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Research Article

Design and Simulation Analysis of Trajectory Planning Algorithm for 6-DoF Manipulator Based on Deep Learning

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At present, the robot developed only has partial intelligence, and it cannot be well controlled independently for some jobs, so it should optimize its path and trajectory. However, as an industrial robotic arm robot necessary for advanced industrial manufacturing enterprises, it has been replacing humans to perform simple and repetitive actions, and it is doing better and better. For the six-degree-of-freedom (6-DoF) manipulator, this paper aims to optimize the trajectory planning of the manipulator based on deep learning technology. Therefore, this paper presents a fuzzy control algorithm for the trajectory planning of the manipulator based on the neural network algorithm. The experimental results show that for the established three-joint dynamic model, the moment received by joint 1 is the largest, followed by joint 2, and joint 3 is the smallest, which can better simulate the trajectory of the robotic arm.

1. Introduction

For a 6-DoF manipulator, the end of the manipulator generally performs tasks in Cartesian space. No matter what kind of trajectory, it is necessary to perform interpolation in Cartesian space to obtain a sequence of interpolation points and then map it to joint space to obtain joint angles through inverse kinematics solution. To complete an ideal trajectory planning, it is necessary to ensure that the curves in both Cartesian space and joint space are smooth. It can be engaged in welding, spraying, handling, blanking, assembly, packaging, palletizing, and other work. On the one hand, it reduces the workload of human beings and liberates human hands. On the other hand, it can improve the production efficiency of enterprises and reduce labor costs through automated production of machinery. After planning the trajectory of the manipulator and obtaining the desired trajectory, the manipulator must accurately track the established trajectory. First, the joint action of the robotic arm requires the servo motor to apply a torque to the joint, and the magnitude of this torque needs to be solved dynamically. The dynamic parameters of the robotic arm itself are not easy to obtain, and there are interference and other unavoidable factors in the outside world. It is a complex, strongly coupled nonlinear system. Its trajectory planning and tracking control is also a complex process. In order to describe the motion state of the manipulator, it is necessary to carry out kinematic analysis and dynamic analysis. These factors cause changes in the tracking accuracy of the robotic arm. At the same time, the dynamic model of the manipulator is difficult to establish accurately. How to choose a suitable control algorithm that does not require an accurate dynamic model is a difficult problem to achieve high-precision trajectory tracking. Therefore, under this situation, the development of Chinese robots faces challenges to varying degrees. This also requires that research and technology in related fields can be quickly followed up, so that the development of robots can keep up with the pace of social development. This article is to conduct research in related fields, and expect to gain something in this field.

This paper takes the 6-DoF manipulator as the research object and studies its trajectory planning and

tracking control. For trajectory planning, a kinematic analysis of the object is required first. It obtains its inverse kinematics solution and then selects an appropriate planning algorithm to obtain the function of joint parameters changing with time. The research of tracking control algorithm requires dynamic modeling of the manipulator. However, the dynamic model of the 6-DoF manipulator is very complicated, and it is difficult to build it completely. Therefore, we propose several tracking control algorithms without detailed model information and compare their tracking performance by simulation.

2. Related Work

The application of 6DOF manipulator in industry is very extensive, and related scholars have conducted in-depth research on it. Huang and Lan proposed a robot-assisted and remotely controlled ultrasound scanning system for 3D imaging. A 6-DoF (DOF) robotic arm that acts as an upper-limb prosthesis remotely controlled by an operator drives an ultrasound probe to scan the skin surface. The quantitative experimental results show that the volume measurement error is less than 1.1%. This shows that the system in this paper can accurately and flexibly control the probe scanning to produce high-quality 3D ultrasound images [1]. Silveira further exploited epipolar geometry and its inherent degeneracy. This degradation always occurs when the stability is close enough to equilibrium, regardless of the shape of the object. He then introduced three new local methods and uses both planar and nonplanar objects. He simulated and experimentally evaluated their closed-loop performance using 6DOF manipulators at small and large displacements [2]. Donnici M designed a system. The system consists of a high-precision 6-DoF self-balancing arm that is able to move in passive and active modes, allowing physicians to accurately insert needles [3]. Zwonarz and Turnau believed that trajectory optimization must be done for the optimization of industrial robots [4]. Smyrnaiou et al. conducted a comparative study of classical control methods for testing mathematical models. This model uses a single controller to control the six actuators of a 6DOF robotic arm and aims to constructively simplify the system. In more detail, he designed the mathematical model of the system, simulating all mechanical components, including the mathematical model of the five-way pneumatic reversing valve, pneumatic actuator/piston, and controller [5]. Song et al. combined CAD technology to optimize the application of manipulator. He thought that the good drawing and model fitting function of CAD can provide good help for the path planning of the robot arm. In the experiment, he simulated with three different mechanical arms, and the results showed that the recognition rates of the three objects were all above 90% [6]. In the actual tracking control research, many scholars use the hybrid control method. They use the abovementioned control methods in combination, because different control methods have their own advantages in different aspects, and the combined use can complement each other.

