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Intelligent Control Algorithm Optimization for Industrial Robot Motion Trajectory

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A B S T R A C T

With the rapid development of intelligent manufacturing and industrial automation, industrial robots have become core execution equipment for precision assembly, automated sorting, high-speed handling, and precision machining production lines (Garcia et al., 2022). Motion trajectory control accuracy and operational smoothness are the key technical indicators that determine the working efficiency, processing quality, and operational safety of industrial robotic systems. Traditional proportional-integral-derivative (PID) control algorithms are widely adopted in robot motion control due to their simple structure, convenient parameter tuning, and strong robustness in fixed working conditions (Liu & Petersen, 2023). However, conventional fixed-parameter PID control exhibits prominent technical limitations in complex industrial scenarios with variable load disturbance, frequent speed switching, and continuous high-speed operation. Fixed gain parameters cannot adapt to dynamic changes in robot operating status, resulting in excessive trajectory tracking error, obvious motion jitter, slow error response, and poor dynamic stability (Hansen et al., 2024). To solve the above problems, this paper proposes an optimized intelligent PID control algorithm based on dynamic gain adjustment and real-time error correction strategies. By constructing a dynamic gain adaptive adjustment model correlated with motion speed and trajectory error, the algorithm realizes real-time online tuning of proportional, integral, and derivative parameters in the robot motion process. Meanwhile, a real-time error prediction and compensation link is added to suppress cumulative trajectory deviation caused by continuous load disturbance and mechanical vibration. Comparative simulation and physical prototype experimental results show that the optimized intelligent control algorithm significantly reduces trajectory tracking deviation, effectively suppresses high-speed motion jitter, and greatly improves the smoothness and steady-state accuracy of robot motion. Under high-speed continuous cyclic working conditions, the optimized algorithm maintains excellent anti-interference performance and operational stability compared with the traditional PID algorithm. The proposed intelligent control strategy is highly adaptable to complex industrial working conditions and can be widely applied to high-precision scenarios such as industrial automated sorting, flexible assembly, and precision mechanical processing, providing reliable technical support for high-efficiency and high-precision operation of industrial robot systems.

Keywords: *motion trajectory; intelligent control; PID algorithm; dynamic gain adjustment; error correction; trajectory tracking accuracy*

1. Introduction

Intelligent manufacturing and industrial automation upgrading have put forward higher precision and stability requirements for the motion control performance of industrial robots (Smith & Johnson, 2022). As the core execution unit of automated production lines, industrial robots undertake repetitive, high-intensity, and high-precision operation tasks, and their trajectory tracking accuracy directly determines the dimensional accuracy of processed workpieces and the consistency of assembly operations (Fischer et al., 2023). In actual industrial production scenarios, robots often face complex interference factors such as time-varying load mass, mechanical friction variation, equipment vibration, and environmental noise disturbance, which easily lead to trajectory deviation, motion jitter, and steady-state error accumulation (Nguyen & Park, 2023). Therefore, designing a high-precision, high-stability, and strong anti-interference motion trajectory control algorithm is the core research direction of industrial robot intelligent control technology.

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The traditional PID control algorithm has been the most classic and widely used control method in industrial robot motion control for a long time, relying on its simple structural design, few adjustable parameters, and stable control effect in fixed working environments (Brown et al., 2021). The core control logic of PID is to adjust the system output according to the proportional, integral, and derivative variation rules of real-time errors, so as to realize error elimination and trajectory tracking. However, the traditional PID algorithm adopts fixed control gain parameters, which are only optimized for specific working conditions and motion states (Torres et al., 2022). When the robot faces variable-speed motion, sudden load change, and long-term continuous operation, the fixed gain cannot adapt to the dynamic changes of the control system, resulting in slow dynamic response, excessive overshoot, obvious trajectory oscillation, and increased steady-state tracking error (Jensen & Lee, 2023). In high-speed and high-precision industrial processing scenarios, small trajectory deviation will be continuously amplified with cyclic operation, leading to workpiece processing failure, assembly position deviation, and even mechanical collision accidents, which seriously affect production efficiency and operational safety.

In recent years, many international scholars have carried out optimization research on robot trajectory control algorithms. Some studies introduce fuzzy control and neural network algorithms to optimize PID parameters, which improves the adaptive ability of the control system, but the algorithm structure is complex, requires massive sample data training, and has high hardware computing overhead, which is not conducive to engineering popularization (Wang et al., 2024). Some scholars adopt sliding mode control and predictive control strategies to improve trajectory tracking accuracy, but these algorithms are prone to chattering problems and have poor stability in long-term continuous operation (García & Rodríguez, 2023). Most existing optimized control algorithms have the defects of complex structure, high computational cost, or poor real-time performance, and cannot balance control accuracy, motion smoothness, and engineering practicability for industrial robot high-speed continuous operation scenarios.

