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Modeling and Simulation of Robotic Arm in MATLAB for Industrial Applications

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***Abstract*— With the increasing use of robots in modern industrial production, it is of great significance to study the robotic arm as a main tool in this field. This paper mainly investigates the modeling and simulation of a robotic arm for polishing applications. Kinematics and dynamics model of the multiple degrees of freedom robot based on MATLAB and Robotics toolbox platform are established. According to the standard D-H modeling method, the forward kinematics of the multiple degrees of freedom manipulator is analyzed, and the joint angle is obtained by using the inverse kinematics and then the dynamics solution of the manipulator is derived. Simulation trials and results are presented and discussed. This work provides a potential basis for the realization of robotic grinding and polishing in industrial field, which is of great significance for improving manufacturing efficiency, ensuring product quality and reducing labor intensity of workers.**

Keywords-robotic arm; simulation; kinamatics model; MATLAB

I. INTRODUCTION

With the development of information and mechanical technologies, robots have been invented and applied to the manufacturing process, which can improve the production efficiency, enhance the productivity, improve the working conditions and accelerate the industrial automation [1-3]. Especially in the case of high temperature, high pressure, dust, noise and radioactivity and pollution environments [4], and the robot arm has also been widely used in medical field [5]. The robotic arm was first used in the automotive industry and is often used for welding, painting, loading and unloading [6]. The robotic arm extends and expands the functions of the hand, foot and brain. It can replace people's work in harsh environments such as danger, harmfulness, toxic, low temperature and high heat: instead of people to do heavy and monotonous repetitive work, which can improve labor productivity and ensure product quality. Its application has been extended to the field of space exploration, deep-sea development, nuclear science research and medical welfare. Robotic arm is a new technology emerging in the field of modern automatic control and has become an important part of modern industrial systems [7]. The robot arm consists of the manipulator, controller, servo drive system, detection and sensing components. It is a type of automated production equipment with features such as human-like operation, automatic control, reprogrammable, and can complete various operations in three-dimensional space.

At present, the industrial robot arm used in production is usually a teaching regenerative robot arm, and the control of many robot arms are open loop, which means the position trajectory and speed are only calculated once, and then executed by the robot arm. There is no correction during the operation. In order to perform precise tasks, closed-loop control of the manipulator is required. The sensor measures the error between the target and the current position, calculates and executes the new trajectory and velocity, and then modifies it in the next update [8]. The robot arm should improve its speed of motion and the accuracy of motion, which requires an efficient and stable control system.

It can be found that the domestic research on the mechanical arm started relatively late, and the technology in the automation control is not advanced. In the current motor control system, the single-chip microcomputer and the power device are used for control. The performance of the control system is relatively stable, but the structure of the single-chip microcomputer and the complex instruction system cause the operation speed to be slow and the processing capability to be limited. In the process of mechanical modeling analysis, the structure of the designed polishing robot is important. Therefore, in this paper, the mathematical description of the robotic arm is established to model the kinematics and dynamics, based on this the path planning of the robot for polishing applications can be investigated.

II. ROBOTIC ARM SIMULATION

The degree of freedom is an important technical indicator of the robot, which is determined by the structure of the robot and is closely related to the flexibility of the robot. In general, the more degrees of freedom, the closer the flexibility to humans, but the more degrees of freedom, the more complex the structure [9]. As shown in Figure 1, the model has six degrees of freedom, all joints are rotated, joints 2, 3, and 4 are all in the same plane, and the last three joint axes of the model intersect at a point.

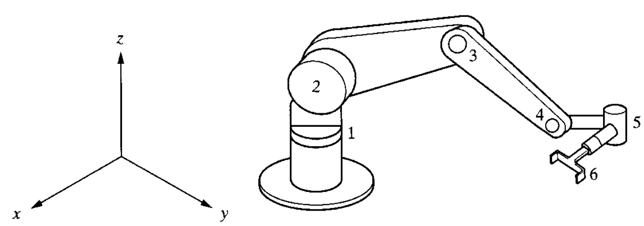

Figure 1. A six-degree-of-freedom robotic arm

The focus of this simulation is the trajectory of the robot and the force control when it encounters the environment. Therefore, the goal of the first stage is to design a free-surface polishing robot based on a multiple degrees of freedom robotic arm, and perform kinematics analysis to establish the forward and inverse solution equations of the robot. MATLAB is used here to realize 3D solid modeling, and the mechanical mechanism dynamics analysis is used to simulate and analyze the kinematics of the robot mechanism. Robotics toolbox [10] supports the modeling functions of various robot models and provides robot inverse and forward kinematics, dynamics solution functions, including Cartesian space and joint space. Figure 2 shows the simulation model established by MATLAB/Robotics toolbox.