3. Robotic Arm Trajectory Planning and Deep Learning Neural Network

3.1. Robotic Arm Trajectory Planning. The trajectory planning of the robotic arm is to plan the angle, speed, and acceleration of each degree of freedom, so that each joint can coordinate and complete the task continuously and stably [7]. The motion of the manipulator has joint friction, which in the long run will lead to the wear and tear of the manipulator structure, resulting in a large error of the manipulator [8]. Among them, the mechanical arm with more applications is shown in Figure 1.

Trajectory planning algorithms have experienced a process from easy to difficult, and there are many kinds. The advantages and disadvantages of various planning algorithms [9, 10] are shown in Table 1.

Trajectory tracking control is defined as the ability to accurately track the given desired trajectory of the manipulator during motion after determining various manipulator parameters and state variables of the working end [11]. Because manipulator control is a complex system, it has characteristics such as uncertainty, strong coupling, and nonlinearity, and there will be some factors in manipulator modeling. As shown in Table 2, these factors are frequently unavoidable. As a result, accurately establishing the manipulator's dynamic model is difficult.

These uncertain factors as shown in the table may reduce the accuracy of tracking control, or even fail to meet expectations, making the system unstable. In order to deal with these problems, the currently commonly used manipulator trajectory tracking control methods are as follows.

(1) PID control: the main feature is that it is simple and easy to understand, and it is the most widely used control algorithm for industrial robots. However, PID control is difficult to ensure the dynamic performance of the manipulator, and the output torque is large when starting, which is easy to cause damage to the manipulator. (2) Adaptive control: when the system is running, it continuously determines the state of the controlled object and compares it with the expected state. It corrects the structure and parameters of the controller in real time and adjusts the system adaptively by changing the operation of the system according to the adaptive law, so that the system can reach the optimal state. Adaptive control needs to identify parameters online, and the real-time requirements are relatively strict. (3) Iterative learning control: each iterative process is equivalent to a control attempt, correcting the deviation between the output and the expectation by the error between the two, and then proceeding to the next attempt until full tracking is achieved. This control algorithm is more suitable for objects with repetitive actions, and the tracking effect of iterative learning is different from that of progressive tracking. Maybe the tracking effect of the first iteration is not very good. However, as the number of iterations increases, it is able to achieve full tracking effect, requiring less prior knowledge [12, 13]. (4) Fuzzy control: using the combination of expert experience and control methods, it can be combined with other control methods and does not require an accurate mathematical model of the robotic arm system. However, there are many

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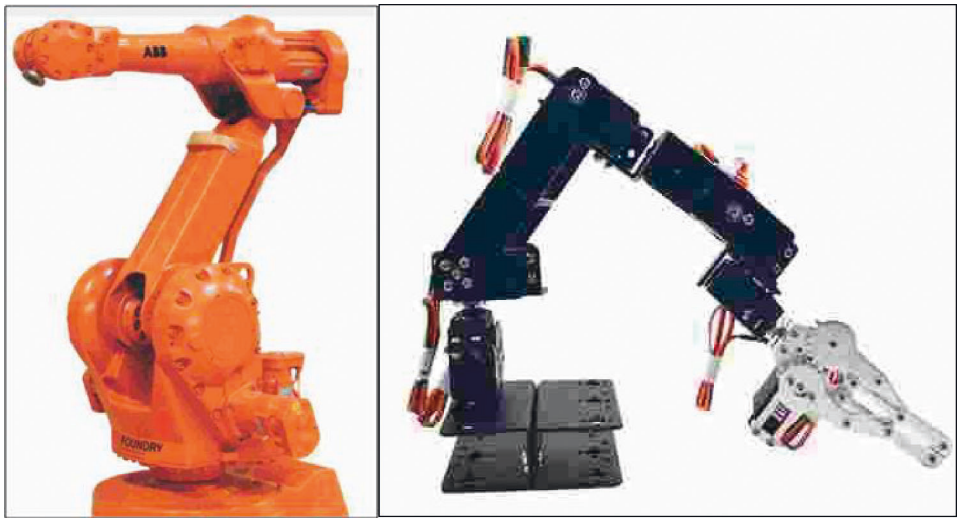

Figure 1: Different types of 6-DoF robotic arms.

Table 1: Trajectory planning algorithms.

