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# Fuzzy PID Control Performance Analysis for Robotic Arm System Research

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***Abstract*—** *The need for robotic arm control in the realm of industrial automation is growing as technology progresses. In view of the challenges of speed step, external disturbance and joint friction leading to the loss in control accuracy in robotic arm trajectory tracking, the classic PID control system is difficult to meet the requirements of high-precision operation. In order to maximize the dynamic responsiveness, this research suggests a fuzzy PID control scheme [1]. In the MATLAB/simulink environment, the KUKA KR6R700 six-axis robotic arm serves as the simulation object. The results demonstrate that compared with the traditional PID control system, the fuzzy PID control system shortens the joint adjustment time by ≥43.72% (reduced by 2.37s), considerably improves the fit of the robotic arm joint trajectory, and has less trajectory deviation and smoother transition. Its capacity to retain great robustness and trajectory tracking even in challenging work situations is particularly impressive. According to research, the suggested approach can significantly increase robotic arms' motion control accuracy in automated production workshops.*

***Keywords*— Robotic arm, PID control, fuzzy control**

## I. INTRODUCTION

Robotic arms, a key component of industrial automation, are indispensable in automated production lines because of their small size, manageable cost, and adaptable deployment. Robotic arm trajectory tracking has long been plagued by issues such speed step changes, external disturbances, and reduced control precision due to joint friction. However, their control performance directly influences their working accuracy. Conventional PID control methods are inadequate to deal with nonlinear elements such joint friction, unknown external disturbances, and model parameter changes. This can easily result in excessive overshoot, delayed response, trouble removing steady-state errors, and even oscillations. This study suggests a fuzzy PID control system as a workable and efficient option for high-precision, high-efficiency, and high-reliability motion control of robotic arms in automated production workplaces.

## II. ESTABLISHMENT OF KINEMATIC MODEL AND MOTION TRAJECTORY OF ROBOTIC ARM

The kinematic model of the robotic arm is the basis for describing its position and posture changes. The KUKA KR6R700 six-axis robotic arm, which is commonly used in automated production workshops, is taken as the research object. [2] This robot has a serial robotic arm with six degrees of freedom. The structure includes a base joint, waist joint, upper arm joint, forearm joint, wrist rotation joint and wrist swing joint. The KR6R700 robotic arm has a load capacity of 6kg and a repeatability of ±0.03 mm, which is suitable for precision assembly tasks in automated production workshops. The structural parameters of the robotic arm are shown in Table 1.

*Table 1. Structural parameters of robotic arm*

| Parameter | Wrist swing joint | Wrist rotation joint | Forearm joint | Upper arm joint | Lumbar joint | Base joint |
|---|---|---|---|---|---|---|
| Maximum rotation Angle/(∘) | ±360 | ±360 | ±130 | ±150 | ±185 | ±360 |
| Member length/mm | 85 | 90 | 210 | 480 | 110 | 0 |

The robotic arm consists of multiple links and joints. The movement of each joint can be described by the joint angle, as shown in Figure 1.

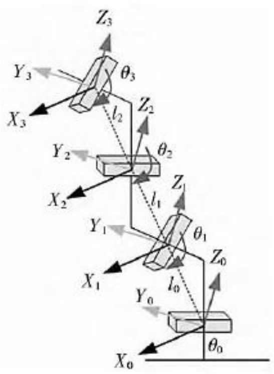


*Fig.1. Kinematic model of the robotic arm*

Let the link length of the robotic arm is $l = \{l_0, l_1, l_2, \dots, l_n\}$, the Joint angle is $\theta = \{\theta_0, \theta_1, \theta_2, \dots, \theta_n\}$, The position of the end effector that controls the movement of the robotic arm $\{x, y, z\}$ can be calculated using kinematic equations, as shown in equation (1).

$$\begin{cases} x = l_0 \cos\theta_0 + l_1 \cos(\theta_0 + \theta_1) + \cdots + \\ \quad l_n \cos(\theta_0 + \theta_1 + \ldots + \theta_n \\ y = l_0 \sin\theta_0 + l_1 \sin(\theta_0 + \theta_1) + \cdots + \\ \quad l_n \sin(\theta_0 + \theta_1 + \ldots + \theta_n) \\ z = \lambda_0 + \lambda_1 + \ldots + \lambda_n \end{cases} \quad (1)$$

where $(\lambda_0, \lambda_1, \dots \lambda_n)$ represents the offset (cm) of the robotic arm link in the Z-axis direction.

