-6L3. First, the DH joint coordinate system of this six-degree-of-freedom robot arm is constructed by the DH parameter method, and the related basic parameters of the linkage are defined. Then, the expression of the chi-square transformation matrix is given, and finally, the kinematic solution results of the robot are verified by using Matlab software to ensure its accuracy.

Keywords: Tandem robots, six degrees of freedom, position and posture, kinesiology

1. INTRODUCTION

Due to the rapid development of science and technology, artificial intelligence technology has long been used as a symbol and manifestation of a country's level of science and technology, it has not only gained universal use in many areas of society, but also along with the development of China's economy and the popularity of electronic computers, high technology is also moving from industrial production to people's lives, this trend of automation is changing the human labor force, not only can significantly improve the quality of products, but also can effectively reduce the input of labor, thus saving overall costs. It is thus clear that the development of robotics is crucial for society. Therefore, if a country wants to improve its comprehensive innovation capability, then it must pay attention to the development of robotics. As shown om Figure 1, robot is a multi-functional, reprogrammable machine with autonomous positioning and control, which can be designed to perform different tasks according to different tasks, covering to many fields such as machine, intelligent hardware, algorithm, structure, system engineering design, robot kinematics analysis, dynamics analysis, trajectory planning and path planning[1].

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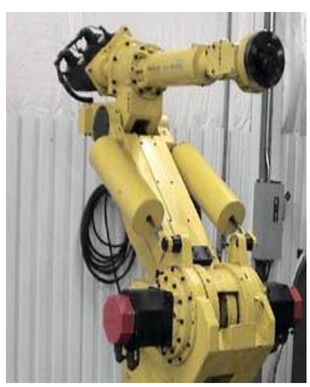

Fanuc manipulator

Hexapod

Figure 1. Series and parallel robots

*327093042@qq.com

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By planning a reasonable robot hand part posture, the activities of the AI can be effectively regulated so that all its major joints can move in a coordinated manner, and the specific amount of variation of all major joints of the AI can be calculated based on the robot hand part posture data information, thus ensuring that the robot can work safely and stably [2]. Mastering the hand part pose velocity of an AI helps to achieve accurate positioning of the key. Dynamics studies the interaction of the AI's motion state parameters with the force relationships of other major joints and provides the AI with accurate acceleration and velocity parameters. In order to ensure that it can move at the optimal acceleration and frequency, the actuator needs to have sufficient forces and moments to propel its own linkages and joints. For this purpose, a dynamics equation that can reflect the dynamic characteristics of the robot needs to be constructed to ensure the optimal propulsion force required for each joint. To ensure safety, AI needs to build a sound dynamics model in order to monitor the robot and the operator's impact with each other in real time and adopt an effective control strategy to ensure that the impact does not cause damage to the operator.

Robots can be divided into tandem robots and parallel robots according to the form of mechanism [3], the former having the characteristics of large working space, high operational flexibility, lower rigidity, smaller load, and the ability to accumulate and amplify deviations, while the latter having the characteristics of higher rigidity, higher load, less easy accumulation of deviations, smaller working space, and smaller posture area. The purpose of this paper is to provide insight into the structural characteristics of the Gluon_6l3 six-axis tandem robotic arm and its influencing factors through kinematic analysis.

With the continuous improvement of Pieper [4] standard, the configuration of tandem automation robots has also changed dramatically. The seven-degree-of-freedom surgical robot of Da Vinci Systems, the UR10 automation robot developed by Yu'ao Automation Engineering Robotics Ltd. and the "Divine Knife Huatuo" surgical automation robot of Shanghai Jiaotong University are no longer limited to Pieper standard, but can be applied to various complex surgical environments more flexibly.

1.1 Status of foreign research

Since tandem robots are gradually being used in various industries, many research institutes and companies are developing efficient and intelligent tandem robots. As for the development of industrial tandem articulated robots, the first paper on repetitive general-purpose robots was written and published by Devol in the United States in 1954, back in the early 1950s. The paper brought the concept of industrial robotics to the forefront of people's minds at the time. Today, the concept of an automated robot is recognized by international standards as an operable machine equipment with multiple functions, which can be programmed to be intelligent, has several articulated axes, can control positions, and can replace humans in the management of any material, appliance, part or specialized mechanical device to accomplish tasks according to human wishes.