Trajectory planning methods	Advantage	Shortcoming
Lines and arcs	Relatively simple and intuitive, small amount of calculation	The applicable surface is relatively narrow
Cubic polynomial	Simple, small amount of computation	Unrestricted acceleration, shocks exist, and limitations are large
Higher-order polynomials	High motion efficiency and smoothness, the higher the polynomial degree, the better the accuracy and fit	Vibration prone to high frequency
S Speed curve	Fully guarantee the smooth transition of the speed and acceleration of the entire trajectory	There is a step in the acceleration curve, which is easy to cause mechanical wear
Spline	Smooth trajectory, continuous speed and acceleration	Large amount of calculation and high hardware requirements

Table 2: Uncertainties.

Robotic arm factor	Joint factor	External factors
Quality	Kinetic friction	Working environment noise
Length	Static friction	Measurement error
Moment of inertia	Joint flexibility	Other factors

parameters to be adjusted in fuzzy control, and it is not used much in practical engineering. (5) Sliding mode variable structure control: this is a type of nonlinear control. There is a switching function in the system, which can transform the system structure according to the law of the switching function according to the current state of the controlled object. If the state reaches the value of the switching function, the system switches the structure, which makes the system state slide along the sliding surface and finally reaches the equilibrium point of the system. The advantages of this control method are fast response, insensitivity to parameter changes and simple implementation.

In 2018, a report on the development of the robot industry pointed out that China has nearly one-third of the world's robots, has a vast application market, and ranks among the best in the world. In the future, China's industrial robot market will increase. The development of industrial robots in China can be divided into five stages, and now it has entered a period of rapid development. However, China's research on robotics technology is relatively backward, and some high-end core technological achievements are mainly concentrated in the United States, Japan, Germany, and other countries. Therefore, it has certain practical significance to conduct in-depth research on all aspects of robotics, as shown in Figure 2.

3.2. Deep Learning Neural Networks. A brief description of machine learning [14, 15] is as follows: it is given a source space x and a target space y. The goal is to learn a mapping from x to y. This makes it possible to obtain the corresponding image in y through f for any sample. For example, for a Chinese to English translation task, x is the source language (Chinese) space, y is the target language (English) space, and f is the translator. Deep learning is to use the artificial neural network to simulate the neural network of biological brain to process data information; that is, f is an artificial neural network. It requires a large amount of data for effective learning, and at the same time, it has high computational complexity and requires hardware system support. Therefore, although it has been proposed in the last century, it has not been paid attention to, and it has been developed rapidly until the last decade.

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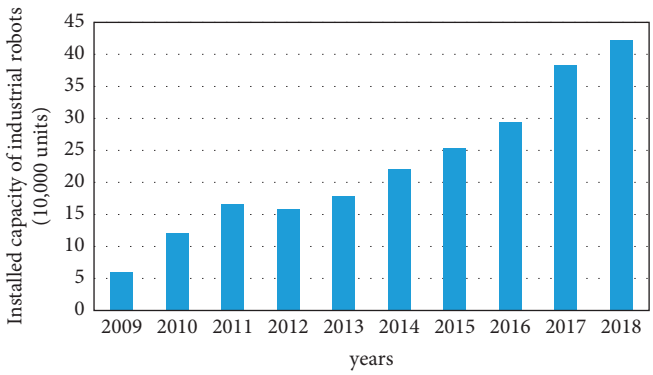

Figure 2: The global installed capacity of industrial robots announced by IFR in 2019.

Deep learning [16, 17] uses artificial neural network as the architecture to perform representation learning on data, and automatically mine and extract the features and information contained in the data for learning. Therefore, the structure of deep neural network [18] is very important for the effect of deep learning. The network model is also getting more and more complex, and the effect is getting better and better. Residual network (ResNet) in 2015 has become a standardized module for processing image information in many tasks due to its excellent performance. The network model applied to target detection is more complex and contains many functional modules. Recurrent Neural Networks (RNNs) applied to sequence learning, especially Long Short-Term Memory Networks (LSTMs) and Gated Recurrent Units (GRUs), are widely used in various sequence learning problems (such as natural language processing). In 2016, the model structure of the Transformer based on the attention mechanism proposed by Google was based on the self-attention network, which greatly surpassed the model based on the long short-term memory network in the neural machine translation task, and was extended to other natural language processing tasks. In speech processing tasks, neural networks also show their advantages. For example, in speech synthesis (TTS) tasks, Google's Tacotron series, Microsoft's Transformer-based model, and Baidu's DeepVoice series all surpass traditional algorithms. It can be seen that different neural network model structures need to be designed for different tasks and different data. This process is not done overnight, but it requires deep expertise. This requires both mastery of deep learning techniques and knowledge of the field of application. This makes the use of deep learning technology more expensive, and the cost of designing a suitable neural network model structure is relatively high. Therefore, researchers have explored a method that can automatically design the neural network structure, and proposed a neural network structure search. It has also become the hottest research area in automated machine learning.

