Design of Industrial Robot Dynamics Controller

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Abstract: In recent years, with the rapid advancement of science and technology, industrial robots have deeply integrated with mechanical technology under the impetus of electronic and control technologies, becoming one of the key areas of national technological development. They are widely applied in manufacturing, logistics, healthcare, and various other fields. Among industrial robots, six-axis collaborative robotic arms represent a significant branch, where dynamics modeling and controller design play a critical role in enhancing their performance. This paper, based on the structural characteristics of six-axis collaborative robotic arms, meticulously constructs a Denavit-Hartenberg (D-H) parameter table and employs the Lagrangian method to establish a comprehensive dynamics model. On this foundation, a dynamics controller based on Proportional-Integral-Derivative (PID) control is designed to achieve precise control and rapid response of the robotic arm in complex environments. To validate the controller's performance, Matlab software was utilized for simulation analysis. The simulation results demonstrate that this control method enables the robotic arm to quickly converge to the desired trajectory within a short period, exhibiting excellent rapid tracking capability and dynamic performance. These findings provide robust technical support for practical engineering applications.

Keywords: Industrial Robot; Dynamic Modeling; Lagrangian Method; PID Control; Simulation

1. Introduction

As a high-tech, knowledge-intensive product developed through the integration of electrical, mechanical, and automatic control technologies, robotic arms not only embody a high degree of fusion between electrical and mechanical systems but also play a pivotal role in driving industrial production toward high levels of automation [1-7]. After years of development, industrial robots have been widely applied across various sectors, including manufacturing, logistics, healthcare, and services, significantly enhancing productivity and precision.

However, with the rapid advancement of science and technology and the ever-changing market demands, the performance and capabilities of industrial robots must be continuously optimized to meet increasingly complex task requirements. This underscores the importance of research on dynamic controllers for industrial robots, where key aspects such as constructing Denavit-Hartenberg (D-H) parameter tables, establishing dynamic models, and designing controllers are crucial for achieving high-performance control.

Among the numerous control methods, studies have shown that PID control is an ideal choice for robotic arm control due to its simplicity, ease of implementation, and adaptability to nonlinear and complex environments. Particularly under challenging conditions, PID controllers exhibit strong robustness and dynamic response capabilities. For robotic arms' specific operational characteristics, PID controllers not only maintain good stability under standard conditions but also effectively enhance control precision and reliability in the presence of external disturbances.

In this context, this paper proposes a dynamic PID controller design for a six-axis robotic arm. By analyzing the robotic arm's dynamic characteristics and leveraging the theoretical advantages of PID control, this study aims to optimize its control performance under complex operating conditions. The objective is to achieve new levels of precision, response speed, and disturbance rejection, thereby providing technical support for the broader application of industrial robots in diverse fields.

2. Kinematic Modeling of Industrial Robots

The D-H parameter method is one of the most commonly used approaches for the kinematic and dynamic analysis of robots. The D-H matrix method describes the motion of lower-pair mechanisms based on matrix transformations. Among the key link parameters, four are particularly significant: link length, link twist angle, link offset, and joint variable.

By establishing a Cartesian coordinate system for the six-axis robotic arm, the D-H parameter table was constructed, and the kinematic model of the robot was developed, enabling the control of the robotic arm and further verifying the accuracy of the kinematic model. The D-H parameter table for the six-axis robotic arm is shown in Table 1.

Table 1. D-H Parameter Table of Cartesian Coordinate Robot

Serial Number	Link Twist Angle	Link Length	Link Offset	Joint Variable
1	0	0	l_0	θ_1
2	90	0	0	θ_2
3	0	l_1	0	θ_3
4	0	l_2	0	θ_4
5	90	d_3	0	θ_5
6	-90	l_3	d_4	θ_6

Forward kinematics involves determining the spatial pose parameters of the robotic arm's end-effector based on known joint parameters. The coordinate system for the six-axis robotic arm model is shown in Figure 1.