Since 1958 the first prototype of a digitally controlled industrial robot for production applications was developed by the American company United Controls. UNIMATION Group in the United States officially marketed its first robot for industrial use in 1959. So far, the main companies manufacturing robots for advanced industrial use in the world are Germany and Switzerland in Europe and Japan in Asia, ABB in Sweden, KUKA and CLOOS in Germany, and COMAU in Italy, one of the largest companies in Europe [5]. The main Japanese companies are OKURA Corporation, Kawasaki Heavy Industries, Yaskawa, FANUC Corporation, Panasonic, etc. Among them, ABB of Sweden, KUKA of Germany and FANUC and Yaskawa of Japan occupy the majority of the market share [6].

South Korea and Germany have a huge presence in the global field of industrial production automation robots. These automated machinery and equipment are mainly used in the production of automotive parts, and they can play an important role in many toxic and harmful jobs, providing great convenience and efficiency for human beings. Along with the 4.0 industrial revolution, industrial robots are developing rapidly in automotive production lines, and it is foreseeable that in the near future, it will become a fully intelligent product line [7].

1.2 Current status of domestic research

China's industrial robots are currently in a state of fast catching up with the international advanced level because the related research is slower than that of developed countries. China's robots started in the early 1970s and have been developed for more than 40 years since then. After laboratory design and development in the 1970s and 1980s, industrial robots were initially realized and reached a practical level in the 1990s.

In 1972, under the guidance of national policies, China started the research and development of industrial robots. During the "Seventh Five-Year Plan" period, government departments actively promoted the research and development of industrial robots in China, and made significant progress in hardware and basic knowledge. Over the years, we have continued to explore and research and become familiar with the process technology of various industrial robots, involving mechanical structure, propulsion drive structure, operation control system, etc., and have developed a series of high-performance industrial robot prototypes. Industrial production robotics has evolved into applications such as painting, arc welding and mobility, and has developed some major components and control systems that allow for small production runs.

In the mid-1990s, in order to better develop and apply welding robots, the country focused on researching related technologies, including key equipment manufacturing, engineering support and field operation. Over time, the industrial robots independently researched and developed in China have gradually achieved mass production, thus realizing the transition from commercialization to industrialization.

Our enterprises have been able to independently design and produce right-angle coordinate system robots, planar joint robots, spot and arc welding robots, palletizing robots and AVG active guidance vehicles and many other models of goods, and some products have occupied the domestic market and exported abroad.

The parameter level of China's industrial robots has basically met the domestic demand, but the overall level still needs to be further improved, in terms of stability and processing accuracy and other parameter indicators are still a large gap with the industry's leading counterparts, in the reducer and other key equipment components can not completely achieve self-production, and in the performance is also inferior to foreign counterparts, still need to import a large number of foreign components. At the same time, most of the new demand for industrial robots in the domestic market each year is still occupied by foreign enterprises. China's robotics industry still has a long way to go.

2. ROBOT KINEMATICS ANALYSIS METHODS

Robot kinematics aims to study in depth the motion of a robot in a specific frame of reference and as a function of duration, without considering the forces and moments to which it is subjected [8]. It uniquely represents the spatial characteristics of the robot as a function of duration and focuses on an in-depth study of the correlation between the spatial structure of the robot's joint variables and the robot's end-effector position and attitude aspects in order to obtain more accurate simulation results of the robot's motion. The motion of a robot is composed of linkages and joints, whose interconnections determine the robot's kinematic properties [9]. Therefore, the study of robot kinematics is to analyze the variation in the spatial structure of these links and joints, as well as their internal interactions, in order to better describe the robot's state of motion. And a set of rules defining the coordinate system is given in order to accurately describe and express the poses of the object [10].

2.1 Two types of problems in kinesiology research

As shown in Figure 2,in the study of robot kinematics, when the geometric shape parameters and joint angle vectors of the rod are known, we can use the chi-square transformation to determine the position and attitude of the manipulator end-effector corresponding to a stable reference coordinate system. However, if we do not know the geometric parameters of the rod, and given the desired position and attitude, can we use kinematic methods to achieve this goal? If so, how many forms will the manipulator have to meet the corresponding requirements?