4. Six-Degree-of-Freedom Robotic Arm

The robotic arm used in this article is the REBot-V-6R-650 6-DoF robotic arm produced by a company. It is a typical tandem robotic arm. The serial manipulator uses multiple links to connect the joint axes of the manipulator in series. It uses the motor to drive the movement of each joint axis and drives the connecting rod to perform relative movement, so that the end of the mechanical arm can complete various tasks. For the convenience of research, it numbers each axis of the manipulator in turn. From the base to the end effector, there are 1–6 axes from bottom to top. As shown in Figure 3:

The robotic arm uses a motion control card as a control unit, providing an open experimental platform, and controlling the robotic arm by accepting commands from the host computer. Its basic parameters are shown in Tables 3 and 4.

The overall hardware structure of the robotic arm mainly consists of two parts: the robotic arm control and the upper computer control part. The upper computer realizes the planning algorithm, the tracking control algorithm, and the design of the human-computer interaction interface through software programming. The command of the host computer is transmitted to the motion controller through the 10 M Ethernet, and the driver of each joint controls the motor to rotate, so that the joint of the robotic arm rotates to an appropriate angle. The system structure diagram is shown in Figure 4.

The hardware part of the upper computer consists of a computer and a network card. Data transmission between devices is realized through the network card. The computer mainly does the work of controlling external devices. The specific work is as follows: it sends control commands and query commands to the motion control card.

The robotic arm control system receives and executes the control commands from the host computer, receives the query commands from the host computer and feeds back the working conditions of the motor. It is mainly composed of four parts, namely, DMC-21X2 motion control card, driver, and motor. The components of the robotic arm motion control system are shown in Figure 5. The specific functions of each part are as follows:

(1) The motion controller DMC-21x2 is an economical multiaxis independent controller. When the value of x is 1–8, the motion controller can be used to control up to 8 axes. The controller can smooth curves for complex contours. In order to reduce the motion impact and achieve smooth tracking, the controller provides infinite linear and arc vector feeds. That is, any complex curve can be represented by straight lines and arcs. (2) The driver should be matched with the servo motor, and the pulse signal of the controller cannot be directly used to control the servo motor. It needs to be converted into electric current by the servo driver to drive the servo motor. (3) The motor converts current into force that produces motion. The magnitude of the current determines the magnitude of the force of motion. The motor drives the joint movement. (4) The encoder is used to record the running state of the motor. It uses its own function to convert the motion state of the motor into electrical pulses and feed it back to the controller, so as to correct the deviation of the motor in the actual operation.

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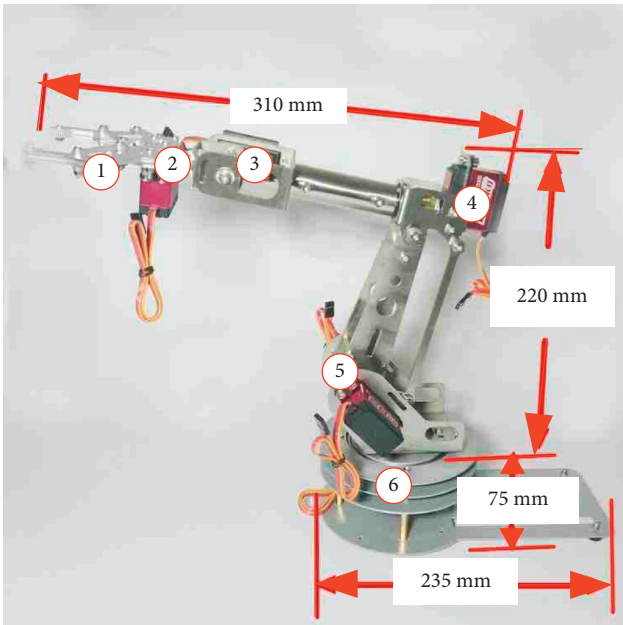

Figure 3: Experimental simulation of the robotic arm control unit.

Table 3: REBot-V-6R-650 technical parameters.

Mechanical structure	6 degrees of freedom in series
Load weight	3 kg
Positioning accuracy	±0.08 mm
Body weight	60 kg
Battery capacity	220 V 1.5KVA
Working radius	723 mm

Table 4: Specific parameters of joint axis.

	Maximum range of motion	Maximum speed (s)
1 axis	±170°	180°
2 axes	+135~ −45°	180°
3 axes	+130°~−70°	225°
4 axes	±170°	300°
5 axes	±120°	375°
6 axes	±360°	500°

The first step, as shown in Figure 5, is to establish a connection with the robotic arm. 10M Ethernet is used for communication between the upper computer and the robotic arm. It assigns each connected device in the same network segment its own IP address and uses the TCP/IP communication protocol. The pose of the robotic arm is judged after the connection is successful, and the trajectory planning information is obtained. At the robotic arm's end, it decomposes trajectory information into pose sequences. The inverse kinematics solution is used to obtain the desired angle of the joint corresponding to the robot arm pose of the trajectory point. After receiving the command, the motion card edits it and sends the parsed command to the motor's driver. At this point, the motor driver directs the robotic arm's joints to move, and the encoder determines the motor's position and adjusts it appropriately.

