Structure Design and Kinematic Analysis of Dual-arm Robot

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Abstract

In order to complete the handling of arms, this paper designed a dual-arm robot with master-slave relationship. By using D-H method, the dual-arm robot kinematics model were established. The position and orientation matrix of the robot is calculated by coordinate transformation. The equation of motion constraint relation of two arms coordinated operation is derived. This formula can be used to convert the pose of the handling target in the global coordinate system to the pose in the basic coordinate system of the arm. The simulation model of dual-arm robot is established by using MATLAB Robotics Toolbox. The use of toolbox for forward kinematics operation verifies the correctness of the D-H method for solving forward kinematics. The trajectory planning is simulated by using toolbox. The kinematics simulation of the dual-arm robot is carried out by using ADAMS, and the displacement, velocity and acceleration curves of the center of the end effector are obtained. By analyzing the kinematic characteristics of the dual-arm robot, the rationality of the structural design of the dual-arm robot is verified.

Keywords

Dual-arm robot; kinematics; Robotics Toolbox; trajectory simulation; ADAMS.

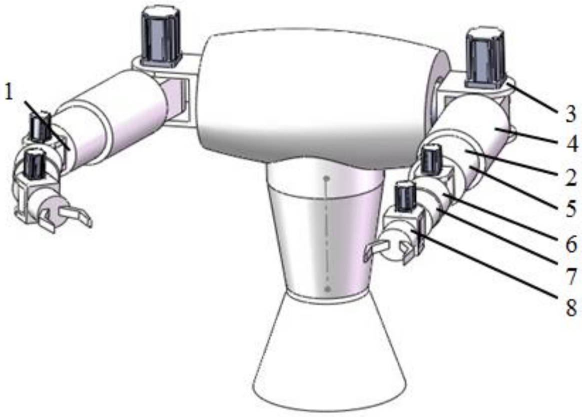
1. Introduction

Traditional single-arm industrial robots have been widely used in the industrial field. In the manufacturing industry, single-arm robots have been widely used as an alternative to manual punching, casting, welding, coating, and palletizing operations [1]. However, traditional single-arm robots are generally only suitable for the operation of rigid workpieces [2]. They are not suitable for some applications with precision assembly and fine operation. Therefore, in order to adapt to the complexity of the task and the continuous improvement of intelligence, it is necessary to design a dual arm robot with cooperative work. Due to their higher flexibility and better adaptability, dual-armed robots are more adaptable to complex and changing work environments and complex operating tasks.

Robot kinematics studies the kinematics of robots from a geometric point of view without considering the forces or moments that cause these movements [4]. Because of the more freedom and complex motion of the dual-arm robot, the kinematics analysis of the robot is an important part of the research [5].

2. Structure Design of Dual-Arm Robot

To complete the two-armed transport operation, the structure of a dual-arm robot is shown in Figure 1. The dual-arm robot is composed of a left arm and a right arm symmetrically arranged on both sides of the base body. The two arms have a master-slave relationship, and the right arm assists the left arm to complete the same object. The left arm and the right arm have 6 rotational joints, and each joint has only one rotational degree of freedom. The left arm and the right arm respectively include the first arm, the second arm, the third arm, the fourth arm, the fifth arm, and the sixth arm that are sequentially connected.



1. Left arm 2. Right arm 3. the first arm 4. the second arm 5. the third arm
6. the fourth arm 7. the fifth arm 8. the sixth arm

Fig. 1 Dual arm robot structure diagram

3. Kinematic Analysis of Dual-Arm Robot

3.1 Establishment of Coordinate System and Determination of D-H Parameters

The D-H method proposed by Denavit and Hartenberg in 1955 is a matrix method used to describe the translational and rotational relations between adjacent bars [6]. This method uses a 4x4 homogeneous transformation matrix to describe the spatial relationship between two adjacent links. The D-H method simplifies the forward kinematics calculation problem to the operation of the homogeneous transformation matrix. This matrix describes the transformation relationship of the robot end-effector with respect to the reference coordinate system.