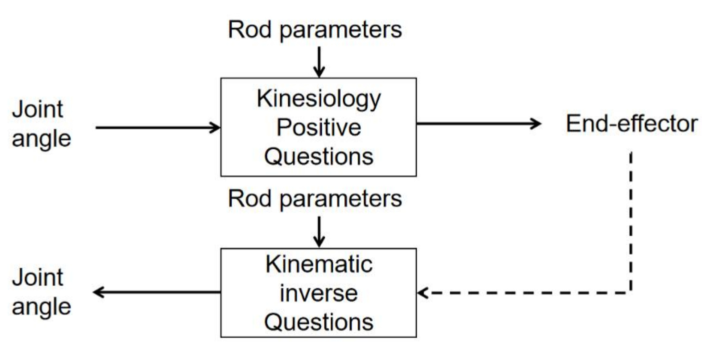

Figure 2. Two types of problems in kinesiology research

2.2 Expression of position and gesture

2.2.1 The position of the point indicates

In the Cartesian coordinate system {A},as shown in Figure 3, the orientation of any point P should be expressed as a 3 × 1 position vector, where the upper left corner represents the chosen reference coordinate system in order to better describe the position information in space:

$$^{A}P = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \tag{1}$$

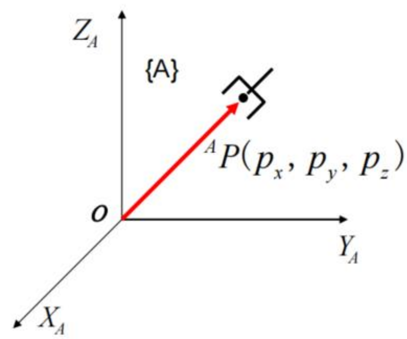

Figure 3. Description of the location of the point

2.2.2 Representation of the gesture

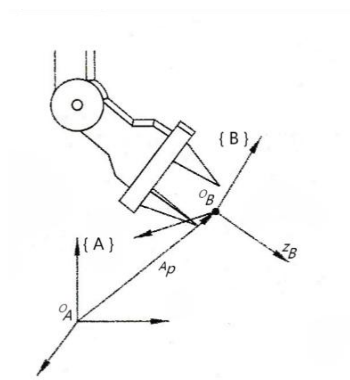

Figure 4. Position and attitude of a rigid body

The coordinate system {A} can be used to describe the rigid body's poses, as shown in Figure 4, and the coordinate system {B} can also be used to describe the shape of the rigid body.

The pose corresponding to {A} can be expressed through the three basis vectors x_B, y_B, and z_B of the coordinate system {B}, and the components of all three basis vectors can be expressed in a 3 × 3 matrix equation, namely [$^{A}x_B$ $^{A}y_B$ $^{A}z_B$]. where:

$$^{A}_{B}R = [^{A}x_B \quad ^{A}x_B \quad ^{A}x_B] = \begin{bmatrix} x_B \cdot x_A & y_B \cdot x_A & z_B \cdot x_A \\ x_B \cdot y_A & y_B \cdot y_A & z_B \cdot y_A \\ x_B \cdot z_A & y_B \cdot z_A & z_B \cdot z_A \end{bmatrix} \tag{2}$$

The basis vector is a unit vector whose dot product can be expressed as the cosine of the angle between the two unit vectors, so the above equation can be expressed as:

$$^{A}_{B}R = \begin{bmatrix} cos\,(x_A \cdot x_B) & cos\,(x_A \cdot y_B) & cos\,(x_A \cdot z_B) \\ cos\,(y_A \cdot x_B) & cos\,(y_A \cdot y_B) & cos\,(y_A \cdot z_B) \\ cos\,(z_A \cdot x_B) & cos\,(z_A \cdot y_B) & cos\,(z_A \cdot z_B) \end{bmatrix} \tag{3}$$

${}^{A}_{B}R$ is the rotation matrix between the coordinate system {B} and {A}; As shown in Figure 5, each of its components can be represented by the direction cosine as a way to describe the relationship between them.