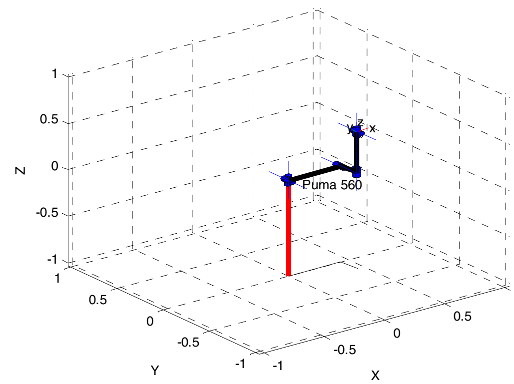

Figure 2. Robotic arm simulation model based on Robotics toolbox

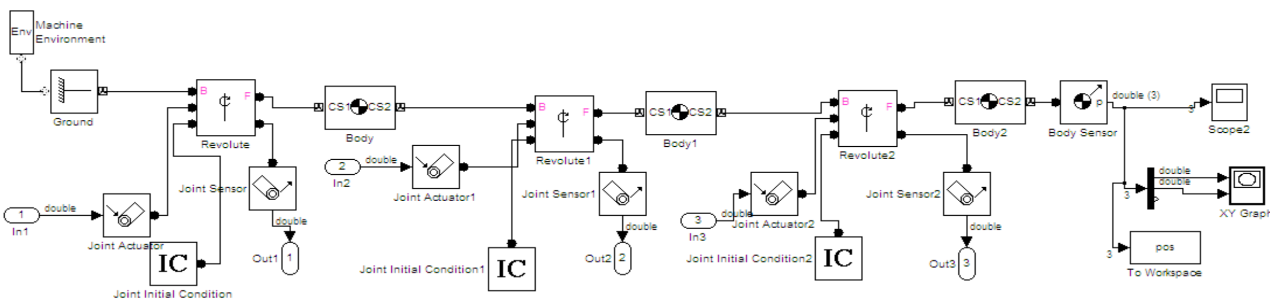

Figure 3. Robot mechanical model based on SimMechanics.

To simulate the robot in an actual control environment, a mechanical model of a three-degree-of-freedom robot is built based on Simulink/SimMechanics, as shown in Figure 3. The output is the joint angle, angular velocity, and angular acceleration vector; the body sensor output is the position coordinates x, y, z in the Cartesian coordinate system at the end of the arm. The Jacobian control model uses the output joint angle variable as the feedback of the Jacobian matrix, introduces real-time joint variables, and calculates the joint position at the next moment based on the current joint variables. As illustrated by Figure 4, the joint trajectory of the robot is calculated by using the Jacobian matrix. T2 is the desired trajectory, T1 is the actual spatial position of the joint position to be fed back, and the joint control trajectory of the robot is obtained through the calculation of the Jacobian matrix via the error between the actual and the desired path.

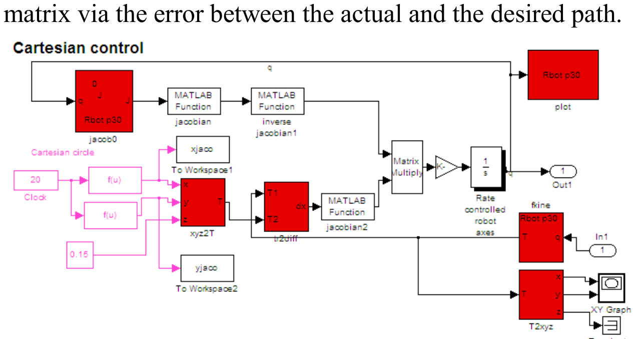

Figure 4. Robot path control model based on Jacobian matrix

III. KINEMATICS AND DYNAMICS MODELING

A. Kinematics Model

In order to realize control of the industrial robot for polishing, it is necessary to establish the kinematics model of the industrial robot. The kinematics description of the robot also establishes the transformation relationship between the coordinate axes of each link. Here, D-H parameters are used to describe the connection of each link of the robot [11]. D-H method uses four parameters to define the rotation of the connecting rod (i) to the connecting rod (i-1). The translation change matrix, D-H parameter description, the robot link expression is simple, as shown in Figure 5, the spatial position relationship between two adjacent robot links and the coordinate system defined on each link are given. After establishing the coordinate system of each link of the robot, the matrix of the change between the coordinate systems of two adjacent links is represented by the D-H parameters.