D-H parameter definition method: Z axis along the direction of the axis of motion of the joint, X axis along the perpendicular line of two adjacent axes, Y axis is determined by the right hand rule. The four basic parameters of the DH method include: the connecting rod twist angle α is the angle between adjacent axes, the connecting rod length a is the distance between two adjacent joint axes along the vertical line, and the two connecting rod angle θ is vertical The angle between two perpendicular lines in the plane of the joint axis, the distance d between two links is the distance between two perpendicular lines along the axis of the joint.

According to the D-H method, the bar coordinate system of the dual-arm robot is established as shown in Fig. 2. The variables are set strictly according to the definition of the D-H parameter. The D-H parameter table of the connecting rod is shown in Table 1.

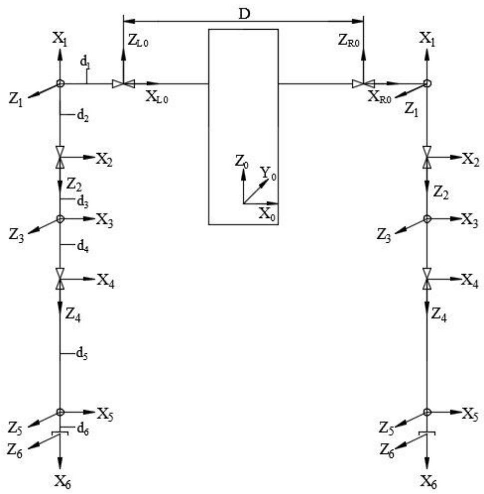


Fig. 2 The structure of the dual-arm robot

Table 1 D-H parameter list of left arm

link	θ/(º)	d/(mm)	a/(mm)	α/(º)
1	θ1	d1=85	0	-90º
2	θ2	0	0	90º
3	θ3	d3=145	0	-90º
4	θ4	0	0	90º
5	θ5	d5=100	0	-90º
6	θ6	0	d6=138	0º

Among them: (X_0, Y_0, Z_0) is the global basic coordinate system, (XL_0, YL_0, ZL_0) is the left arm basic coordinate system, (XR_0, YR_0, ZR_0) is the right arm basic coordinate system.

3.2 The Forward Kinematics Solution

The forward kinematics problem of the robot arm is the joint angle of each joint of the known robot arm, and the position of the end effector is determined. The homogenous transformation matrix ${}^{i-1}T_i$ is used to describe the position and orientation of the i-th coordinate system with respect to the (i-1)-th coordinate system.

$$
{}^{i-1}T_i = Rot(z,\theta)Trans(z,d)Trans(x,a)Rot(x,\alpha)
= \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_{i-1} & s\theta_i s\alpha_{i-1} & a_{i-1}c\theta_i \\ s\theta_i & c\theta_i c\alpha_{i-1} & -c\theta_i s\alpha_{i-1} & a_{i-1}s\theta_i \\ 0 & s\alpha_{i-1} & c\alpha_{i-1} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)
$$

In the formula, $c\theta_i = \cos\theta_i$, $s\theta_i = \sin\theta_i$, $c\alpha_{i-1} = \cos\alpha_{i-1}$, $s\alpha_{i-1} = \sin\alpha_{i-1}$.

The transformation matrix of the coordinate system of each connecting rod can be obtained by replacing the parameters of the D-H parameter table (1).

$$
{}^0T_1(\theta_1) = \begin{bmatrix} c\theta_1 & 0 & -s\theta_1 & 0 \\ s\theta_1 & 0 & c\theta_1 & 0 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^1T_2(\theta_2) = \begin{bmatrix} c\theta_2 & 0 & s\theta_2 & 0 \\ s\theta_2 & 0 & -c\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^2T_3(\theta_3) = \begin{bmatrix} c\theta_3 & 0 & -s\theta_3 & 0 \\ s\theta_3 & 0 & c\theta_3 & 0 \\ 0 & -1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^3T_4(\theta_4) = \begin{bmatrix} c\theta_4 & 0 & s\theta_4 & 0 \\ s\theta_4 & 0 & c\theta_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^4T_5(\theta_5) = \begin{bmatrix} c\theta_5 & 0 & -s\theta_5 & 0 \\ s\theta_5 & 0 & c\theta_5 & 0 \\ 0 & -1 & 0 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^5T_6(\theta_6) = \begin{bmatrix} c\theta_6 & -s\theta_6 & 0 & a_5c\theta_6 \\ s\theta_6 & c\theta_6 & 0 & a_5s\theta_6 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