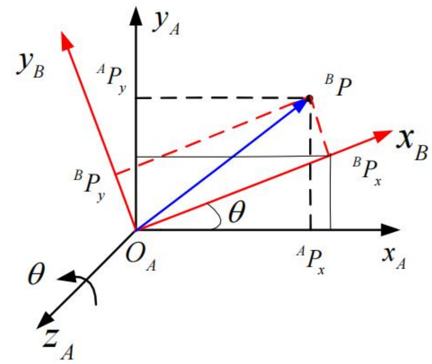

Figure 5. Rotating coordinate system

The coordinate system {B} shown in Figure 5 above can be obtained by rotating the coordinate system {A} around the z-coordinate axis by an angle of θ. The component of the vector ${}^{B}P$ in the {B} coordinate system in the coordinate system {A} is:

$$\begin{cases} {}^{A}P_x = {}^{B}P_x cos\theta - {}^{B}P_y sin\theta \\ {}^{A}P_y = {}^{B}P_x sin\theta + {}^{B}P_y cos\theta \\ {}^{A}P_z = {}^{B}P_z \end{cases} \tag{4}$$

Written in matrix form as:

$$\begin{bmatrix} {}^{A}P_x \\ {}^{A}P_y \\ {}^{A}P_z \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} {}^{B}P_x \\ {}^{B}P_y \\ {}^{B}P_z \end{bmatrix} \tag{5}$$

where Rot(z,θ)= $\begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is the rotation matrix.

If the coordinate system {B} can be obtained through one of the axes of the coordinate system {A}, then the rotation matrix around the x, y and z axes is as follows:

Rotation matrix around x-axis: Rot(x,θ)= $\begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta & -sin\theta \\ 0 & sin\theta & cos\theta \end{bmatrix}$

Rotation matrix around y-axis: Rot(y,θ)= $\begin{bmatrix} cos\theta & 0 & sin\theta 0 \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix}$

Rotation matrix around z-axis: Rot(z,θ)= $\begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$

The position and pose of the coordinate system {B} with respect to {A} can be represented by a set of four-vector matrices [R P], as shown in Figure 6 below. where R denotes the pose of {B} with respect to {A} and P denotes the position of the origin of {B} with respect to {A}.

As shown in Figure 6, we can describe the {B} coordinate system with respect to the {A} coordinate system as:

$$\{B\}=\{{}^{A}_{B}R \; {}^{A}P_{BORG}\} \tag{6}$$

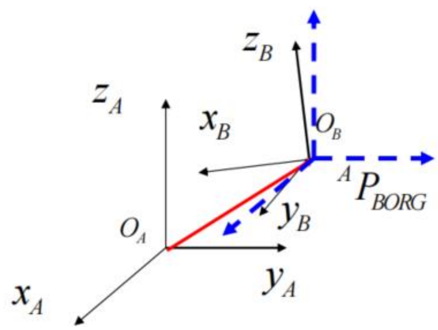

Figure 6. Rotation and translation of coordinate systems

2.3 Coordinate transformation

2.3.1 Translational transformation of coordinate systems

If the coordinate system {A} and the coordinate system {B} have the same locus, but their origins do not coincide, as shown in Figure 7, then the displacement vector $^{A}P_{BORG}$ is the amount of their translation compared to the origin.

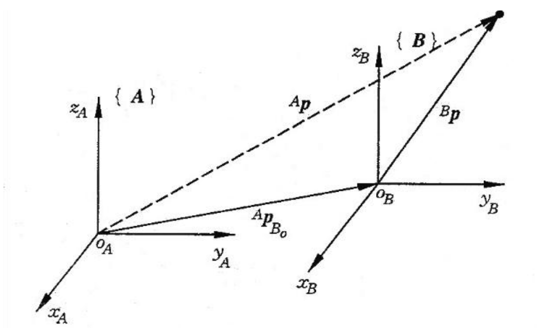

Figure 7. Translational transformations

The position vector of the point P in the two coordinate systems satisfies the following equation:

$$^{A}P = {}^{B}P + {}^{A}P_{BORG} \tag{7}$$

2.3.2 Rotational transformation of coordinate system

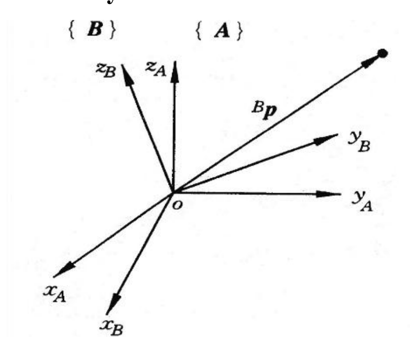

Figure 8. Rotational transformation

If the coordinate systems {A} and {B} have the same origin, but they have different poses, as shown in Figure 8, then the position vector of the point P in the two coordinate systems can be expressed in the following way:

$$^{A}P = {}^{A}_{B}P \cdot {}^{B}P \tag{8}$$

$$^{A}_{B}R = {}^{A}_{B}R^{-1} = {}^{A}_{B}R^{T} \tag{9}$$

2.3.3 Composite transformation of rotation and translation

In general, the origins of the two coordinate systems {A} and {B} neither coincide nor have different postures. As shown in Figure 9, in this case for any point P in the two coordinate systems the vector has the following expression:

$$^{A}P = {}^{A}_{B}P \cdot {}^{B}P + {}^{A}P_{BORG} \tag{10}$$

$$^{C}P = {}^{C}_{B}R \cdot {}^{B}P = {}^{A}_{B}R \cdot {}^{B}P \tag{11}$$

$$^{A}P = {}^{C}P + {}^{A}P_{CORG} = {}^{A}_{B}R \cdot {}^{B}P + {}^{A}P_{BORG} \tag{12}$$

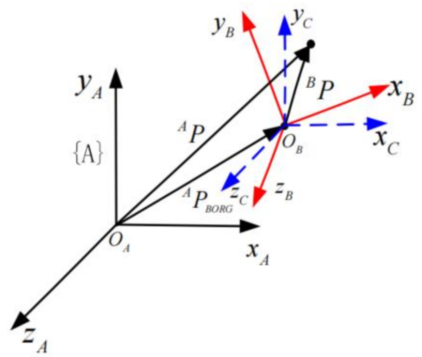

Figure 9. Composite transformation of rotation and translation

2.4 Establishment of D-H joint coordinate system

2.4.1 Principles of Coordinate System Establishment

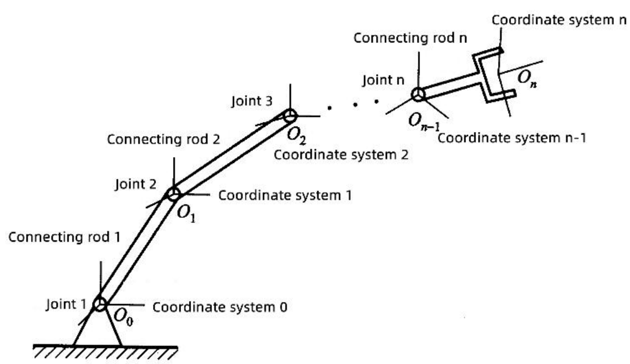

Figure 10. Classification of robot joint coordinate system markings

In order to construct the robot joint coordinate system, we should follow the following principle: all the bars should form a set of Cartesian coordinate systems (x_i, y_i, z_i) at the joint axes as shown in Figure 10, where i=1, 2, ..., n, which denote the number of degrees of freedom, respectively, plus the base coordinate system, which has a total of (n+1). The $\sum O_0$ coordinate system is the inertial coordinate system of the robot, which is able to be set at random on the base but needs to ensure that the z_0 axis coincides with the main axis of joint 1 and the position and orientation can be chosen arbitrarily, while the n-joint coordinate system is able to be set at any position of the hand but needs to ensure that zn is perpendicular to zn-1. Figure 10 shows the different markings of the robot joint coordinate system [11, 12].

2.4.2 Coordinate system establishment method

Using the method of D-H coordinate system, the origin O_i should be set at the intersection of l_i and A_i+1 main axis; z_i axis should coincide with A_i+1 joint axis, which can refer to any direction; x_i axis should coincide with the common normal l_i, which refers to pointing from A_i main axis to A_i+1 main axis along l_i; y_i axis should be set according to the right-hand rule.

The length l_i of the bar represents the spacing along the x_i axis, from the intersection line of the z_i-1 axis to O_i; the torsion angle α_i represents the rotation around the x_i axis, from the z_i-1 axis to z_i; the bar offset d_i represents the spacing along the z_i-1 axis, from the intersection line of the x_i axis to the origin of the $\sum O_i$-1 coordinate system; and the rotation angle θ represents the rotation around the z_i-1 axis, from the x_i-1 axis to x_i. The creation of the robot joint coordinate system is shown in Figure 11 below [13, 14].