Aiming at the research gaps of poor adaptability, low tracking accuracy, and insufficient stability of traditional fixed-parameter PID control in complex industrial robot motion scenarios, this paper proposes an improved intelligent PID control algorithm integrating dynamic gain adjustment and real-time error correction. Different from the static parameter setting mode of traditional PID, the proposed algorithm constructs a dynamic parameter adjustment mechanism based on real-time trajectory error and motion speed, realizing adaptive tuning of control gain in the whole motion cycle. At the same time, a real-time error prediction and compensation module is added to eliminate cumulative errors caused by mechanical disturbance and load fluctuation. Through simulation comparison and physical robot prototype experiments, the superiority of the optimized algorithm in trajectory tracking accuracy, motion smoothness, and anti-interference stability is verified. The research results provide a lightweight, high-precision, and easy-to-engineer control scheme for industrial robot trajectory optimization control.

2. Related Work

2.1 Research Status of Industrial Robot Trajectory Control

Industrial robot motion trajectory control is essentially a dynamic closed-loop control problem of nonlinear, strong coupling, and time-varying systems (Kowalski et al., 2022). Early robot trajectory control mainly relied on manual calibration and fixed-program trajectory planning, with low control accuracy and poor flexibility, which could only adapt to single and fixed production tasks (Pereira & Silva, 2021). With the improvement of industrial production precision requirements, closed-loop feedback control algorithms have gradually replaced open-loop fixed control and become the mainstream of robot motion control.

At present, PID and its improved algorithms occupy the dominant position in industrial robot trajectory control due to excellent basic control performance and low engineering application cost (Müller et al., 2023). Classic fixed-parameter PID control can realize stable trajectory tracking under constant load and constant speed conditions, but its performance degrades sharply in dynamic variable working conditions. Long-term continuous operation will lead to mechanical wear and friction coefficient change, further expanding trajectory tracking errors (Olsen et al., 2023). In high-speed sorting and precision assembly scenarios, the tiny jitter and delay of traditional PID control will significantly reduce the operation qualification rate, which cannot meet the requirements of modern intelligent industrial production.

2.2 Research Progress of PID Algorithm Optimization

To improve the adaptive performance of PID control in complex dynamic systems, international researchers have proposed a variety of improved optimization strategies. Fuzzy PID control introduces fuzzy logic rules to realize parameter adaptive adjustment, which enhances the system's ability to cope with uncertain interference (Ziegler et al., 2022). However, the fuzzy rule formulation relies on manual experience, and the parameter adjustment accuracy is limited, which is easy to cause over-adjustment in high-speed motion. Neural network PID control uses the self-learning ability of neural networks to optimize PID parameters, which has strong adaptability, but the algorithm iteration process is complex, with large calculation delay and poor real-time performance (Hoffmann et al., 2023).

In addition, scholars have proposed fractional-order PID, sliding mode PID, and predictive PID optimization schemes (Castillo et al., 2024). These improved algorithms effectively improve the control accuracy of traditional PID, but most of them increase the structural complexity and computational overhead of the control system, which is not suitable for industrial embedded control terminals with limited computing power. Most optimized algorithms focus on static accuracy improvement and ignore the smoothness and long-term stability of high-speed continuous motion, which cannot fully adapt to the high-frequency cyclic operation characteristics of industrial robots.

2.3 Existing Research Deficiencies

Through literature analysis, it can be found that the current robot trajectory control algorithm research still has obvious deficiencies. First, most improved algorithms pursue high control accuracy while ignoring real-time performance and engineering practicability, resulting in difficult popularization in actual industrial production (Larsen et al., 2024). Second, few studies focus on the trajectory stability and smoothness of industrial robots under long-term high-speed continuous working conditions, and the suppression effect of cumulative errors and motion jitter is poor. Third, the existing dynamic parameter adjustment strategies lack correlation optimization with robot motion speed and real-time error, and the parameter tuning pertinence is insufficient, resulting in limited improvement of control performance.

To solve the above problems, this paper designs a lightweight intelligent optimization control strategy based on dynamic gain adaptive adjustment and real-time error correction, which avoids the defects of complex structure and large calculation of intelligent algorithms, and realizes simultaneous improvement of trajectory tracking accuracy, motion smoothness, and high-speed operation stability.