The positive kinematics equation of the dual-arm robot is:

$$
{}^0T_6 = {}^0T_1(\theta_1)\,{}^1T_2(\theta_2)\,{}^2T_3(\theta_3)\,{}^3T_4(\theta_4)\,{}^4T_5(\theta_5)\,{}^5T_6(\theta_6) = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)
$$

If we set the tip of the left arm at the end of the joint, the angle of the joint is as follows: $\theta_1 = \frac{\pi}{8}$, $\theta_2 = -\frac{\pi}{8}$, $\theta_3 = \frac{\pi}{6}$, $\theta_4 = -\frac{\pi}{4}$, $\theta_5 = \frac{\pi}{5}$, $\theta_6 = \frac{\pi}{9}$. When the joint angle is replaced (2), the position matrix of the left arm manipulator can be obtained as follows:

$$
{}^{0}T_{6} = \begin{bmatrix} -0.0963 & 0.7134 & -0.6941 & -0.1283 \\ 0.8997 & 0.3608 & 0.2459 & 0.0382 \\ 0.4258 & -0.6008 & -0.6765 & 0.3196 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

3.3 Coordinate the Movement of the Constraint Relationship

The two arms carry the same rigid body together. In this operation, there is a strict motion constraint between the two arms. The positional relationship between the coordinate systems is shown in Figure 3.

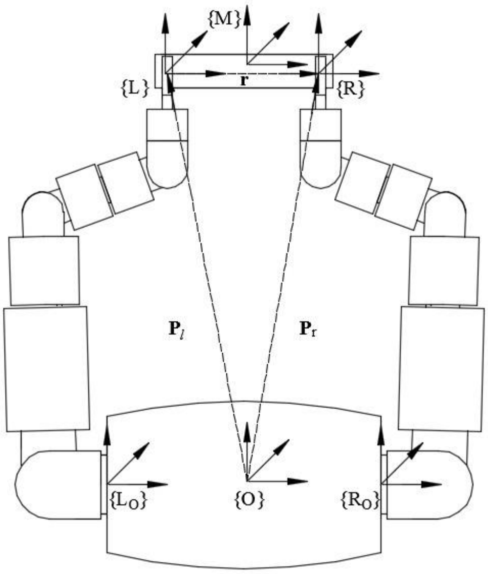


Fig. 3 Schematic representation of arms carrying the same object

The homogeneous coordinate transformation matrix ${}^{O}_{M}T$ of the conveyed object coordinate system with respect to the global base coordinate system can be expressed as:

$$ {}^{O}_{M}T = {}^{O}_{R_O}T\,{}^{R_O}_{R}T\,{}^{R}_{M}T \tag{3} $$

$$ {}^{O}_{M}T = {}^{O}_{R_O}T\,{}^{R_O}_{R}T\,{}^{R}_{M}T \tag{4} $$

1) Position constraint relationship:

From the expansion of both sides of Equation 3 and Equation 4, it is possible to derive the position matrix expression of the center of mass of the transported object in the global base coordinate system.

$$ {}^{O}_{M}P = {}^{O}_{L_O}P + {}^{O}_{L_O}R\,{}^{L_O}_{L}P + {}^{O}_{L}R\,{}^{L}_{M}P \tag{5} $$

$$ {}^{O}_{M}P = {}^{O}_{R_O}P + {}^{O}_{R_O}R\,{}^{R_O}_{R}P + {}^{O}_{R}R\,{}^{R}_{M}P \tag{6} $$

From Equation 5 and Equation 6, the position constraint relationship between the two arms can be further deduced.

$$ {}^{O}_{L_O}P + {}^{O}_{L_O}R\,{}^{L_O}_{L}P + {}^{O}_{L}R\,{}^{L}_{M}P = {}^{O}_{R_O}P + {}^{O}_{R_O}R\,{}^{R_O}_{R}P + {}^{O}_{R}R\,{}^{R}_{M}P $$