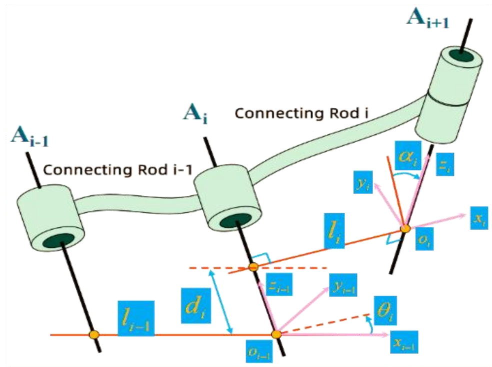

Figure 11. Establishment of joint coordinate system

3. SIX-AXIS ROBOT KINEMATICS ANALYSIS

3.1 GLUON-6L3 six-axis robotic arm

The purpose of this paper is to conduct kinematic analysis based on the desktop-level six-axis robotic arm GLUON-6L3, which has an arm length of up to 425mm and an end load of up to 500g, and the QDD Lite series runner made of materials that can effectively reduce the development cost of advanced mechanical equipment, so it is widely used in education, laboratories, research institutes, competitions and other fields. The model and dimensions of the robot arm are shown in Figure 12 below. It is a robotic arm with six degrees of freedom joints, which consists of six connecting rods, each equipped with a motor at the joint, allowing it to move freely in the motion space and thus achieve precise control at any point.

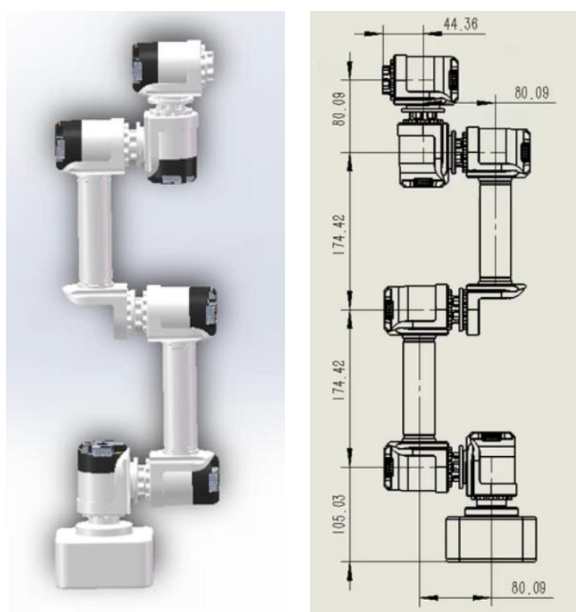

Figure 12. Robotic arm model and dimensions

3.2 Establish D-H joint coordinate system

As shown in Figure 13 below, the initial position of the arm is set to be straight and oriented upward, with joints at each motor, and the joint numbers are joint 1, joint 2, joint 3, joint 4, joint 5, and joint 6 from top to bottom and from left to right in order. The lowermost part of the robot arm is the base, between the base and joint one is the link 0, between joint one and joint two is the link 1, between joint two and joint three is the link 2, between joint three and joint four is the link 3, between joint four and joint five is the link 4, between joint five and joint six is the link 5, and between joint six and the end-effector is the link 6.

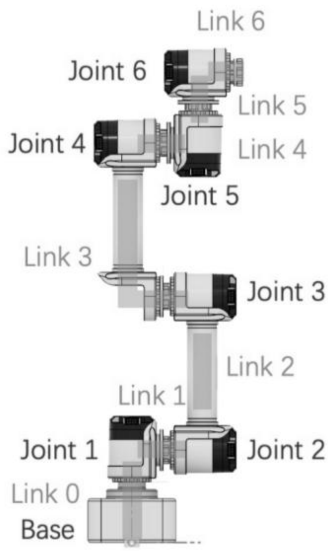

Figure 13. Determining joints and connecting rods

The axis of rotation of each joint is called the z-axis, and then the origin of the ith coordinate system is found to determine the x_i-axis. If the two axes cross in parallel, the intersection point is their origin, and the x_i axis lies on the vertical line of the plane in which the two principal axes are located, in any direction. If the two main axes do not intersect, the x_i axis lies on the common perpendicular of the two main axes, and the direction can be arbitrary. The figure 14 shows the DH coordinate system established on this six-axis robot arm.