To achieve precise motion control of the robotic arm, its motion trajectory needs to be planned. The motion trajectory can be divided into three stages: the initial acceleration stage, the intermediate constant speed stage, and the final deceleration stage. Assuming the total motion time of the robotic arm is T, and the acceleration time of the initial and final stages is $t_1$, then in the initial stage, the motion trajectory of the serial robotic arm is a parabola with constant angular acceleration. The change law of the joint angle $\theta(t)$ can be expressed as equation (2).

$$\theta(t) = \theta_0 + \frac{at^2}{2}, (0 \le t \le t1) \quad (2)$$

where $\theta_0$ is the initial joint angle and a is the angular acceleration.

The change law of the joint angle is given by equation (3).

$$\theta(t) = \theta(t_1) + \varepsilon(t - t_1), (t_1 < t < T - t_1) \quad (3)$$

where $\varepsilon$ is the angular velocity during the uniform velocity phase.

The robotic arm descends to the target point along a parabolic trajectory, and the change in joint angles follows the formula (4).

$$\theta(t) = \theta(T - t_1) + \varepsilon(T - t_1) - \frac{\alpha(T - t_1)^2}{2}, \quad (T - t_1 < t < T) \quad (4)$$

By planning the motion trajectory as described above, the speed jump during the transition from acceleration to constant speed in the robotic arm can be eliminated. This allows for smoother movement of the robotic arm and reduces trajectory tracking errors.

Based on the above analysis of the motion trajectory and modeling of the robotic arm joint drive system, the input angle $\theta(s)$ and output angle $U(s)$ of the robotic arm joint motion are calculated, and the transfer function formula (5) is established.

$$G(s) = \frac{U(s)}{\theta(s)} = \frac{s + 5}{s^2 + 4s + 5} \quad (5)$$

where $U(s)$ is the Laplace transform of the joint output angle and $\theta(s)$ is the Laplace transform of the joint angle input.

We can obtain the undamped natural frequency of the system is $\omega_n = \sqrt{5} \approx \frac{2.236rad}{s}$ and the damping ratio is $\xi = \frac{2}{\sqrt{5}} \approx 0.894$. Its control system is a minimum-phase second-order underdamped system.

Dynamic performance analysis shows that the system has excellent transient response characteristics: extremely small overshoot. After zero-point correction, it is about 0.5%-1%), the rise time is $t_r \approx 2.6$ s, the settling time is $t_s$ (±5% error band) about 1.5 s, the convergence speed is fast and the operation is stable; however, since the system is a zero-type system (without an integral element), there is a steady-state error of $e_{ss}=0.5$ for a unit step input. The frequency domain analysis results are shown in Figures 2 and 3.