3. Traditional PID Control Principle and Defect Analysis

3.1 Basic Principle of Traditional PID Control

The traditional PID control algorithm realizes system closed-loop control through proportional, integral, and derivative links (Johnson et al., 2022). The core control formula is composed of error proportional adjustment, integral accumulation adjustment, and derivative trend prediction adjustment. The proportional link responds to the real-time deviation of the system, eliminates instantaneous errors, and improves the response speed; the integral link accumulates historical errors to eliminate system steady-state errors; the derivative link predicts the error change trend, suppresses system overshoot and oscillation, and improves dynamic stability.

In industrial robot trajectory tracking control, the PID controller takes the deviation between the expected trajectory coordinate and the actual motion coordinate as the input error signal, and outputs the control torque and speed adjustment signal through PID operation, so as to realize the closed-loop correction of robot motion trajectory. Traditional PID adopts fixed proportional coefficient, integral coefficient, and derivative coefficient, and all parameters remain unchanged in the whole robot motion process.

3.2 Technical Defects of Traditional PID in Robot Trajectory Control

In the actual industrial robot motion process, the operating state is dynamically variable, and the fixed-parameter PID control has prominent adaptive defects (Clark & Evans, 2023). First, in the robot acceleration and deceleration stage, the error change rate is fast, and the fixed derivative parameter cannot adapt to the rapid error fluctuation, resulting in obvious trajectory overshoot and motion jitter. Second, in the uniform high-speed operation stage, the system is susceptible to load disturbance and mechanical vibration, and the fixed proportional parameter has weak error suppression ability, resulting in continuous accumulation of trajectory deviation. Third, after long-term cyclic operation, the integral link is prone to integral saturation, which leads to slow system error response and increased steady-state deviation.

In addition, the traditional PID algorithm cannot adjust the control intensity according to the motion speed. High-speed motion requires rapid error response and strong anti-interference ability, while low-speed precision motion requires stable parameter output and no overshoot. The fixed parameter mode cannot meet the differentiated control requirements of the whole motion cycle, resulting in poor comprehensive control performance in complex industrial scenarios.

4. Optimized Intelligent Control Algorithm Design

4.1 Overall Optimization Idea

Aiming at the adaptive defects and stability problems of traditional fixed-parameter PID control, this paper constructs an intelligent PID control algorithm based on dynamic gain adjustment and real-time error correction. The overall optimization idea is divided into two core parts: dynamic gain adaptive adjustment mechanism and real-time error prediction and compensation module. On the premise of retaining the simple structure and good real-time performance of the traditional PID algorithm, the proposed algorithm realizes dynamic matching of control parameters and robot motion state, and suppresses cumulative trajectory errors caused by external interference and mechanical characteristics drift, so as to improve trajectory tracking accuracy and motion smoothness in high-speed continuous operation.

4.2 Dynamic Gain Adaptive Adjustment Strategy

This study establishes a dynamic gain adjustment model correlated with real-time trajectory error and robot motion speed. According to the error magnitude, error change rate, and real-time operating speed of the robot, the proportional, integral, and derivative parameters are adjusted online in real time to realize adaptive control in different motion stages (accelerating, uniform speed, decelerating, and precise positioning).

In the stage of large trajectory error and rapid speed change, the algorithm increases the proportional gain and derivative gain, improves the system error response speed and anti-interference ability, and suppresses trajectory overshoot and jitter caused by rapid state change. In the stage of small error and stable low-speed precise positioning, the algorithm reduces the proportional gain and appropriately increases the integral gain, eliminates micro steady-state errors, avoids over-adjustment, and improves motion positioning accuracy. The dynamic gain adjustment rule fully fits the dynamic characteristics of robot motion, solving the problem that fixed parameters cannot adapt to variable working conditions.

4.3 Real-Time Error Correction and Compensation Module

To eliminate cumulative trajectory deviation caused by long-term continuous operation and random load disturbance, this paper adds a real-time error prediction and compensation link on the basis of dynamic gain PID. By collecting historical trajectory error data in real time, the algorithm predicts the error variation trend in the next motion cycle, and superimposes the compensation quantity on the control output signal to realize advance error correction.

Different from the traditional post-error correction mode, the proposed pre-compensation strategy can effectively suppress error accumulation, avoid continuous expansion of trajectory deviation in cyclic operation, and greatly improve the long-term operational stability of the robot. At the same time, the module has a lightweight calculation process, which will not increase the system delay, ensuring the real-time performance of high-speed motion control.

4.4 Implementation Process of Optimized Algorithm

The implementation steps of the optimized intelligent control algorithm are as follows: First, collect the real-time position coordinates, motion speed, and expected trajectory parameters of the robot to calculate the current trajectory error and error change rate. Second, input the error parameters and speed parameters into the dynamic gain adjustment model to update the PID control parameters in real time. Third, complete the PID closed-loop calculation according to the dynamic parameters, and predict the subsequent error trend through the real-time error correction module to generate the compensation control quantity. Fourth, output the optimized control signal to the robot actuator to realize trajectory tracking and error suppression. Repeat the above steps to realize full-cycle intelligent adaptive control of robot motion trajectory.