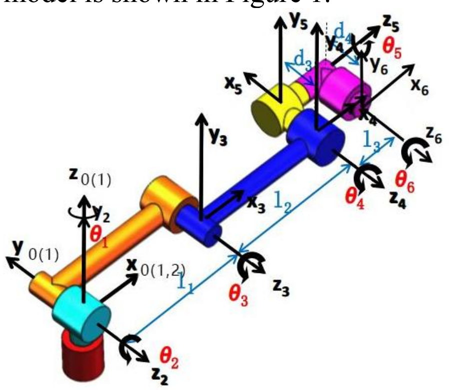

Figure 1. Robot Coordinate System

3. Dynamic Modeling of Industrial Robots

3.1 Lagrangian Dynamics Model

Compared to the Newton-Euler method, the Lagrangian method is based on the principle of energy balance and does not require solving internal forces, making it more suitable for multi-degree-of-freedom and highly complex robotic arms. In this paper, the Lagrangian method is primarily used to establish the dynamic equations for the six-axis robotic arm. By applying the Lagrangian method, the analytical formulas for the robot's dynamic equations can be directly obtained, as well as the recursive computation methods. For any mechanical system, the Lagrangian function is defined as the difference between the system's kinetic energy K and potential energy P [8-11].

$$L = K(\theta, \dot{\theta}) - P(\theta) \tag{1}$$

$K(\theta, \dot{\theta})$ —The total kinetic energy of each moving part of the system; $P(\theta)$ —the total potential energy of the system.

The kinetic and potential energies of the system can be expressed in terms of any chosen coordinate system. For a robot composed of rigid links, generalized coordinates such as joint angles can be used, or Cartesian coordinates can be adopted to establish the system's motion equations.

The dynamic equations of the system are given by:

$$T_i = \frac{d}{dt}\left(\frac{\partial L}{\partial \theta_i}\right) - \frac{\partial L}{\partial \theta_i} \quad (i = 1,2,3,\cdots,n) \tag{2}$$

In the equations:

θ_i— Represents the generalized coordinate of the i-th component of the system.

$\dot{\theta}_i$ — Represents the generalized velocity corresponding to the generalized coordinate.

T_i— Represents the external generalized force or generalized torque acting in the direction of motion of the i-th component.

3.2 Lagrangian Dynamics Model

For a six-degree-of-freedom robotic arm, its dynamic equations can be derived using the Lagrange equation. The total kinetic energy of the six-axis robotic arm is equal to the sum of the kinetic energies of each joint. By establishing the coordinate system at the end of the joints and neglecting the rotational kinetic energy of the joints, the kinetic energy of the joints consists only of the translational kinetic energy. Therefore, the total kinetic energy of the six-axis robotic arm is:

$$K = K(\theta, \theta) = \sum_{i=1}^{n} \frac{1}{2} \mathrm{m}_i \mathrm{v}_i^2 \quad (3)$$

$$v_i^2 = \dot{\mathrm{x}}_\mathrm{i}^2 + \dot{\mathrm{y}}_\mathrm{i}^2 + \dot{\mathrm{z}}_\mathrm{i}^2 \quad (4)$$

In the equations:

m_i— Represents the mass of the i-th link.

v_i—Represents the magnitude of the absolute linear velocity vector.

$\dot{\mathrm{x}}_\mathrm{i}$ $\dot{\mathrm{y}}_\mathrm{i}$ $\dot{\mathrm{z}}_\mathrm{i}$—Represents the position vector of the end-effector of each joint.

The potential energy of a six-axis robotic arm is equal to the sum of the potential energies of each joint. Letz_i represent the position vector of the end-effector of each joint, then the total potential energy of the robotic arm is:

$$P = P(\theta) = \sum_{i=1}^{n} m_i \, g z_i \quad (5)$$

3.3 Dynamic Modeling of the Six-Axis Robotic Arm

The flowchart of the robotic arm dynamics modeling is shown in Figure 2.