2) azimuth constraint relation:

The azimuth rotation matrix of the operated object coordinate system in the global base coordinate system is ${}^{O}_{M}R$

$$ {}^{O}_{M}R = {}^{O}_{L_O}R\,{}^{L_O}_{L}R\,{}^{L}_{M}R \tag{7} $$

$$ {}^{O}_{M}R = {}^{O}_{R_O}R\,{}^{R_O}_{R}R\,{}^{R}_{M}R \tag{8} $$

Joint vertical formula 7 and formula 8 can be used to derive the positional restraint relationship between the two arms.

$${}^{O}_{L_O}R\,{}^{L_O}_{L}R\,{}^{L}_{M}R = {}^{O}_{R_O}R\,{}^{R_O}_{R}R\,{}^{R}_{M}R$$

3) Speed constraint relationship:

In Figure 3, ***r*** is a vector that points to the {R} origin of the coordinate system from the {L} origin of the coordinate system. P_l is a vector that points to the {L} origin of the coordinate system from the {O} origin of the global basic coordinate system. P_r is a vector that points to the {R} origin of the coordinate system from the {O} origin of the global basic coordinate system. Then the complete constraint between the arms is as follows.

$$\boldsymbol{P}_l + \boldsymbol{R}_o^n(\theta_l)\cdot \boldsymbol{r} - \boldsymbol{P}_r = 0 \tag{9}$$

We perform processing about time differentiation of formula 9.

$$\left[\boldsymbol{J}_\lambda(\theta_l) + \frac{\partial\left[\boldsymbol{R}_o^n(\theta_l)\cdot \boldsymbol{r}\right]}{\partial \theta_l}\right]\cdot \dot{\theta}_l - \boldsymbol{J}_\lambda(\theta_r)\cdot \dot{\theta}_r = 0 \tag{10}$$

There is no relative movement between the arms, so the angular speed between the arms is the same. $\omega_l = \omega_s$, The following formula can be derived.

$$\boldsymbol{J}_\alpha(\boldsymbol{\theta}_l)\cdot \dot{\theta}_l = \boldsymbol{J}_\alpha(\theta_r)\cdot \dot{\theta}_r \tag{11}$$

We combine formulas 10 and 11 to derive the speed constraint relationship between the two arms.

$$\dot{\theta}_r = \begin{bmatrix} \boldsymbol{J}_\lambda(\theta_r) \\ \boldsymbol{J}_\alpha(\theta_r) \end{bmatrix}^{-1} \cdot \begin{bmatrix} \boldsymbol{J}_\lambda(\theta_l) + \dfrac{\partial\left[\boldsymbol{R}_o^n(\theta_l)\cdot \boldsymbol{r}\right]}{\partial \theta_l} \\ \boldsymbol{J}_\alpha(\theta_l) \end{bmatrix} \cdot \dot{\theta}_l$$

4. Kinematics Simulation Based on MATLAB Robotics Toolbox

MATLAB Robotics Toolbox is a function model library that contains the functional relationships between the robot's links.Using the toolbox, users can directly use function commands to establish an industrial robot parameter model, which can be simulated by kinematics, dynamics, and trajectory planning [7]. The toolbox can simulate the robot and analyze the experimental data of robot control [8].

4.1 Dual-Arm Robot Modeling

When building a double arm industrial robot model, we can use the Link ( ) function and the robot( )function and combine the D-H parameters to complete the construction of each joint. The initial position of the double arm robot is as shown in Figure 4, assuming that the angle of each joint is zero at the initial moment of the double arm robot.