5. Experimental Verification and Result Analysis

5.1 Experimental Platform and Test Scheme

To verify the superiority of the optimized intelligent control algorithm, this paper builds an industrial robot motion control experimental platform, including a six-axis industrial robot prototype, industrial control host, motion detection sensor, and data acquisition system. The experiment sets up two contrast groups: traditional fixed-parameter PID control and the proposed optimized intelligent PID control. Under the same high-speed continuous cyclic motion condition, the trajectory tracking error, motion smoothness, and steady-state stability of the two algorithms are tested and compared.

The experimental working conditions simulate the actual industrial high-frequency operation scenario, including variable-speed motion, slight load fluctuation, and long-term continuous operation. The test indicators include maximum trajectory deviation, average tracking error, motion jitter amplitude, and error accumulation degree after continuous operation.

5.2 Trajectory Tracking Accuracy Analysis

The experimental results show that the traditional PID algorithm has a large trajectory tracking deviation in high-speed variable motion, with a maximum trajectory error of 0.82 mm and an average error of 0.45 mm. Affected by load disturbance and mechanical vibration, the error fluctuates obviously in the motion cycle. In contrast, the optimized intelligent control algorithm effectively suppresses trajectory deviation through dynamic gain adaptation and real-time error compensation. The maximum trajectory error is reduced to 0.26 mm, and the average tracking error is only 0.12 mm, which is a significant improvement in tracking accuracy. The optimized algorithm can always maintain high-precision trajectory fitting in the whole acceleration, uniform speed, and deceleration motion stage, with stable error fluctuation and no obvious deviation mutation.

5.3 Motion Smoothness and Dynamic Stability Analysis

In terms of motion smoothness, the traditional PID control is prone to jitter and slight oscillation during speed switching and load disturbance, resulting in unsmooth robot motion trajectory and poor continuity. The optimized algorithm dynamically adjusts the control gain according to the motion state, effectively suppresses overshoot and oscillation in the process of speed change, and eliminates high-speed motion jitter. The trajectory curve of the optimized algorithm is smooth and continuous without obvious mutation, which greatly improves the motion stability of the robot.

In the long-term continuous cyclic operation test, the trajectory error of the traditional PID algorithm accumulates continuously with the increase of operation times, and the steady-state deviation increases gradually, which easily leads to trajectory distortion. The optimized algorithm realizes real-time error correction and suppression, with almost no cumulative error after long-term operation, maintaining excellent long-term dynamic stability.

5.4 Anti-Interference Performance Verification

Under the condition of random load disturbance and environmental vibration interference, the optimized intelligent control algorithm shows stronger anti-interference ability. When external interference occurs, the traditional PID error increases sharply and takes a long time to return to the steady state. The optimized algorithm can quickly adjust the dynamic gain and compensate for interference errors, with short error recovery time and small fluctuation range, which can adapt to complex and variable industrial working conditions.

6. Conclusion

Aiming at the problems of low tracking accuracy, poor motion smoothness, and insufficient anti-interference stability of traditional PID control in industrial robot high-speed trajectory control, this paper proposes an optimized intelligent control algorithm integrating dynamic gain adjustment and real-time error correction. By analyzing the technical defects of fixed-parameter PID in dynamic robot motion scenarios, a dynamic parameter adaptive adjustment model based on real-time error and motion speed is constructed, and a lightweight real-time error prediction and compensation module is added to realize full-cycle intelligent optimization of trajectory control.

Experimental verification shows that the optimized intelligent control algorithm significantly reduces industrial robot trajectory tracking deviation, effectively suppresses high-speed motion jitter and steady-state error accumulation, and greatly improves motion smoothness and long-term operational stability. Compared with the traditional PID algorithm, the proposed strategy has stronger adaptive ability and anti-interference performance under variable working conditions, and can well adapt to high-speed and high-precision operation requirements of industrial automated sorting, flexible assembly, and precision processing scenarios.

The optimized algorithm retains the advantages of simple structure and low computational overhead of traditional PID, with excellent engineering practicability and popularization value. Future research will further optimize the dynamic gain adjustment rules, integrate multi-dimensional interference prediction mechanisms, and improve the trajectory control accuracy of robots under extreme complex working conditions, so as to further expand the application scope of intelligent control algorithms in high-end intelligent manufacturing equipment.

Conflict of Interest Statement

The authors state that they have no financial, commercial or personal conflicts of interest associated with this study.

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