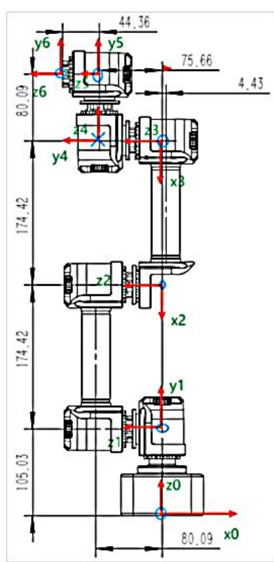

Figure 14. Establish D-H coordinate system

3.3 Kinematic problem solving

After studying the dimensional parameters of the main joints and connecting rods of the six-axis robot arm, thus solving the end-effector positional challenge, which is only a kinematic positive problem. The D-H parameter table shown in Table 1 below can be obtained from the dimensional diagram of the measured robot arm.

Table 1. Six-axis robotic arm D-H parameter table

i	θ_i	d_i	a_i	α_i	offset
1	q1	105.03	0	pi/2	0
2	q2	0	-174.42	0	-pi/2
3	q3	0	-174.42	0	0
4	q4	75.66	0	pi/2	-pi/2
5	q5	80.09	0	-pi/2	0
6	q6	44.36	0	0	0

From the above parameters of each linkage, the transformation matrix of each linkage can be calculated as follows:

$$ {}^{i-1}_{i}T = A_i = Rot(z,\theta_i) \times Trans(0,0,d_i) \times Rot(x,\alpha_i) \times Trans(\alpha_i,0,0) $$
$$ = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & 0 \\ s\theta_i & c\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c\alpha_i & -s\alpha_i & 0 \\ 0 & s\alpha_i & c\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13} $$

$$ A_i = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14} $$

Thus the total transformation of the base and end-effector of the six-axis robot arm is:

$$ {}^{0}_{6}T = A_1 A_2 A_3 A_4 A_5 A_6 \tag{15} $$

The Link function of Matlab Robotics Toolbox is used to generate the corresponding rod models from the parameters of the six rods in Table 1, and then the SerialLink function is used to link the six rod models, and finally the corresponding overall model is generated, and the fkine function is used to calculate the positive kinematic solution of this robot model, that is, the end attitude is calculated given the corresponding joint angle. The results of the created robot model are shown in Figure 15 below.

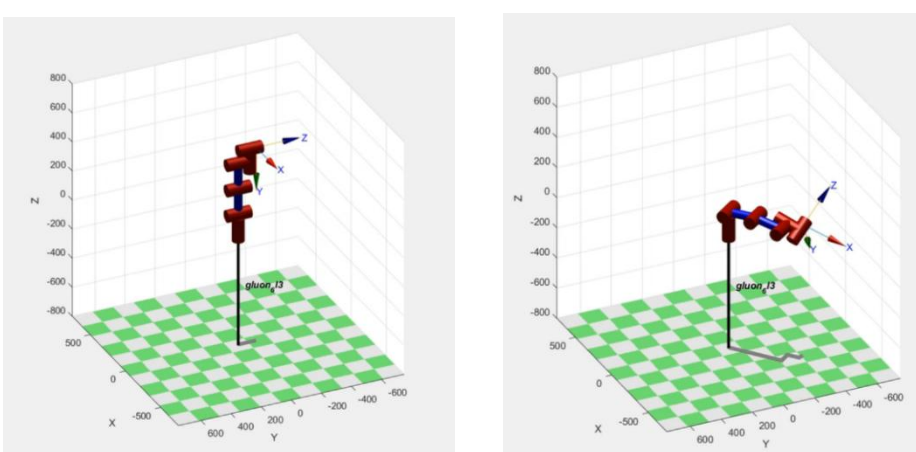

Figure 15. Modeling of robot geometric relations

From the above, it can be seen that by using the D-H method, the set relationship of this six-axis robot arm can be modeled, and when the rotation angle θ_i of each joint is given, the position of the end-effector and its attitude can be found, and this process is the positive kinematics problem solution of this robot arm; If the position and attitude of the end-effector are known and the rotation angle θi of each joint is found, this process is the solution of the inverse kinematic problem of the robot arm.

3.4 Six-axis robot arm simscape simulation and verification

By importing the frame of simscape's six-axis manipulator, the corresponding system is constructed by world coordinate system, mechanical properties and primitive solver functions. In the setting, each joint is given an input and an output, and the torque of the joint is calculated automatically. The joint Angle drive is set as input, and the joint Angle input is set as output [15].