4.2 Positive Kinematics Solution

The use of fkine ( ) function in the solution of positive kinematics. Set the moment of the left arm at the end of the joint as follows: $\theta_1=\frac{\pi}{8}$, $\theta_2=-\frac{\pi}{8}$, $\theta_3=\frac{\pi}{6}$, $\theta_4=-\frac{\pi}{4}$, $\theta_5=\frac{\pi}{5}$, $\theta_6=\frac{\pi}{9}$

The kinematics solution statement is as follows:

```
L1=Link ('d',0.085,'a', 0,'alpha',-pi/2);
L2=Link ('d', 0,'a', 0,'alpha' ,pi/2);
L3=Link ('d',0.145, 'a', 0,'alpha' ,-pi/2);
L4=Link ('d',0,'a', 0,'alpha' ,pi/2);
L5=Link ('d',0.100, 'a', 0,'alpha' ,-pi/2);
L6=Link ('d', 0,'a', 0.138, 'alpha' ,0);
robot=SerialLink([L1, L2,L3,L4,L5,L6]);
robot.name='Left arm ';
```

T=robot.fkine([pi/8 -pi/8 pi/6 -pi/4 pi/5 pi/9])

We can calculate the final pose T.

$$T = \begin{bmatrix} -0.0963 & 0.7134 & -0.6941 & -0.1283 \\ 0.8997 & 0.3608 & 0.2459 & 0.0382 \\ 0.4258 & -0.6008 & -0.6765 & 0.3196 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

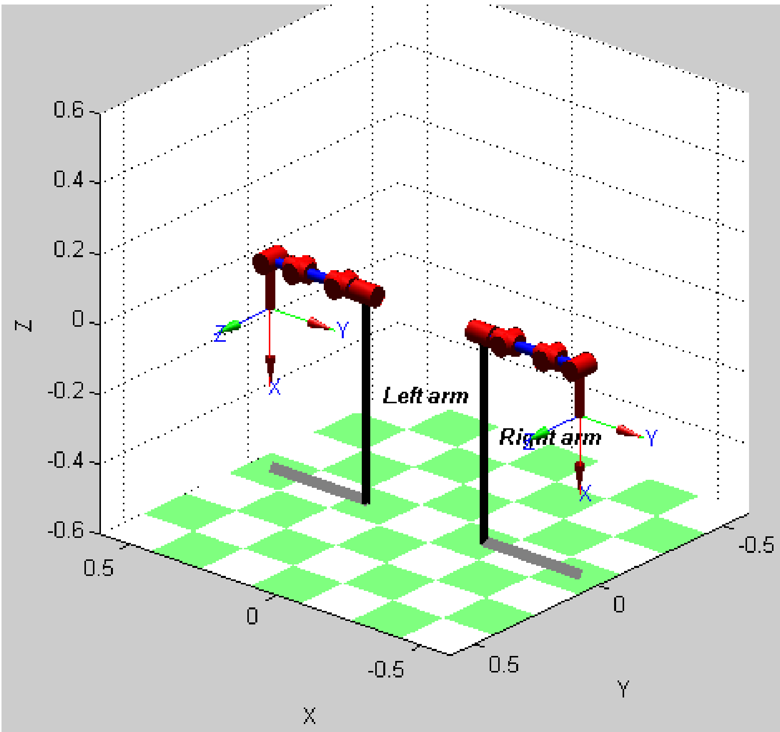


Figure 4 Initial position of the dual-arm robot

4.3 Trajectory Simulation Based on MATLAB Robotics Toolbox

Trajectory planning refers to calculating a continuous motion trajectory according to the task's motion requirements [9].The following is based on the MATLAB Robotic Toolbox to simulate the motion curve of the left arm.

Set the angle between the initial and final positions of the joint: q1=([0 0 0 0 0 0 0]), q2=([pi/8 -pi/8 pi/6 -pi/4 pi/5 pi/9]). Using the fifth-degree polynomial interpolation function, the trajectory between the starting point and the ending point of the robot in the joint space is calculated, and the relationship between the angle, angular velocity, and angular acceleration of each joint from time q1 to time q2 is obtained.

The simulation program is as follows:

```
t= [0:0.2:5];
q1= ([0,0,0,0,0,0]);
q2= ( pi/8 -pi/8 pi/6 -pi/4 pi/5 pi/9]);
[q qd qdd] =jtraj(q1,q2,t);
```

The curves of angle, angular velocity and angular acceleration of each joint are plotted with time, as shown in Figure 5, Figure 6 and figure 7.

