

Kinematic Analysis and Simulation of a Seven-degree-of-freedom Robot

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Abstract:

With the popularization of robots in various manufacturing and assembly plants, robots are gradually replacing humans in complex and dangerous work situations, playing an increasingly important role. However, in narrow working terrain, the performance of six-degree-of-freedom robots is significantly limited. This essay put forward a seven DOF robotic arm to solve this problem, which uses redundant degrees of freedom to solve the problem of limited robot use under complex working conditions and narrow terrain conditions. Then, the Denavit-Hartenberg parameter method is applied to analyze the positive kinematic model of the robotic arm by mathematical modeling, and the MATLAB software is used to verify the obtained positive kinematic model. In the end, the trajectory planning of the robotic arm is made in a straight line, and the relationship between position, velocity and acceleration with time is obtained, which proves that the structural rationality of the robotic arm is in line with expectations.

Keywords: Seven DOF robotic arm, D-H parameter method, Positive kinematic analysis, Joint trajectory planning

1. Introduction

In today's era, robots are usually used in mass manufacturing plants and assembly plants, where they can replace humans to perform high-intensity or dangerous tasks. Because the robot is very susceptible to external interference in the process of working, there is also uncertainty in its control modeling, for this reason, the robustness of the robot should be studied and optimized, which is also an important part of the high-precision control of the robot. Compared with PID control and sliding mode control, which are sensitive to model parameters, adaptive control can sup-

press the vibration and play a greater role in the case of changing working conditions [1].

At present, the D-H parameter method describes the pose transformation relationship of the joint by fixing the coordinate system on the joint. Many scholars have used this method to conduct many studies, and Xie Jia used the D-H method to establish a mathematical model of housekeeping service robots [2]. Zhao Xiuqi et al. used the improved D-H method to establish the equation of motion of the robotic arm [3], which is conducive to the kinematic modeling and motion characteristics analysis of the robotic arm, but there are problems such as the kinematic

parameters are not easy to identify, and the singular topology of adjacent joints is parallel or almost parallel. Zichong Wang and Ziyang Jin present an optimization approach for the motion of a six DOF robotic arm based on the Denavit-Hartenberg parameter method and NSGA-II [4]. Wen Shuhui et al. used the D-H method to derive the positive kinematic equation in the humanoid NAO model [5]. Therefore, many scholars have proposed different modified D-H models, which have good universality for the normal kinematic solution of the robotic arm.

The seven-degree-of-freedom robotic arm has significant advantages in motion flexibility, obstacle avoidance ability and task adaptability, which is closer to the joint structure of the human arm, and when the end effector maintains a fixed position, the robotic arm body can still adjust the joint configuration through redundant degrees of freedom, which can not only avoid collision with obstacles, but also independently optimize the joint shape[6,7]. In this paper, a seven DOF robotic arm is selected to solve the problem of limited robot use under complex working conditions and narrow terrain conditions. Then, the D-H method is applied to establish the positive kinematic model of the connecting structure of the robotic arm, the normal kinematic model of the manipulator is analyzed by mathematical modeling.

2. Structure and Modeling of Seven-de-

gree-of-freedom Robotic Arm

2.1 Structure of the Robotic Arm

The robotic arm referenced in this study has seven degrees of freedom, which can complete the target action well. The structure of the robotic arm is similar to the structure of the human arm, and seven motors complete the rotation of each joint. The base joint and shoulder joint are directly connected to the harmonic reducer by the motor to complete the rotation of the base, and the pitch and expansion of the shoulder joint are completed; The elbow joint completes the flexion and extension of the elbow through the long-distance transmission of the synchronous belt, and the end uses a harmonic reducer to output torque; The wrist joint completes the pitch, yaw and rotation of the wrist through the wire rope differential drive and the motor directly connected to the harmonic reducer. Seven joints use servo motor modules with different powers. In the selection of degrees of freedom of the robotic arm, the redundant design of the seven DOF robotic arm allows it to avoid obstacles by adjusting the elbow height when working in narrow spaces, while keeping the end-effector trajectory unchanged, which is not possible with the six DOF robotic arm [8]. Fig. 1 shows The coordinate system of the seven DOF connecting rod established in this paper.