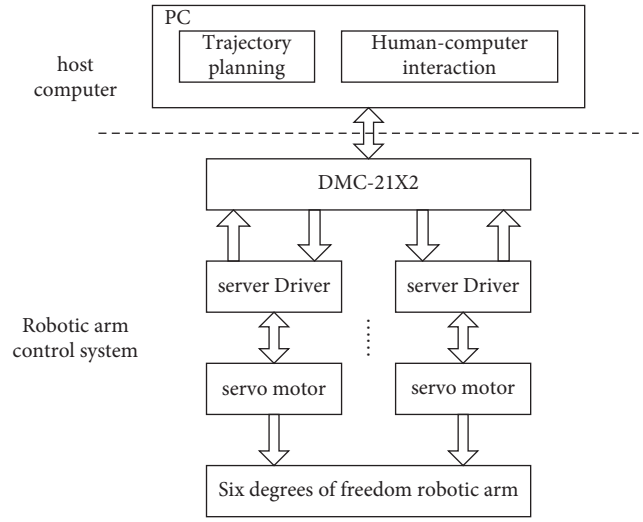

Figure 4: Hardware system structure diagram.

Kinematics analysis [19] (Kinematic Analysis) includes forward kinematics analysis (Forward Kinematic Analysis) and inverse kinematics analysis [20] (Inverse Kinematic Analysis). Forward analysis refers to the angle through the joint and the length of each link. It calculates the end information of the robotic arm, and the process is relatively simple. Reverse analysis refers to calculating the angle of each joint according to the mathematical method under the condition of obtaining the information of the end of the manipulator and the length of each link. Reverse analysis is much more difficult than forward solution. In order to solve the trajectory planning problem, we must first carry out kinematic analysis to find out the poses of the other joints when the end effector of the robotic arm is located at a certain point, and determine its joint angle.

5. Simulation Analysis of 6-DOF Robotic Arm

The idea of the inversion design method is to decompose a complex nonlinear system into multiple subsystems. It then designs the Lyapunov function (V function) for the subsystem to ensure the stability of the system and introduces virtual control quantities. The former system must achieve a stable effect through the virtual control of the latter system. If the order of the original system is n, then the system needs to be decomposed into n or less than n subsystems. The inversion method is often combined with a Lyapunov-type adaptive law to make the entire system meet the desired dynamic and static performance. The robotic arm system is a complex nonlinear system. As a universal approximator, fuzzy control is widely used in the study of nonlinear systems. It can be used to approximate the control law of the system directly, or it can be used to approximate the dynamic characteristics of the system, and then design the control law. The dynamic formula of the manipulator is

$$\{M(q)\ddot{q} + C(q,\dot{q}) + G(q) + d = \tau, y = q. \quad (1)$$

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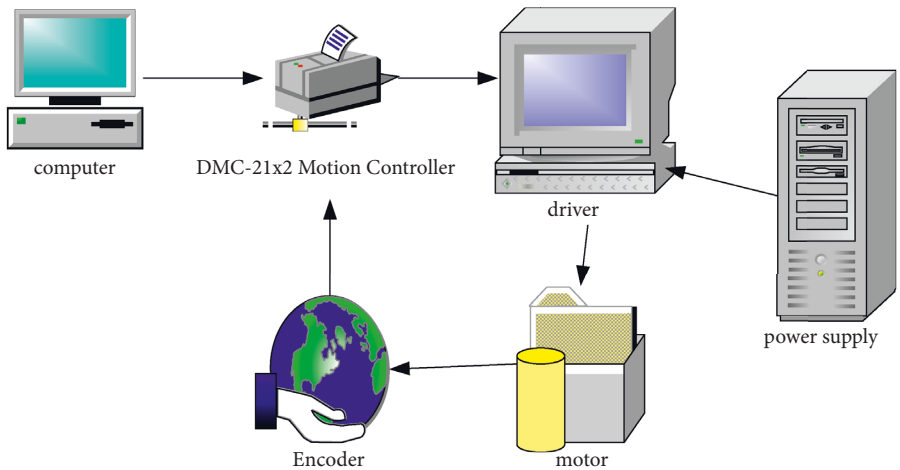

Figure 5: Motion control system components.

It is assumed that the parameters are unknown and bounded, and the system has the following characteristics:

(1) (q) is a positive definite matrix and bounded.

(2) The inertia matrix (q) has the following relationship with the centripetal force and Coriolis moment $(q, \dot{q})$:

$$x(\dot{M}(q) - 2C(q, \dot{q}))x^T = 0. \tag{2}$$

The main purpose of designing the control system is to make the output q_{d} of the control system well track the desired trajectory q_d.