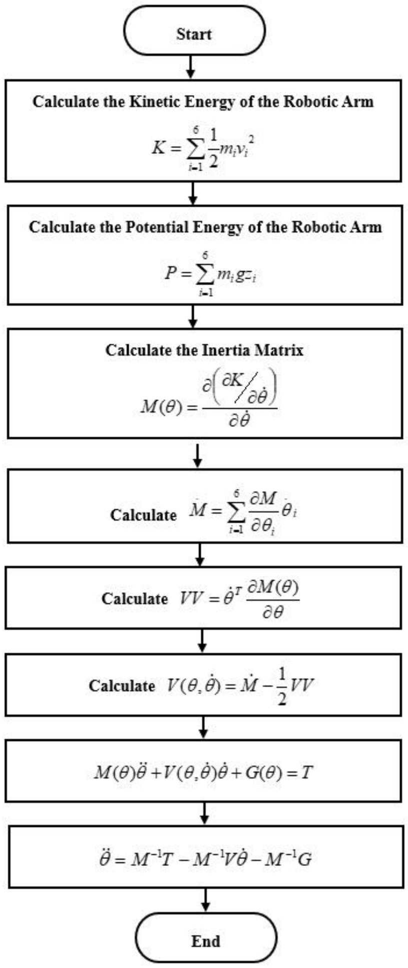

Figure 2. System Flow Chart of Mechanical Arm Dynamics Modeling

The joint parameters of the six-axis robotic arm are shown in Table 2.

Table 2. Parameters of the Joints of Robotic Arm

Joint	1	2	3	4	5	6
m (kg)	1.9	2.267	2.23	1.9	2.9	1.036
l (mm)	224	224	164	52.4	80.5	15

Note: and represent the total mass and arm length of each arm, respectively.

The acceleration due to gravity = 9.8 m/s².

4. PID Controller Design

Before designing the PID controller, the PID parameters need to be tuned, mainly adjusting three parameters: K_P, K_i and K_d.

The three main steps for PID parameter tuning are summarized as follows:

1) Proportional Gain Tuning:

Set the system to pure proportional control mode (with integral time set to infinity and derivative time unchanged). Adjust the proportional gain, gradually increasing it from a small value, and observe the system output to ensure it accurately reflects the input.

2) Integral Time Tuning:

Introduce the integral term to achieve zero steady-state error regulation. Gradually reduce the integral time, observing the changes in system output until zero steady-state error is achieved. Note that at this point, overshoot may increase, and the proportional gain should be reduced accordingly.

3) Derivative Time Tuning:

After tuning the proportional and integral terms, if the result is unsatisfactory, introduce the derivative term. Gradually increase the derivative time to check the system's stability. Adjust the proportional gain and integral time as needed to ultimately achieve the required static error and response speed.

In the PID controller, the control law is defined as:

$$T = k_p e + k_\mathrm{d} \dot{\mathrm{e}} \quad (6)$$

According to the dynamic equations:

$$M(\theta)\dot{\theta} + V(\theta, \dot{\theta})\dot{\theta} + G(\theta) = T \quad (7)$$

It can be obtained that:

$$\ddot{\theta} = M^{-1}(T - G - V\dot{\theta}) \quad (8)$$

$$\text{Let:} x = \dot{\theta}$$

$$\dot{X} = M^{-1}(T - G - VX) \quad (9)$$

From the state-space expression:

$$\dot{X} = AX + BT \quad (10)$$

The matrices AA and BB are obtained as follows:

$$A = -M^{-1}V \quad (11)$$

$$B = M^{-1} \quad (12)$$

$$GG = -M^{-1}G \quad (13)$$

This chapter investigates the dynamic control problem of the robotic arm and proposes a control algorithm based on PID structural theory. After designing the PID control law, the parameters K_P and K_d were continuously adjusted so that the output curve could ultimately track the desired input curve [12], resulting in a PID-based control system for the six-axis robotic arm.

5. PID Control Simulation of the Robotic Arm

The PID control of the robotic arm is simulated using MATLAB [13-18].