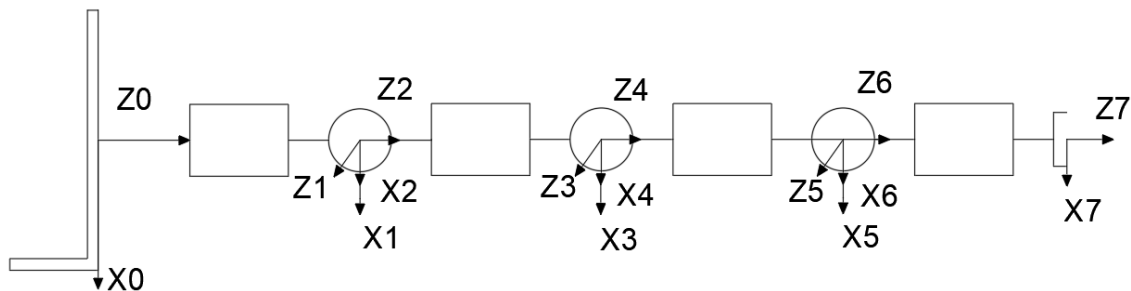


Fig.1 Coordinate system of robot connecting rods (Picture credit: Original)

Table 1. Parameters of robot D-H connecting rods

joint	Connecting rod length a_i (mm)	Distort the angle ($^\circ$)	Joint angle	Connecting rod offset d_i (mm)	Variable range ($^\circ$)
1	81	0		331.5	$\pm 175^\circ$
2	192.5	90		0	$\pm 175^\circ$
3	400	-90		316.5	$\pm 175^\circ$
4	168.5	-90		0	$\pm 175^\circ$
5	400	90		384.0	$\pm 175^\circ$
6	136.3	90		0	$\pm 175^\circ$
7	133.75	0		184.0	$\pm 270^\circ$

2.2 D-H Parameter Modeling

Based on the fundamental configuration of the robotic arm presented in this study, the Denavit-Hartenberg (D-H) coordinate transformation method—widely employed in research and recognized for its effectiveness—was utilized to develop the three-dimensional model of the robotic arm. In accordance with the essential principles of this method, the coordinate systems for the links were established, as illustrated in Figure 2. Furthermore, the D-H parameters and the motion ranges of each joint for the seven-degree-of-freedom robotic arm are detailed in Table 1.

In the field of robot kinematics modeling, there are two implementation methods of the Denavit-Hartenberg (D-H) parameter method: the standard D-H method and the improved D-H method. In the standard D-H parameter table, the parameters are defined based on the relative relationship between the adjacent coordinate system z_{i-1} and the z_i axis, while the improved D-H parameter table relies on the geometric constraints of the coordinate system z_i and z_{i-1} axes. In the application path, the standard D-H method is more suitable for open-chain structure robots, because the coordinate system of this structure is more intuitive to align with the joint drive axis. The improved D-H method is designed for closed-chain mechanisms, such as robots at the beginning, which can avoid the parameter ambiguity that may occur in non-tandem mechanisms of the standard method. In this paper, the modified D-H method is used to complete the simulation of kinematic analysis in MATLAB.

The transformation from the first joint determined first to the next joint is actually a transformation between two joint coordinate systems. Therefore, through this coordinate system transformation method, the total transformation matrix of the robot can be derived. For example, the base is determined as the starting point, and the transformation matrix obtained from the base to the first joint is determined to be the total transformation matrix.

The general formula of the homogeneous coordinate transformation matrix of the coordinate system i of the adjacent connecting rod with respect to $i-1$ is:

Thereinto, $s=\sin$, $c=\cos$.

From this, the homogeneous coordinate transformation matrix general formula can solve the homogeneous transformation matrix of the rest of this items.

The parameters in the resulting connecting rod parameter table are fed into the D-H method, and the normal kinematic equation can be produced using the following homogeneous transformation matrix general formula:

2.3 Results of Kinematic Derivation

The positive kinematic equation obtained by homogeneous transformation, where the unknown is the angle of each joint, can be solved by the above equation (n, o, a, p) and the joint variable (θ, d, a, α). Among them, the three vectors n, o, a represent the pose of the end effector of the robotic arm relative to the base reference coordinate system, and the p vector represents the position of the end effector in the base reference frame. The results enable be obtained by this solution:

Thereinto, $S=\sin$, $C=\cos$. Defined by the pose matrix, the pose and coordinates of the robot end are respectively:

From Equations (15) and (16), it can be seen that when a determined angle is given, the robot arm posture is always determined. In addition, a θ can only correspond to a set of poses, and poses at the same end may have different angles to meet the conditions.

3. Simulation Experiments

3.1 Simulation Platform and Parameter Settings

For the kinematic simulation method of the robotic arm, the kinematic model that meets the research objectives can be obtained by calling the written functions in the robotics tool in the software environment of MATLAB. The corresponding program can be written from the relevant parameters of the robotic arm in Table 1.