According to the backstepping method, the control system is decomposed into two subsystems.

It defines $x_1 = q$, and $x_2 = q$, then combined with formula (1), the values of $\dot{x}_1 \dot{x}_2$ and y can be solved as follows:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = M^{-1}(x_1)\tau - M^{-1}(x_1)C(x_1, x_2)x_2 - M^{-1}(x_1)G(x_1) - M^{-1}(x_1)d, \\ y = x_1. \end{cases} \tag{3}$$

It assumes that y is the control objective, y_d is the desired trajectory, and y_d has a second derivative.

For the ith subsystem, the alternative Lyapunov function V_i is chosen as

$$V_i = V_{i-1} + \frac{1}{2b_i}e_i^2, \tag{4}$$

$b_1 = 1$ and $b_2 = M^{-1}$.

Step 1. For the first subsystem $\dot{x}_1 = x_2$, it defines the error as e_1 and introduces a virtual control variable a_1

$$\begin{cases} e_1 = y - y_d \\ e_2 = x_2 - \alpha_1. \end{cases} \tag{5}$$

It makes the value of e_2 approach zero by choosing a_1. Then,

$$\dot{e}_1 = \dot{x}_1 - \dot{y}_d = x_2 - \dot{y}_d = e_2 + \alpha_1 - \dot{y}_d. \tag{6}$$

It defines the virtual control quantity as

$$\alpha_1 = -\lambda_1 e_1 + \dot{y}_d, \tag{7}$$

$\lambda_1 > 0$.

For the first subsystem in formula (1), it takes the Lyapunov function as

$$V_1 = \frac{1}{2}e_1^T e_1. \tag{8}$$

Then,

$$\dot{V}_1 = -\lambda_1 e_1^T e_1 + e_1^T e_2. \tag{9}$$

If $e_2 = 0$, the first subsystem is stable.

Step 2. It designs the control law

From formulas (1) and (4), we get

$$\dot{e}_2 = -M^{-1}Cx_2 - M^{-1}G - M^{-1}d - M^{-1}\tau - \dot{\alpha}_1. \tag{10}$$

It takes the control law as

$$\tau = -\lambda_2 e_2 - e_1 - \varphi. \tag{11}$$

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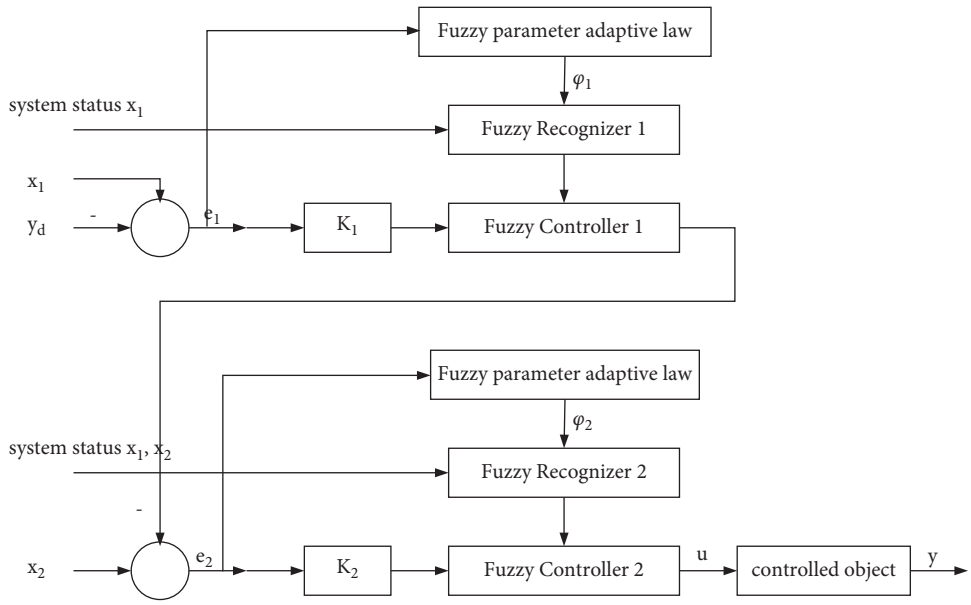

Figure 6: Adaptive fuzzy inversion control.

For the second subsystem in formula (4), it takes the Lyapunov function as

$$V_2 = V_1 + \frac{1}{2}e_1^T M e_2. \tag{12}$$

Then,

$$\dot{V}_2 = -\lambda_2 e_1^T e_1 - \lambda_2 e_2^T e_2 + e_1^T (f - \varphi) - e_2^T d. \tag{13}$$

In

$$\mathrm{f} = -\mathrm{C}\alpha_1 - M\dot{\alpha}_1 - G, \tag{14}$$

the function f contains the inertia matrix C the Coriolis force matrix M and the gravity matrix G of the robotic arm and contains the modeling information of the system. The derivative of the unknown function and virtual control term in the system needs to be approximated by a fuzzy system. Assuming that φ is a fuzzy system used to approximate f, it needs to be defuzzified by single-valued fuzzification, product inference engine, and centroid-averaged defuzzification.