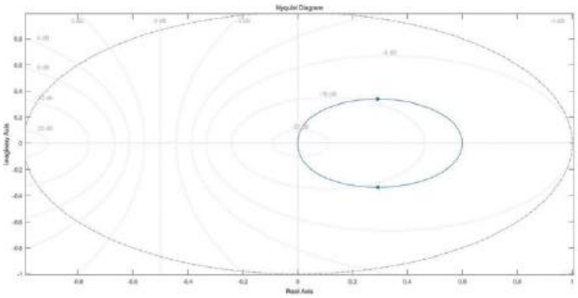

*Fig.2. Nyquist Diagram*

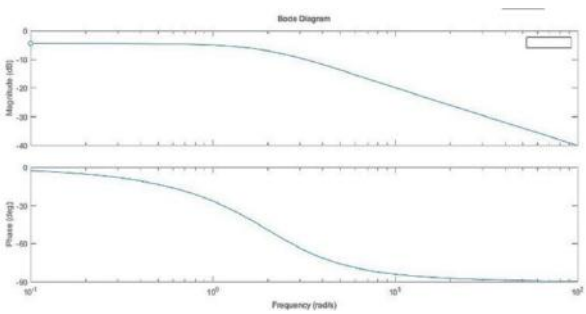

*Fig.3. Bode Diagram*

The system amplitude expression is as $|G(j\omega)| = \frac{\sqrt{\omega^2+25}}{\sqrt{\omega^4+6\omega^2+25}}$ and phase angle is $\angle G(j\omega) = \tan^{-1}\left(\frac{\omega}{5}\right) - \tan^{-1}\left(\frac{4\omega}{5-\omega^2}\right)$ . Its amplitude-frequency response exhibits monotonically decaying across the entire frequency range with an amplitude consistently ≤0dB, no resonant peak (due to $\xi > 0.707$), a phase margin of 180°, and an amplitude margin of GM = ∞. Furthermore, the closed-loop characteristic curve is entirely located in the left half-plane. This indicates that the system possesses absolute stability and high resistance to high-frequency interference. Overall, this system demonstrates outstanding dynamic stability and is suitable for applications requiring moderate tracking accuracy from the robotic arm while prioritizing operational stability and interference resistance.

## III. TRADITIONAL PID CONTROL SYSTEM PRINCIPLE

PID control is the most common classical control method in control systems. [3] It uses the set value and the actual output value to form the control deviation, and combines the deviation with proportional (P), integral (I) and derivative (D) to form the control quantity, so as to control the controlled object and make its system output accurately and stably track the target value. Due to its simple structure, good robustness and no need for an accurate system mathematical model, PID control is widely used in industrial automation and other fields. The working principle of the PID control system is shown in Figure 4.

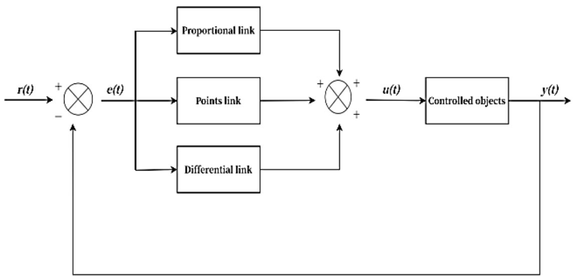


*Fig.4. Working principle of PID control system*

The expression for the traditional PID control as.

$$u(t) = K_p e(t) + k_i \int e(t)d(t) + k_d \frac{de(t)}{dt} \quad (6)$$

where $K_P$ is the proportional coefficient, $K_I$ is the integral coefficient, $K_D$ is the derivative coefficient, $e(t)$ is the error between the set value and the actual output value, and $u(t)$ is the controller output.

## IV. TRADITIONAL PID CONTROL SYSTEM PRINCIPLE

Fuzzy PID control algorithm is a new type of control method that combines traditional PID control with fuzzy logic theory [4]. It combines the reliability of traditional PID control with the advantages of fuzzy logic theory in dealing with uncertainty and nonlinear problems. Its control system can dynamically adjust the PID parameters according to the real-time running state of the controlled object, thereby effectively overcoming the limitations of traditional PID control in dealing with complex systems such as nonlinearity, time-varying and large delay. The core of the algorithm is to adjust the proportional ($K_P$), integral ($K_I$) and derivative ($K_D$) coefficients online adaptively according to the real-time error (e) and error change rate (ec) of the system using a set of pre-designed fuzzy control rules, so that the system can obtain good dynamic performance with small overshoot, fast response and strong robustness. The working principle of the fuzzy PID control system is shown in Figure 5.

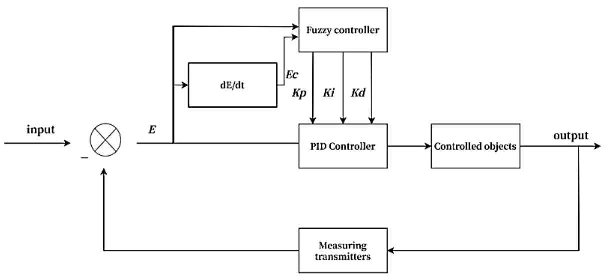


*Fig.5. Working principle of fuzzy PID control system*

The fuzzy controller mainly consists of three modules: fuzzification, fuzzy inference, and defuzzification as Figure 6.