The seven joints in this paper are established through Table 1, and the joints are connected by calling the Serial-Link function, and the final robotic arm model is shown in Fig. 2:

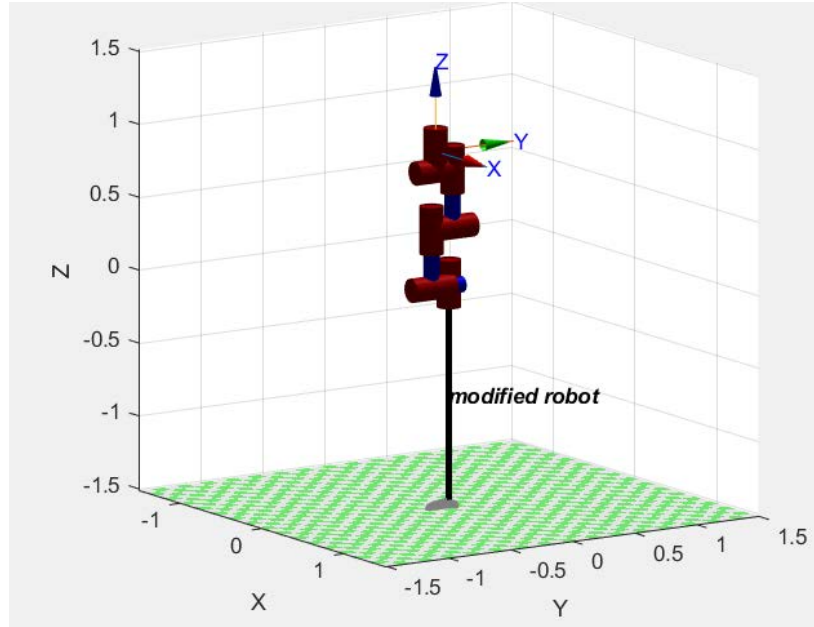


Fig.2 Kinematic model of the seven DOF robotic arm (Picture credit: Original)

3.2 Simulation Results and Analysis

For the verification of the normal kinematics of the robotic arm, this paper use the algorithm of the robotic arm positive kinematics of the robotic toolbox to randomly select any angle within the allowable range of changes of each target joint variable, and this paper selects a set of data to verify, and verifies the situation that the selection is $\pi/2$, and the robot end pose matrix can be obtained by bringing the data into the formula:

In this paper, the correctness of the positive kinematic equation obtained above is verified by comparing the robot terminal position matrix solved by the teach function programming in MATLAB with the terminal position matrix obtained by the standard D-H method. Due to the influence of rounding error in the calculation process, there is a small error in solving the terminal pose matrix in the last two, but it does not affect the correctness of the conclusion.

Trajectory planning refers to selecting key points of the robot end effector on the working path, and calculating the motion parameters of every joint through kinematic inverse solution [9]. The corresponding points are then interpolated in the joint space to construct the equation of

motion and generate a smooth continuous fitting curve. Cartesian space planning and joint space planning are the two primary approaches to robotic arm trajectory planning [10]. To guarantee the continuity and stability of joint movement, joint spatial planning fits and interpolates each joint, but does not directly plan the end trajectory. Complementing this, Cartesian spatial planning directly plans the trajectory of the end effector, aiming to ensure that it strictly follows a predetermined path, but special joints may occur. In this paper, the motion law of each joint is analyzed through the model, and the trajectory planning of the joint space is given by giving the initial angle and the final angle of the joint, and the displacement trajectory is obtained.

Joint space trajectory planning by setting start point and end point, inserting the trajectory points with the equivalent number of joints between them, and selecting the optimal interpolation function due to the constraints to solve the variables of each joint and obtain a smooth fitting curve. The `jtraj()` function is used to set the starting point of the joint as $[0,0,0,0,0,0,0]$, and the end point to $[\pi/4, -\pi/3, \pi/5, \pi/2, -\pi/4, \pi/2, \pi/3]$, and the step size is set to 200, and the trajectory planning process diagram is obtained as shown in Fig. 3.

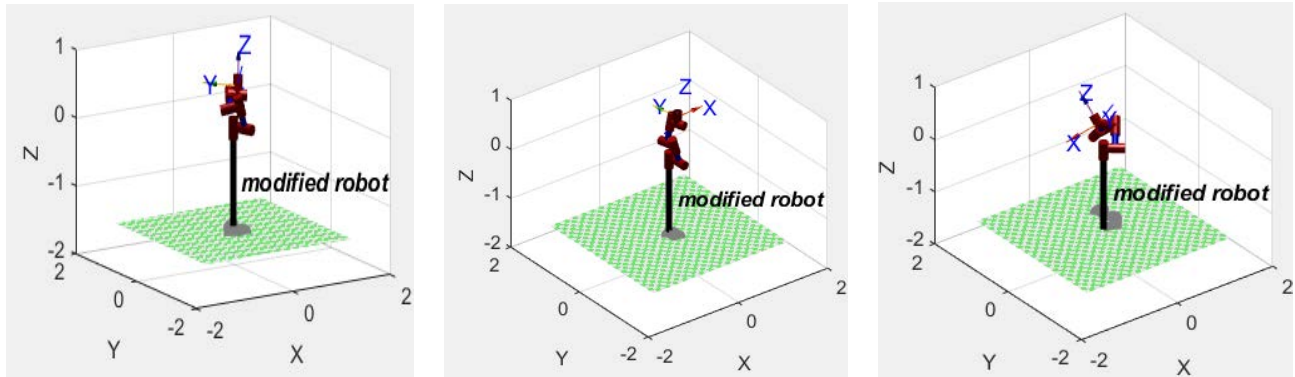


Fig.3 Trajectory planning process diagram (Picture credit: Original)