The following assumptions are made:

The tracking trajectory of each robotic arm is:

$\theta_{d1} = \sin(t), \theta_{d2} = \cos(t)$,

$\theta_{d3} = t. \times \sin(t), \theta_{d4} = 3t. \times \cos(t)$,

$\theta_{d5} = \sin(t)$

The MATLAB simulation is then performed, and the simulation structure is shown in Figure 3- Figure 7.

MATLAB simulation results:

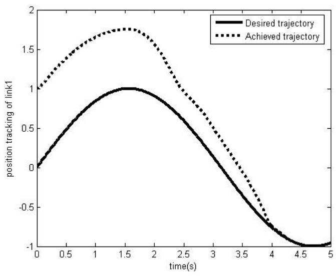

Figure 3. PID Structure Control of Joint 1

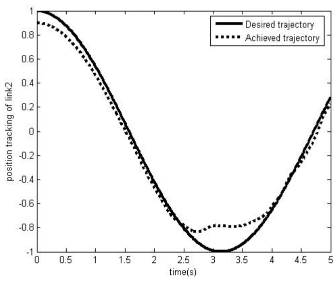

Figure 4. PID Structure Control of Joint 2

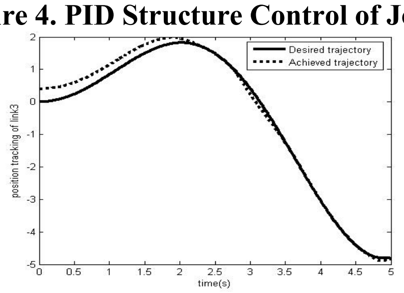

Figure 5. PID Structure Control of Joint 3

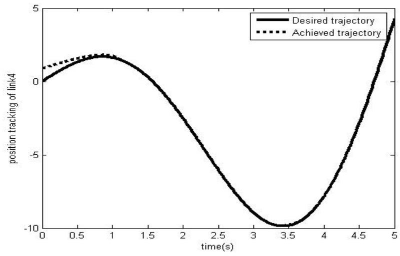

Figure 6. PID Structure Control of Joint 4

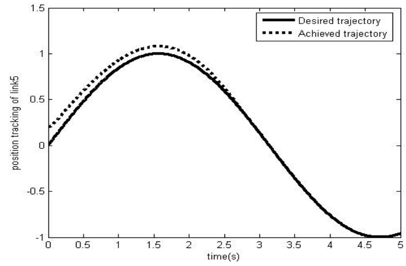

Figure 7. PID Structure Control of Joint 5

The simulation results show that, even with relatively large initial values for the system, each joint is able to asymptotically track its desired trajectory in a short time, achieving the expected goal. The ability to track the target trajectory in such a short time demonstrates that the PID control structure theory has advantages in robotic arm trajectory tracking that other methods cannot match.

6. Conclusion

Based on the structural characteristics of the six-axis robotic arm, this paper mainly explores the dynamics of the robotic arm. After completing the theoretical analysis and calculations, the dynamic model of the robotic arm is established, and a dynamic simulation experiment of the robotic arm is conducted using MATLAB. At the same time, after an in-depth discussion of some key issues encountered during the research process, a method using PID control structure is proposed, and a PID controller is designed and tested with simulation experiments.

The main conclusions of this paper are as follows:

Firstly, based on a thorough understanding of the structural characteristics of the six-axis robotic arm, the Lagrangian dynamic method is used to derive the dynamic model of the robotic arm. Using MATLAB's powerful computational capabilities, the parameter values for the robotic arm's dynamic modeling are obtained.

Secondly, based on the previously established dynamic model of the robotic arm, the PID control structure principle is applied to design a PID controller for the robotic arm. The feasibility of the controller is verified using MATLAB's powerful computational and plotting functions. The simulation results show that this control method not only enables the robotic arm's output to quickly track the desired trajectory but also requires a very short time, achieving rapid tracking.

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