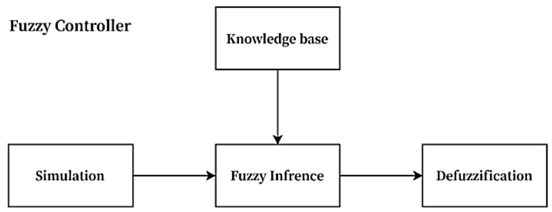


*Fig.6. Fuzzy rule base structure framework diagram*

As shown in Figures 5 and 6, the system introduces a fuzzy control rule based on the traditional PID control loop. The rule takes the system deviation e and its rate of change ec as inputs, performs fuzzy inference calculations to output the PID parameter corrections ($\Delta K_p$, $\Delta K_i$, and $\Delta K_d$) as shown in Equation (7), thereby achieving online automatic optimization of PID parameters.

$$\begin{cases} \Delta K_p = K_p + K_{pp} \\ \Delta K_i = K_i + K_{ii} \\ \Delta K_d = K_d + K_{dd} \end{cases} \quad (7)$$

In the fuzzy rule setup, the membership functions of input variables all adopt smoothly curved Gaussian functions, with the fuzzy linguistic values divided into five levels: {Negative Big (NB), Negative Medium (N), Zero (ZE), Positive Small (P), Positive Big (PB)}. The output variables are the adjustment amounts $\Delta K_p$, $\Delta K_d$, and $\Delta K_i$ for the three PID parameters. To ensure computational simplicity and output clarity, the membership functions for output variables employ simple triangular functions, with fuzzy linguistic values categorized into four levels: {Extremely Small (MS), Small (S), Medium (B), Extremely Big (MB)}. Fuzzy rules are established based on the fuzzy rule table, as shown in Table (1). The system dynamically adjusts the PID parameters in real-time according to pre-defined fuzzy control rules to adapt to different operational states of the robotic arm.

## V. CONTROL SYSTEM SIMULATION EXPERIMENT

To investigate the impact of PID controllers on the control system of robotic arms, a simulation model of joint angle changes in PID control of robotic arms was first constructed based on MATLAB/Simulink environment (as shown in Figure 8) for simulation experiments [5]. In this model, the KUKA KR6R700 industrial robot is taken as the research object, and the input angle of the robotic arm joint is set to 120°, while the output results reflect the angle changes of the robotic arm joint. Through the model and dynamic simulation process, the working principle of the PID controller and the impact of parameter adjustment on the system's dynamic performance can be intuitively understood.

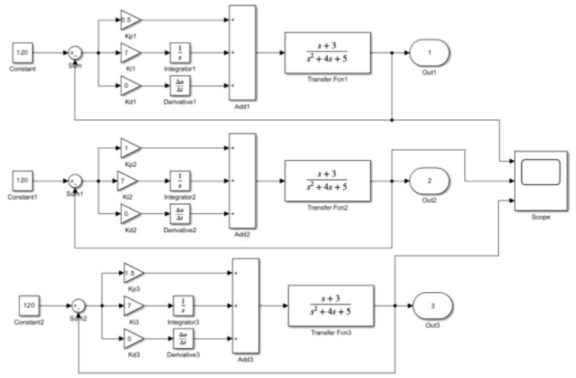


*Fig.7. MatLab/Simulink*

In the study of the influence of the comparative coefficient $K_p$ on the dynamic characteristics of the robotic arm control system, control variables were set in SIMULINK simulation: integral coefficient $K_i$ and differential coefficient $K_d$ were set as initial values ($K_i$=6, $K_d$=0.4), the input angle of the robotic arm joint was set to 120 °, and the proportional coefficient $K_p$ was set to three different values of 0.8, 1, and 1.2, respectively. The dynamic characteristic curves of the control system were analyzed under different proportional coefficients $K_p$. As shown in Figure 8. Within the selected range of $K_p$ values, the output angle response of the robotic arm can gradually converge to the target angle of 120° after experiencing brief fluctuations, indicating overall stability of the system. Further analysis of the dynamic characteristics reveals that as the value of $K_p$ increases, the maximum overshoot of the system shows a decreasing trend, and the response time required to reach steady state is correspondingly shortened, resulting in an improvement in response speed. This rule indicates that an appropriate increase in the proportional coefficient $K_p$ can optimize the control system's regulation capability. In PID control, the integral and derivative stages are the core components for achieving "zero static error regulation" and "leading suppression of overshoot". The influence of the integral coefficient $K_i$ and differential coefficient $K_d$ of the PID controller on the dynamic characteristics of the robotic arm control system was studied. Simulation experiments were conducted using the control variable method: the input angle of the robotic arm was set to 120°, and the proportional parameter $K_p$=1. The integral parameter $K_i$ and differential parameter $K_d$ were adjusted separately to observe the changes in the dynamic characteristics of the control system. The corresponding simulation results are shown in Figures 8, 9 and 10