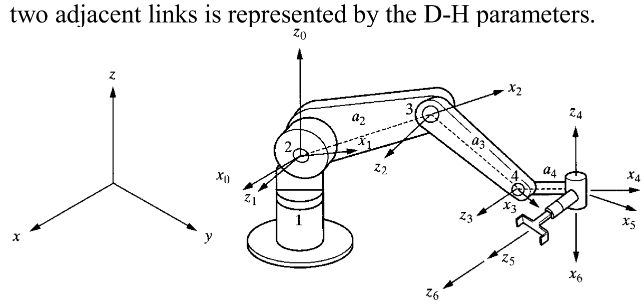

Figure 5. Reference coordinate system of the robotic arm

Assuming that the robot system has five degrees of freedom, based on the transformation matrix Ai (i = 1, 2,..., 5) described by the D-H notation, we can get the pose of the robot's end effector only given the individual joint variables and the rod length parameters of the robot.

$$A_1 A_2 A_3 A_4 A_5 = {}^R T_H . \tag{1}$$

The transformation matrix Ai (i = 1, 2,..., 5) of the robot is:

$$A_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & \alpha_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & \alpha_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} . \tag{2}$$

Finally, solve the above equation to get the solution of the forward kinematics equation:

$$\begin{bmatrix} n_x & a_x & o_x & p_x \\ n_y & a_y & o_y & p_y \\ n_z & a_z & o_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^R T_H = A_1 A_2 A_3 A_4 A_5 . \tag{3}$$

The inverse kinematics problem is that the corresponding joint variable is reversed from the pose of the known robot end effector, and the equation (1) can be transformed into:

$$A_2 A_3 A_4 = A_1^{-1}\, {}^R T_H A_5^{-1} . \tag{4}$$

$$A_i^{-1} = \begin{bmatrix} \cos\theta_i & \sin\theta_i & 0 & -\alpha_i \\ -\sin\theta_i \cos\alpha_i & \cos\theta_i \cos\alpha_i & \sin\alpha_i & -d_i \sin\alpha_i \\ \sin\theta_i \sin\alpha_i & -\cos\theta_i \sin\alpha_i & \cos\alpha_i & d_i \cos\alpha_i \\ 0 & 0 & 0 & 1 \end{bmatrix} . \tag{5}$$

According to the calculation and transformation of A, the inverse kinematic solution can be obtained by (6).

$$\begin{cases} \theta_1 = \arctan(p_y / p_x) \\ \theta_2 = \arctan \dfrac{p_x(z_2 - d_4 s\theta_3) - d_4 c\theta_3 (p_x c\theta_1 + p_y s\theta_1)}{(p_x c\theta_1 + p_y s\theta_1)(a_2 - d_4 s\theta_3) + d_4 p_x c\theta_3} \\ \theta_3 = \arctan(s\theta_3 / c\theta_3) \\ \theta_4 = \arctan \dfrac{c\theta_5 (n_x s\theta_1 - n_y c\theta_1) + s\theta_5 (a_x s\theta_1 - a_y c\theta_1)}{(o_x s\theta_1 - o_y c\theta_1)} \\ \theta_5 = \arctan \dfrac{a_x s\theta_1 - a_y c\theta_1}{n_x s\theta_1 - n_y c\theta_1} \end{cases} . \tag{6}$$

There are two kinds of problems in the positional kinematics of the robot polishing motion: one is to solve the problem of kinematics of the polishing motion points by adjusting different joint rotation angles. The other is to give the end position of the polishing action point, and the robot is required to follow a certain path. Then the constraint will reach the inverse kinematic solution problem at a given position. Kinematics solves the problem by calculating the position and orientation in Cartesian coordinates by given kinematics and joint space coordinates. Robotics toolbox supports modeling functions for various robots, provides forward and inverse robot kinematics and dynamic solution functions, which also includes Cartesian space and joint space trajectory planning. It supports both the standard D-H system and the modified system. The simulation experiment result of robot kinematics model is shown in Figure 6.