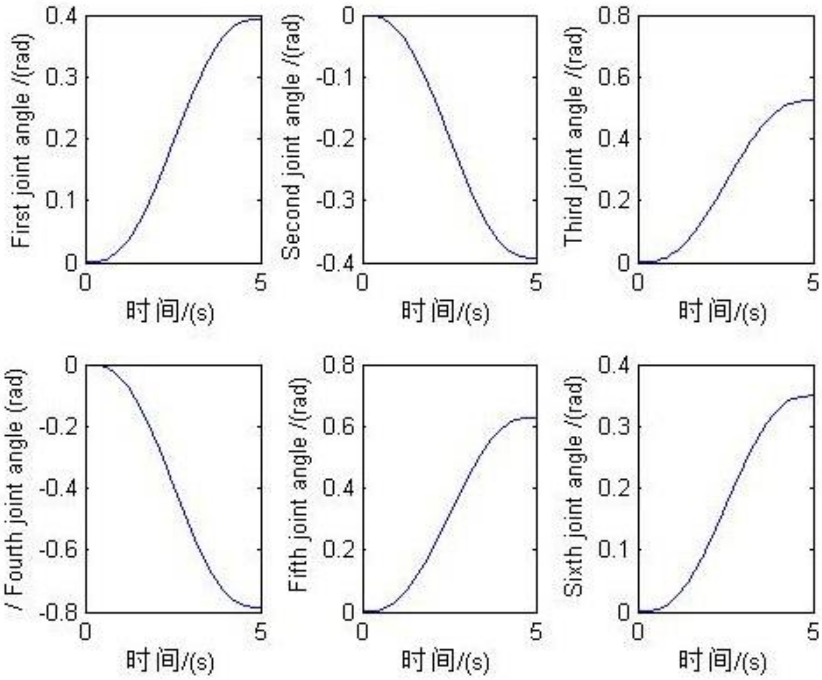


Fig. 5 Curve of the angle of each joint over time

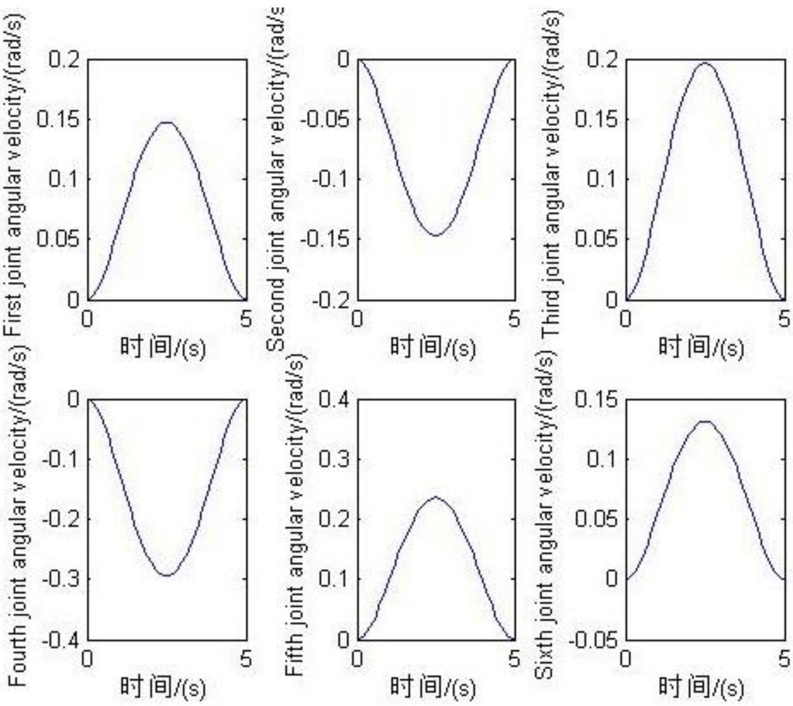


Figure 6 Curves of angular velocity of each joint over time

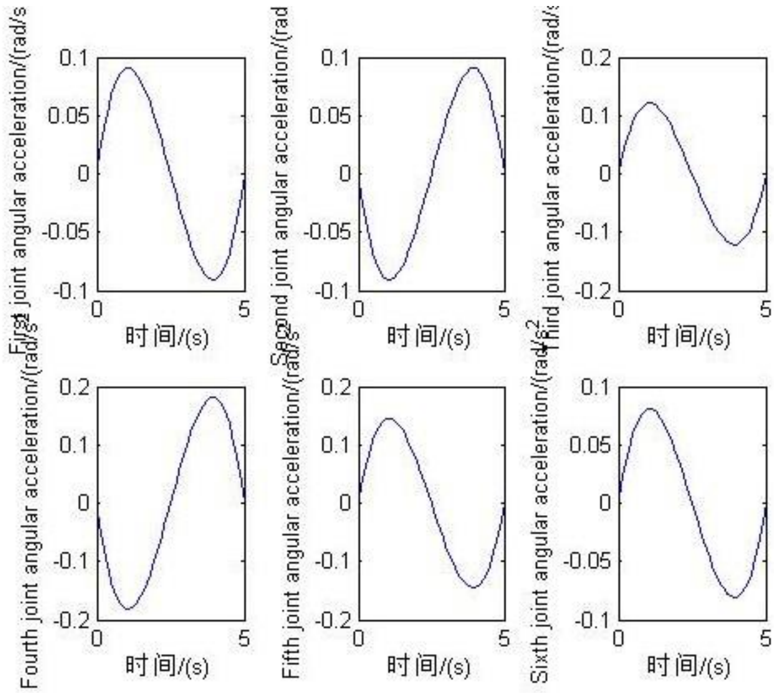


Fig. 7 Curve of angular acceleration of each joint over time

From the above simulation curves, it can be seen that the angular displacement, angular velocity, and angular acceleration of the joints of the left arm of the dual-arm robot are relatively stable, and there is no sudden change, which shows that the dual-arm robot can move continuously and smoothly.

5. Dynamic Simulation Based on ADAMS

In order to simulate with ADAMS, it is necessary to establish a simplified model which can not only analyze and calculate the dynamic model, but also reflect the dynamic characteristics of the actual system objectively [10]. To facilitate simulation research, the model is simplified without affecting the simulation analysis, and some parts, such as bolts, washers and motors that do not affect