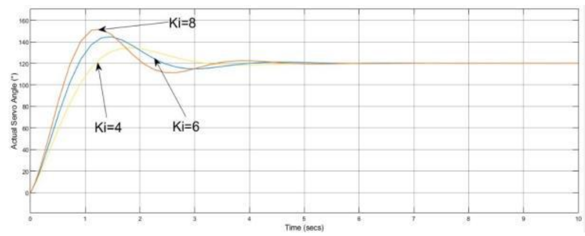


*Fig.8. The Influence of Scale Coefficient $K_p$ on the Dynamic Characteristics of Control System*

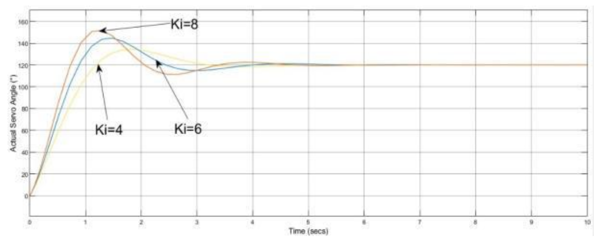


*Fig.9 The Influence of Integral Coefficient $K_i$ on the Dynamic Characteristics of the Control System*

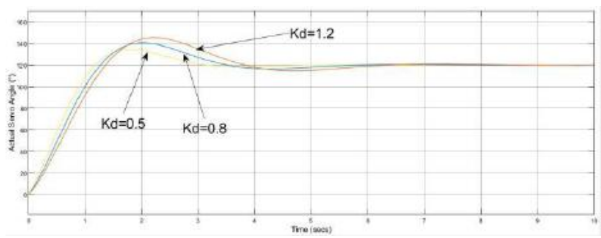


*Fig.10. The Influence of Differential Coefficient $K_d$ on the Dynamic Characteristics of Control System*

As shown in Figure 9, when $K_i$ is set to 4, 6, and 8, the control system can ultimately converge to the target angle of 120°. However, the dynamic performance shows a significant increase in maximum overshoot and adjustment time as Ki increases. The frequency of system oscillations increases, and the stability gradually weakens. From the perspective of control principles, the integration process eliminates static errors by accumulating deviations. However, if the value of $K_i$ is too high, it will accelerate the accumulation rate of errors, increase the phase lag of the system, break the balance between "deviation adjustment response feedback", and cause oscillation instability. Therefore, $K_i$ needs to seek a balance between static error elimination ability and dynamic stability.

From Figure 10, it can be observed that as the differential coefficient $K_d$ increases (with $K_d$ values of 0.4, 0.8, and 1.2), the maximum overshoot of the system increases, the response speed slows down, and the adjustment time also increases accordingly. In the analysis of PID control principle, the differential coefficient $K_d$ can mainly predict the future error, provide the response to the error change rate, play the role of advance regulation and enhance the stability of the system. However, if the differential coefficient $K_d$ is too large, the system will become unstable and prone to introducing high-frequency noise. Therefore, the differential coefficient $K_d$ should be appropriately selected.

Study the influence of PID controller and fuzzy PID controller on the dynamic characteristics of robotic arm control system. Based on MATLAB/Simulink environment, taking KUKA KR6R700 industrial robot as the research object, a traditional PID control simulation model and a fuzzy PID control simulation model of the robotic arm control system are established. The joint input angle of the robotic arm is set to 120°, and the controller parameters are set as proportional coefficient ($K_p$=0.8), integral coefficient ($K_i$=8), and differential coefficient ($K_d$=1.2). A dynamic performance comparison analysis of the two control strategies is carried out.