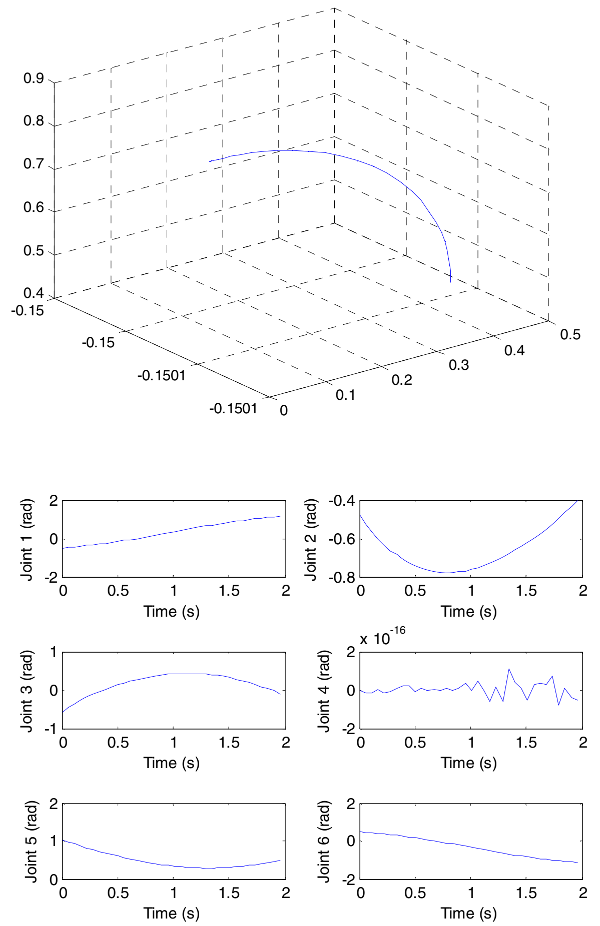

Figure 6. Simulation results of the robot kinematics model (a) trajectory in taskspace (b) trajectory of each joint.

B. Dynamics Model

Regardless of external disturbances such as friction, the dynamic equation of the n-degree-of-freedom manipulator is:

$$\tau = M(q)\ddot{q} + h(q,\dot{q}) + G(q) . \tag{7}$$

in which $M(q)$ is the positive inertia matrix, $h(q,\dot{q})$ the centrifugal force and the Coriolis force vector, $G(q)$ the gravity vector; q the joint position, and τ the joint torque. Taking the model of the two-degree-of-freedom manipulator in the plane as an example, suppose that the arm is rigid, both joints are rotating joints, and the mass of each link is concentrated at the end of the link. The masses of the two links are m_1 and m_2, respectively; the lengths are l_1 and l_2, respectively; the joint angular position is $q=[\theta_1 \quad \theta_2]^T$ and the joint moment is $\tau=[\tau_1 \quad \tau_2]^T$. The dynamic equation of the plane two-degree-of-freedom manipulator is:

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}=\begin{bmatrix}M_{11} & M_{12}\\ M_{21} & M_{22}\end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{bmatrix}+\begin{bmatrix}h_1\\ h_2\end{bmatrix}+\begin{bmatrix}g_1\\ g_2\end{bmatrix}. \tag{8}$$

In the Cartesian coordinate system, when the end effector of the arm contacts the external environment, the arm and the outside will generate mutual force F_e. In order to maintain the balance of the arm, a certain driving torque must be applied to each joint $\tau = J^T F_e$, J is the Jacobian matrix. The Cartes force acting at the end of the arm can be mapped to an equivalent joint torque. When contact with the environment, the dynamic equation of the manipulator is:

$$\tau = M(q)\ddot{q} + h(q,\dot{q}) + G(q) - J^T F_e. \tag{9}$$

The forward dynamics is used to calculate the joint acceleration by the given joint position, velocity and moment. The integral speed and position/angle of the joint can be calculated based on this. The inverse problem of dynamics is to calculate the joint torque through the position, velocity and acceleration information of the joint. The torque required for each joint can reach the desired position, speed, and acceleration. The inverse kinetics are calculated using the Newton's Euler method. The calculation of the inverse kinetics requires understanding the inertia, mass, and kinematic parameters of each joint, and extending the kinematics description matrix of each joint by adding inertia and mass parameters. The simulation experiment result of the dynamics model is shown in Figure 7.

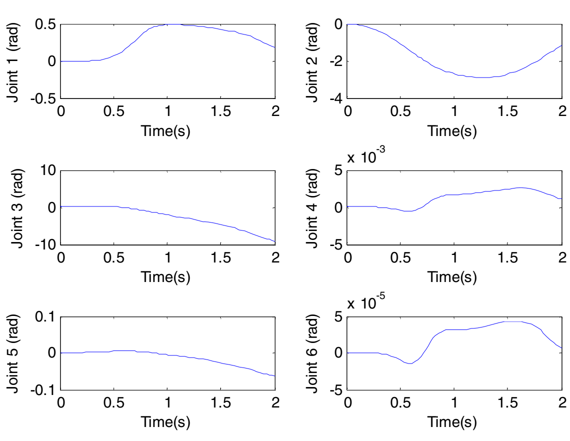

Figure 7. Joint angle calculated by robot dynamics

IV. CONCLUSION

The robotic arm system is able to provide higher reliability during the polishing of machined workpieces in intelligent manufacturing. Literatures have discussed the use of robotic automated systems instead of manual operations for polishing. Researchers have presented various methods to integrate the information technology and manufacturing technology to adapt to the increasing competition in the global manufacturing market. This paper studied a multi-degree-of-freedom chain joint robotic arm, and the standard D-H modeling method was used to establish the mechanical arm model of this study. Then the kinematics and dynamics of the robotic manipulator is analyzed and simulated in MATLAB/Simulink environment with Robotics toolbox. In the future, we will investigate the robot trajectory generation and explore the force control in industrial applications.

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