the structural performance are deleted. The simplified 3D model of dual arm robot is established by SolidWorks, save the file as Parasolid (*.x_t) format, import it into ADAMS software, define the material properties for each component, add rotation pairs, and add drivers, the simplified model is shown in Figure 8.

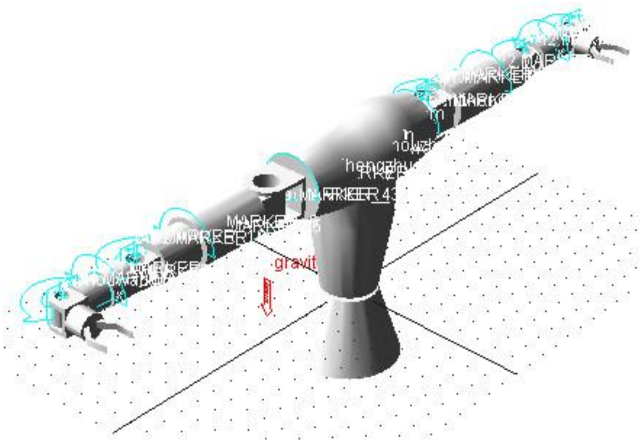


Fig. 8 Virtual prototype model

Use the MATLAB Robotics Toolbox trajectory simulation to derive the left arm and shoulder joint angle change data and save for “guanjie1. txt” format, in ADAMS software menu the “File Type”, select the “Test Data”, then select “Create Splines”, the “File To Read” the menu options found in shoulder joint changing with Angle “guanjie1. txt” File, the time as an Independent Data in the “Independent Column Index” in the input box enter 1, Create a good first “Spline_1” drive function.

The following “Spline_1” function is applied to “Motion1”, select the “Motion1” to be used, open the function constructor, and enable the “AKISPL” function.