In traditional PID control models, the research object is directly controlled through the proportional integral derivative process. The fuzzy PID control model introduces a fuzzy logic controller with "e" and "ec" as inputs. After fuzzification, fuzzy inference, and deblurring, the parameters $K_p$, $K_i$, and $K_d$ are adaptively adjusted online to achieve dynamic optimization control of the joint angle changes of the robotic arm. Comparison simulation model between PID control and fuzzy PID control, as shown in Figure 11; Comparison of system dynamic performance between fuzzy PID control and PID control, as shown in Figure 12

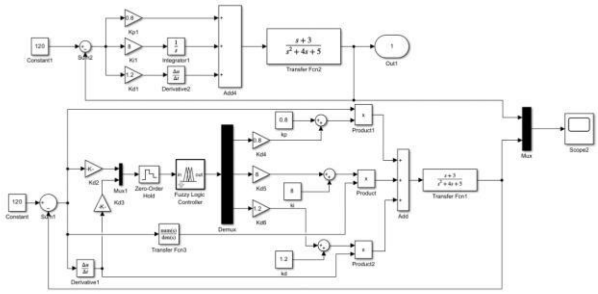

*Fig.11. Comparison simulation model between PID and fuzzy PID control*

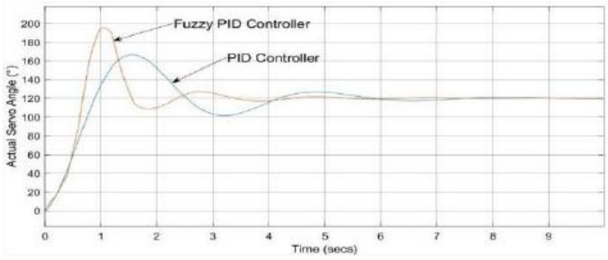


*Fig.12. The Influence of PID Control and Fuzzy PID Control on the Dynamic Characteristics of the System*

From the perspective of control principles, PID control systems have fixed parameters, which limits their adaptability to controlled objects with nonlinearity and time-varying characteristics such as robotic arms. They are prone to problems such as overshoot, large amplitude, or slow adjustment time; The fuzzy PID control system achieves real-time online adjustment of PID parameters through fuzzy rules, significantly improving the robustness and dynamic performance of the system. Experiments have shown that fuzzy PID control, with its parameter adaptive mechanism, effectively compensates for the shortcomings of PID control systems in nonlinear time-varying systems. Enable the robotic arm to have higher positioning accuracy, fast response speed, and stable dynamic performance in complex working environments. This provides a more advantageous control solution for precise trajectory tracking and operation of robotic arms.

Study the influence of fuzzy rule levels on the dynamic performance of robotic arm control systems, based on MATLAB/Simulink environment, using KUKA KR6R700 industrial robot as the research object. In the design of a fuzzy PID control system, error e and error change rate ec are used as inputs for the fuzzy PID, and $\triangle K_p$, $\triangle K_i$, and $\triangle K_d$ are used as outputs. Fuzzy Logic Toolbox is used to construct 3, 5, and 7 level fuzzy inference systems (FIS) with 9, 25, and 49 rules, respectively. To eliminate the interference of membership function types on the dynamic performance of the control system, Gaussian membership functions are used for input variables and triangular membership functions are used for output variables, with only the density of language variable partitioning adjusted; The simulation model of the fuzzy PID control system for the robotic arm under different levels of fuzzy rules is shown in Figure 13; The influence of fuzzy rule levels on the dynamic performance of robotic arm control systems is shown in Figure 14

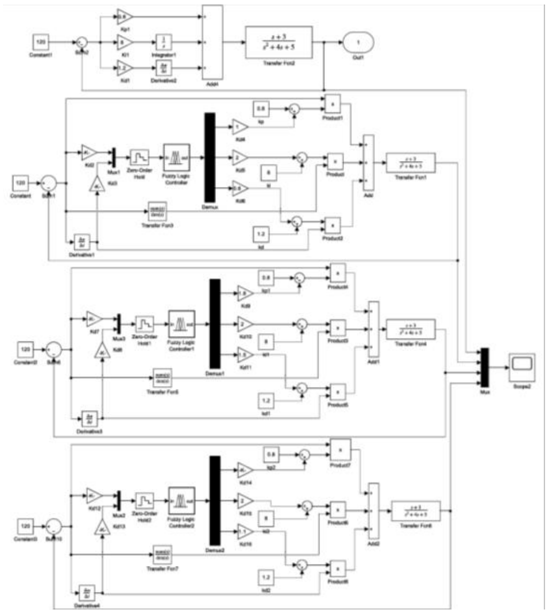

*Fig.13. Simulation models of different levels of fuzzy PID*

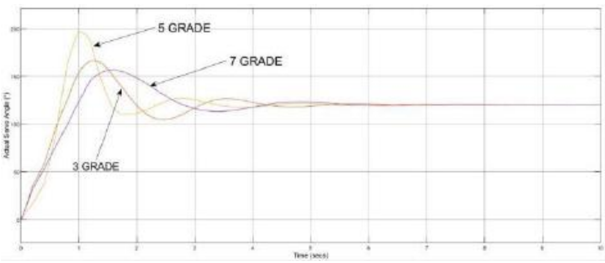


*Fig.14. The Influence of Fuzzy Rule Levels on the Dynamic Performance of Robot Arm Control Systems*