After generating a subsystem, the system will automatically add the corresponding ports for the previously defined inputs and outputs. Then add an input for the system, at this time it is necessary to convert the signal inside Simulink to a physical signal, change the input signal to an angle signal, change the processing of the input signal to second order, and change the output signal to an angle signal; when the input angle is given a conversion should be done first, to convert a scalar signal to a vector signal, and in the output it is necessary to convert the vector signal to a scalar signal. The input will be set as shown in Figure 16 below for the process of building the system.

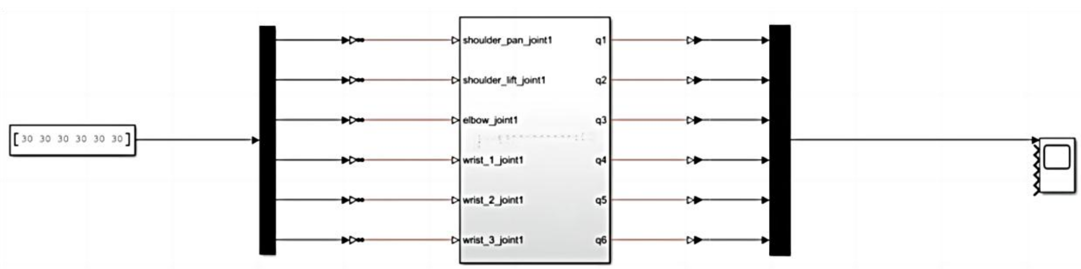

Figure 16. Build system

The positive kinematic solution of this robot model is calculated in matlab and using the fkine function, given that the angle of each joint is 30 degrees, the end pose is calculated, and the input joint angles are also given as 30 degrees in simscape, and the resulting poses of this six-axis robot arm are exactly the same, as shown in Figure 17 below.

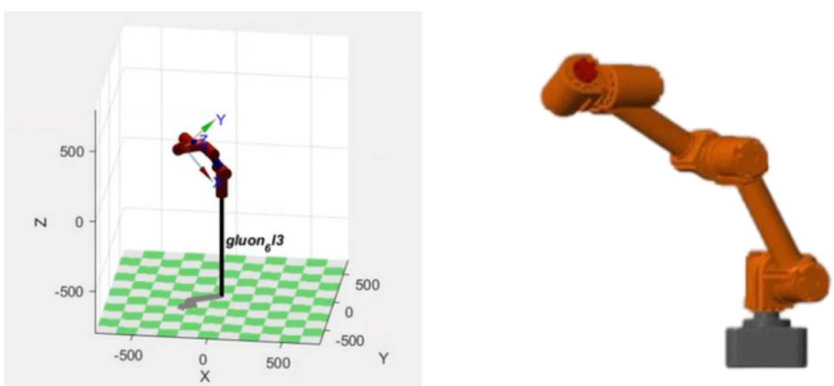

Figure 17. Verify the solution results

4. CONCLUSION

In this paper, based on the kinematic analysis of the desktop-level six-degree-of-freedom tandem robot GLUON-6L3, two types of problems in the study of robot kinematics, namely, the kinematic positive problem and the kinematic inverse problem, are firstly presented, and then the expressions of position and pose, the expressions of coordinate transformation, and how the D-H joint coordinate system are established in the robot field are introduced, followed by the establishment of the corresponding D-H joint coordinate system for this six-degree-of-freedom tandem articulated robot according to the corresponding rules, and a table of D-H parameters is listed, from which the flush transformation matrix of this six-axis robot arm is also derived. By using the Link function of Matlab Robotics Toolbox to generate the corresponding rod models from the parameters of the six rods of this robot arm, and then use the SerialLink function to link the six rod models, and finally generate the corresponding overall model. And use the fkine function to calculate the positive kinematic solution of the robot model, that is, given the corresponding joint angle to calculate the end attitude, set the angle of each joint of the robot arm to 30 degrees, the effect of the rod model, and finally import the six-axis robot arm into simscape for simulation verification. After building the complete system framework, the input angle was changed to 30 degrees as well. By comparing the two results, it can be found that the motion posture of the robot arm is exactly the same, thus verifying the correctness of the kinematic solution results of the robot arm.

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