The “AKISPL” function is in the form of:

AKISPL (lst_Indep_Var, 2nd_Indep_Var, Spline-_Name, Deriv_Order)

Among them:

“Lst_Indep_Var” is the first variable in “Spline”;

“2nd_Indep_Var” is the second variable in “Spline”;

“Spline_Name” is the name of the data unit “Spline”;

“Deriv_Order” is the differential order of the interpolated point.

Use the above function format to modify the expression to:

“AKISPL (time, 0, Spline_1, 0)”. Using the same method, add the drive functions for the remaining five joints of the left arm in turn.

Click the Simulation button in Simulation to set the simulation time to t=5s and the number of simulation steps to 5000. Run the simulation analysis. Using the PostProcess module of ADAMS software, the displacement, velocity, and acceleration curves at the center of mass of the left arm are shown in Figure 9, Figure 10, and Figure 11.

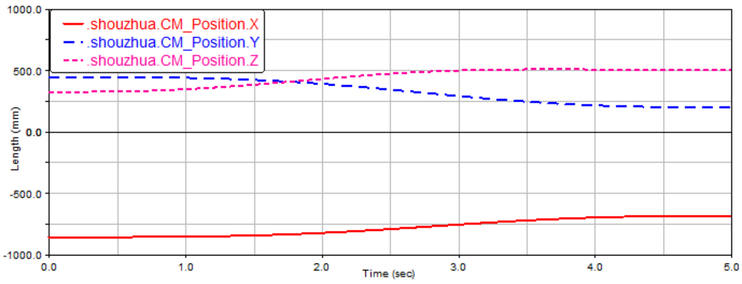


Fig. 9. Left arm grasps the displacement curve of the center of mass

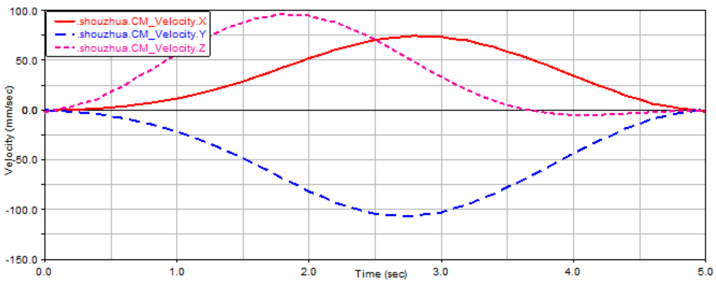


Fig. 10. Left arm grasps the velocity curve of the center of mass

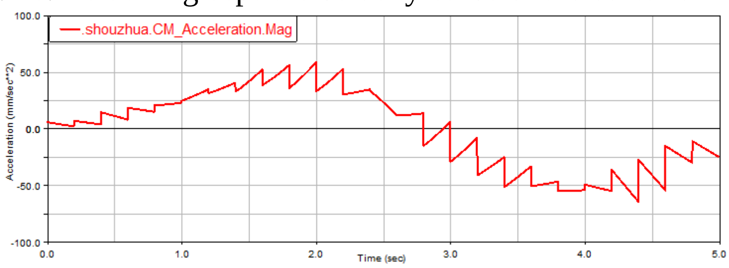


Fig. 11. Left arm grasps the acceleration curve of the center of mass

From the above displacement, velocity and acceleration curves, it can be seen that the curve is smooth and there is no large fluctuation, indicating that the dual-arm robot has a smooth motion and no major abrupt change during operation, which satisfies the stability requirements.

6. Conclusion

D-H method was used to establish the kinematics model, the pose matrix of the end effector was solved, and the equation of motion constrained relationship was derived. Using MATLAB Robotics

Toolbox simulation toolbox to perform the kinematics operation on the two-armed robot, further verified the correctness of the D-H method to find the positive solution of the operation. Using the toolbox to carry out the trajectory planning simulation of the robot, the simulation results show that: the changes in angular displacement, angular velocity, and angular acceleration are relatively smooth. The kinematics model of the dual-arm robot was established by using the ADAMS simulation software. The displacement, velocity and acceleration curves at the center of mass of the end effector were obtained through the PostProcess module. By analyzing the kinematics characteristics of the dual-arm robot, the rationality of the dual-arm robot's structural design is verified.

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