According to the simulation results, the rise time of the 3-level fuzzy PID control system is 0.78 seconds, but its fuzzy rule division is relatively simple, and the accuracy of the angle error and error change rate of the robotic arm is insufficient, resulting in overshoot reaching 0.383%, adjustment time of 3.71 seconds, and poor dynamic adjustment performance; Although the 7-level fuzzy PID control system has improved accuracy by increasing the number of rules and reducing overshoot to 0.30%, excessive rules can easily lead to rule redundancy and logical contradictions, resulting in delayed system response. The rise time is extended to 0.98s, the adjustment time is also increased to 3.81s, and the overall dynamic response speed is significantly reduced; The 5-level fuzzy PID control system achieves a good balance between rule refinement and system response characteristics. It not only shortens the rise time to 0.68s and the adjustment time to 3.05s, but also controls the overshoot within a reasonable range of 0.625%, making it a good fuzzy rule level scheme suitable for this robotic arm control system. In summary, it can be concluded that in the rule design of fuzzy PID control systems, the number of fuzzy rule levels is not necessarily better. Excessive increase in levels can lead to rule redundancy and contradictions, which in turn can reduce system control performance; The optimal control effect can only be achieved when the partition density of fuzzy rules matches the dynamic characteristics of the controlled system and a balance point between performance and rule rationality is found.

In addition, to investigate the trajectory tracking capability and stability of the PID control system and fuzzy PID control system mentioned above. Based on MATLAB/Simulink environment, establish traditional PID control simulation model and fuzzy PID control simulation model for robotic arm control system, and set a step disturbance input signal at time=10s. The dynamic performance comparison chart of the system is shown in Figure 15.

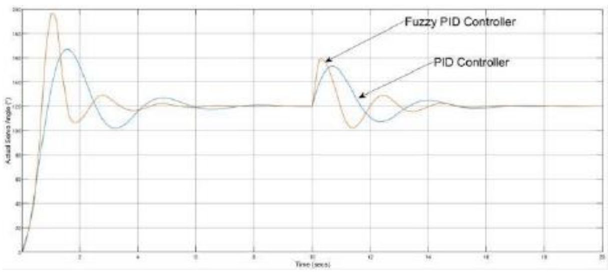


*Fig.15. Dynamic characteristic curve of control system under interference signal*

Based on the above dynamic performance indicators, the trajectory tracking performance of the PID control system and the fuzzy PID control system is compared. Compared with the traditional PID control system, the fuzzy PID control system improves the response speed by 10.59% (reducing 0.32s) under the influence of interference signals, significantly improves the joint trajectory fit of the robotic arm, and reduces trajectory deviation. Especially in the face of complex work environments, it maintains strong robustness and trajectory tracking ability.

## VI. CONCLUSION

This study focuses on the complex working environment of automated production workshops, where the trajectory tracking of robotic arms suffers from long-term problems such as speed steps, external disturbances, and reduced control accuracy caused by joint friction. The traditional PID control system lacks the ability to handle nonlinear factors and cannot meet the requirements of high-precision operations. Therefore, a fuzzy PID adaptive control method is proposed. The MATLAB/SIMULINK simulation experiment on the KUKA KR6R700 six axis robotic arm shows that the proposed method significantly improves control performance. Compared with traditional PID control systems, the joint adjustment time of the robotic arm is shortened by ≥ 43.72% (reduced by 2.37 seconds), and the joint trajectory fit of the robotic arm is significantly improved. The trajectory deviation is small and the change is smoother. Especially in the face of complex work environments, it maintains strong robustness and trajectory tracking ability. Research has shown that the proposed solution can effectively improve the motion control accuracy of robotic arms in automated production workshops.

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