It assumes that the fuzzy system consists of N fuzzy rules, where the f fuzzy rule is expressed as

$$R^i\text{: IF } x_i \text{ is } u_1^i \text{ and} \ldots x_n \text{ is } u_n^i, \text{then } y \text{ is } B^i\ (i = 1, 2, \ldots, N), \tag{15}$$

where u_j^i is the membership function of x_i $(j = 1, 2, ..., N)$.

Then, the output of the fuzzy system is defined as

$$\mathrm{y} = \sum_{i=1}^{N} \theta_i \frac{\prod_{j=1}^{n} u_j^i(x_j)}{\sum_{i=1}^{N}\prod_{j=1}^{n} u_j^i(x_j)} = \xi^T(x)\theta. \tag{16}$$

In

$$\xi = [\xi_1(x)\xi_2(x)\ldots\xi_N(x)]^T,$$
$$\xi_i(x) = \frac{\prod_{j=1}^{n} u_j^i(x_j)}{\sum_{i=1}^{N}\prod_{j=1}^{n} u_j^i(x_j)}, \theta = [\theta_1\theta_2\ldots\theta_N]^T. \tag{17}$$

For the fuzzy approximation of the f function, it adopts the form of approximating $f(1)$ and $f(2)$, respectively, and the corresponding fuzzy system is designed as

$$\varphi_1(x) = \frac{\sum_{i=1}^{N} \theta_{1i} \prod_{j=1}^{n} u_j^i(x_j)}{\sum_{i=1}^{N}\prod_{j=1}^{n} u_j^i(x_j)} = \xi_1^T(x)\theta_1,$$
$$\varphi_2(\mathrm{x}) = \sum_{i=1}^{N} \theta_{2i} \frac{\prod_{j=1}^{n} u_j^i(x_j)}{\sum_{i=1}^{N}\prod_{j=1}^{n} u_j^i(x_j)} = \xi_2^T(x)\theta_2. \tag{18}$$

It defines

$$\Phi = [\varphi_1\varphi_2]^T = \begin{bmatrix} \xi_1^T & 0 \\ 0 & \xi_2^T \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \xi^T(x)\theta. \tag{19}$$

It defines the optimal approximation constant θ^* , for a given arbitrarily small constant ε $(\varepsilon > 0)$, the following inequality holds as $\|f - \Phi^*\| \le \varepsilon$.

It makes $\tilde{\theta} = \theta^* - \theta$, and the adaptive control law is designed as

$$\dot{\theta} = r\left(e_2^T \xi^T(x)\right)^T - 2k\theta. \tag{20}$$

The adaptive fuzzy inversion control process is shown in Figure 6.

For the variation range of the input value of the fuzzy system, it defines the fuzzy set: negative N, zero Z, and positive P and takes the fuzzy membership function. The function design is shown in Figure 7.

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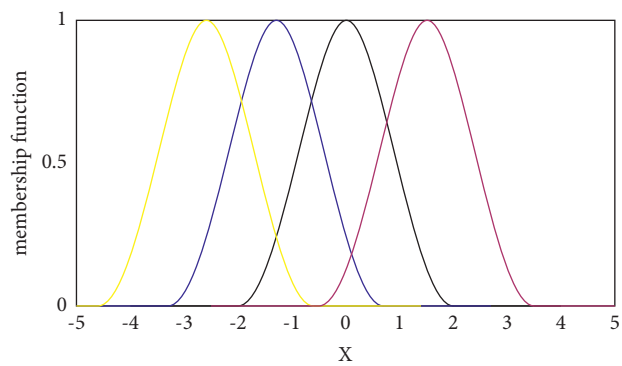

Figure 7: Design of membership function of fuzzy system.