Using the MATLAB application, Fig. 4 displays the linear trajectory from the beginning to the end of the trajectory planning as well as angular displacement, angular velocity, and angular acceleration curves of the robotic arm's seven joints over time:

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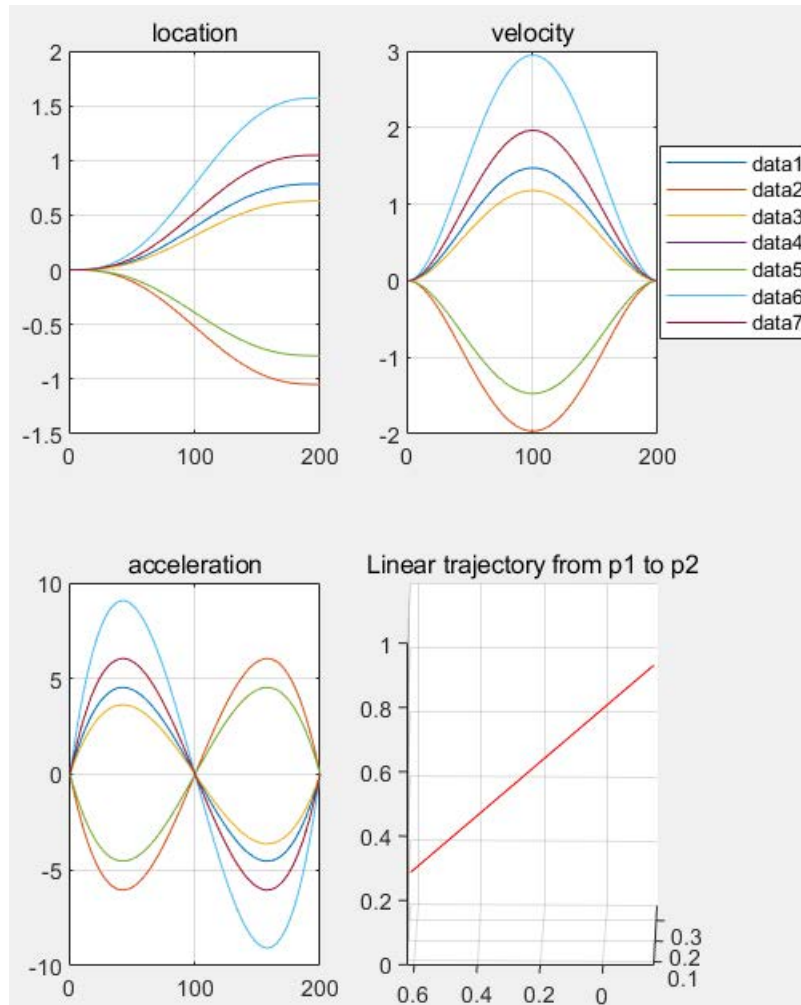


Fig.4 Relationship diagram of position, velocity, acceleration with time and trajectory planning diagram (Picture credit: Original)

It can be seen from Fig. 4 that except for the fixed reference joint, during the whole movement of the step size of 200, the velocity of each joint increases first, increases to

the maximum value and then gradually drops, and the acceleration raise first, then decline to the opposite increase, and finally decreases to 0. There is no sudden change in

angular velocity and acceleration curve during trajectory planning, which means that the robotic arm is quite stable and does not have severe tremor during operation, and the design of the robotic arm is reasonable.

4. Conclusions

This paper examines a robotic arm that can be used in confined terrain. After comparison, a seven DOF robotic arm with redundant degrees of freedom was finally chosen. By studying the general configuration of the seven DOF robot, a reasonable linkage coordinate system is obtained, the D-H parameter table of the manipulator arm is obtained by improving the D-H method, and then the positive kinematics is derived by mathematical methods, and the pose matrix of the robotic arm is obtained. A manipulator with reasonable structure and stable operation was designed and trajectory planning was carried out, and the relationship diagram of position, velocity and acceleration with time and the trajectory planning diagram were obtained. This paper offers an innovative idea for the structural design of seven DOF robots as well as specific guidelines for their mobility under constrained working situations. The authors intend to carry out additional study on the control of the robotic arm in this paper in the future, as the control portion was not investigated due to time constraints.

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