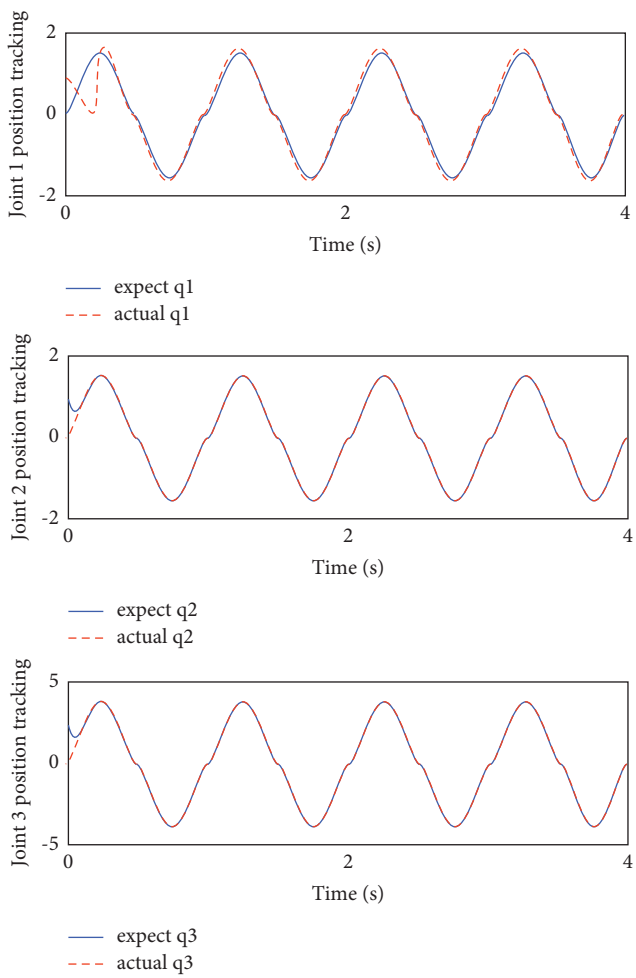

Figure 8: Position tracking trajectory of the three-joint robotic arm.

It adopts control law 10, adaptive law 22, and takes $\lambda_1 = 30$, $\lambda_2 = 50$, $k = 1.5$, and $\gamma = 2$. The desired trajectory of the three joints is $y_d = \sin(2\pi t)$. Its simulation result is shown in Figure 8, and the control input signal is shown in Figure 9.

Figure 8 shows that when the system begins to move, there is a large difference between the actual and expected trajectory due to the presence of disturbance. However, over time, the fuzzy inversion control algorithm can gradually

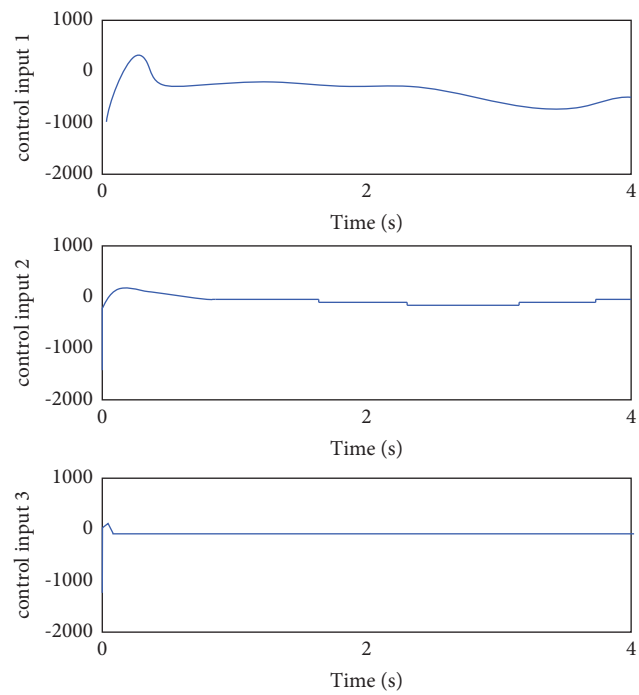

Figure 9: Control input signal of three-joint robotic arm.

compensate for the system's impact from this repeated disturbance. Although the three joints are better at tracking the established trajectory, there are still errors. Figure 9 shows that for the established three-joint dynamic model, joint 1 receives the largest moment during motion, followed by joint 2, and joint 3 receives the smallest. In addition, in the presence of disturbances, different torques are required to control the joint movement and bring the tip to the desired position. Because a large torque is required to overcome the disturbance, the torque fluctuation is high at the start of the movement. The moment of joint 2 and joint 3 will, however, tend to be stable due to the repeatability of the disturbance.

6. Conclusion

The manipulator is an extremely complex system with nonlinearity, strong coupling, and numerous input and output parameters. The trajectory tracking control of the 6-DoF manipulator must be studied step by step in order to be realized. The following is the overall research concept of this paper. It first models the manipulator's forward kinematics and then solves for its inverse kinematics. In order to achieve high-precision control of the trajectory due to the presence of disturbances in practice, it is necessary to investigate the system's trajectory tracking control algorithm. It plans the manipulator's trajectory and simulates it using fifth-order polynomial interpolation and spatial linear interpolation. It obtains the changing process of each joint variable and intuitively demonstrates the trajectory planning process of the robotic arm. However, this paper only investigates the kinematics analysis, trajectory planning, and tracking control of the manipulator and does not actually control the

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manipulator. The robotic arm research is extensive, and there are numerous aspects that can be explored further.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors have no conflicts of interest.

Acknowledgments

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