Research of Advanced Control Algorithms for Robotic Manipulators in Precision Manufacturing

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Abstract. In the global trend of transformation towards intelligent and precision manufacturing, robotic manipulators, as core equipment for flexible production, high-precision assembly, and complex process machining in the field of precision manufacturing, their control performance is crucial. However, traditional control algorithms struggle to maintain stable high-precision control effects when facing parameter variations, external disturbances, and complex constraints, becoming a key bottleneck restricting technological breakthroughs. This paper focuses on the development of advanced control algorithms for robotic manipulators in precision manufacturing and proposes a hybrid control strategy integrating adaptive mechanisms and robust compensation, aiming to ensure trajectory tracking accuracy while enhancing the system's ability to suppress external disturbances. By improving the PID control algorithm with the introduction of friction compensation and designing an adaptive robust control algorithm based on the recursive least squares method and Lyapunov stability theory, the problems of parameter uncertainty and external disturbances are effectively solved. Experimental results show that robotic manipulators adopting the adaptive control algorithm exhibit higher control precision, faster response speed, and stronger robustness in complex precision assembly tasks and scenarios with environmental interference. This provides a new direction for high-precision control of robotic manipulators in the field of precision manufacturing and promotes the integration of control theory and advanced manufacturing technology.

Keywords: Precision Manufacturing; Robotic Manipulator; Advanced Control Algorithm; Adaptive Control; PID Control.

1. Introduction

In the global wave of transformation towards intelligent and precision manufacturing, robotic manipulators, as core equipment for flexible production, high-precision assembly, and complex process machining, their control performance directly determines the production efficiency and product quality in the field of precision manufacturing [1]. From the precise positioning of micron-level solder joints in microelectronic packaging, to ultra-precision grinding of aerospace components, and to cell-level operations in the biomedical field, unprecedentedly stringent requirements are imposed on the trajectory tracking accuracy, dynamic response speed, and environmental adaptability of robotic manipulators [2]. Traditional control algorithms (such as PID control), although widely used in industrial scenarios due to their simple structure and easy implementation, struggle to maintain stable high-precision control effects when facing parameter variations (e.g., load changes, mechanical wear), external disturbances (e.g., temperature fluctuations, vibration interference), and complex constraints (e.g., multi-joint coupling, nonlinear friction), thus becoming a key bottleneck restricting breakthroughs in precision manufacturing technology [3].

In recent years, the integration of advanced control theory and intelligent algorithms has provided new solutions to break this limitation [1-4]. Adaptive control effectively improves the robot's robustness to model uncertainty by real-time estimating system parameters and dynamically adjusting control strategies; robust control ensures system stability even in the presence of modeling errors by constructing anti-interference frameworks; and intelligent control methods based on deep learning, relying on data-driven pattern recognition and decision-making capabilities, offer new ideas for handling high-dimensional nonlinear systems [5]. However, existing studies mostly focus on performance optimization of a single algorithm. Regarding the collaborative requirements of "high precision - high dynamics - strong robustness" in precision manufacturing scenarios, how to design a hybrid control architecture with parameter adaptability, disturbance suppression capability, and computational efficiency remains a core issue to be solved [4-6].

Against this background, this paper focuses on the development of advanced control algorithms for robotic manipulators in precision manufacturing, aiming to propose a hybrid control strategy integrating adaptive mechanisms and robust compensation, to ensure trajectory tracking accuracy (micron-level) while enhancing the system's ability to suppress external disturbances. This research provides a method for high-precision control of robotic manipulators in the field of precision manufacturing and promotes the integration of control theory and advanced manufacturing technology.

2. Basic Principles and Structure of Robotic Manipulators

2.1 Basic Structure of Robotic Manipulators

In the field of precision manufacturing, robotic manipulators are core equipment for high-precision machining, micro-assembly, and complex process operations. Their basic principles and structural design form the foundation for supporting automation and intelligence in precision manufacturing. The design of manipulators centers on the integration of mechanical engineering, electronic engineering, and computer science, enabling precise movements in three-dimensional space through combinations of multi-joints and links. In terms of structural composition, robotic manipulators typically include six core components: base, joints, links, actuators, sensors, and control systems.

The base, as the supporting foundation of the entire manipulator, must have sufficient rigidity and stability to avoid micro-deformations during high-speed movement or load changes (which may cause micron-level errors in precision manufacturing).

Joints and links are the core of the manipulator's kinematic chain. Joints can be divided into rotational types (e.g., shoulder joints, elbow joints) and sliding types (e.g., linear guides), driven by servo motors, precision hydraulic, or pneumatic systems to achieve flexible movements with multiple degrees of freedom (usually 4-6 degrees of freedom). Their transmission accuracy directly affects the end positioning error of the manipulator.

Actuators (e.g., end effectors, grippers) are designed according to task requirements and must match precision manufacturing scenarios (such as vacuum suction cups in the microelectronics industry, flexible grippers for medical implant assembly).

The sensor system includes position sensors (e.g., grating encoders), force sensors (e.g., six-dimensional force sensors), and vision sensors (e.g., microscopic vision systems), which real-time feedback end position, force, and environmental information to provide data support for high-precision control.

2.2 Control System of Robotic Manipulators

The control system is the "nerve center" of the robotic manipulator, and its performance directly determines the accuracy and efficiency of precision manufacturing. The system uses a microprocessor (such as DSP, FPGA) or industrial PC as the core, and adjusts the manipulator's movement through a closed-loop control mechanism with preset programs and real-time feedback:

At the software level, it needs to integrate inverse kinematics algorithms (calculating the mapping relationship between joint angles and end poses), path planning algorithms (such as B-spline curve planning to ensure movement smoothness), and control algorithms (such as PID, adaptive control).

At the hardware level, servo drives receive control signals to drive motors for action, and sensors real-time collect joint position, speed, and end state data, forming a closed-loop control process of "perception - decision - execution".

In precision manufacturing, the control system must meet microsecond-level response speed to cope with dynamic errors during high-speed movement (such as trajectory deviation caused by sudden load changes).

2.3 Dynamic Modeling of Robotic Manipulators

Dynamic modeling is the theoretical basis for high-precision control of robotic manipulators. Its core is to describe the relationship between force and motion state of the manipulator during movement through mathematical equations, providing an accurate model support for control algorithm design. In precision manufacturing scenarios, modeling must focus on the following factors:

(1) Physical parameters: mass, moment of inertia, centroid position of each link of the manipulator. Errors in these parameters (such as deviations caused by material wear or load changes) may significantly affect control accuracy.

(2) Nonlinear factors: including joint friction (Coulomb friction, stick-slip friction), transmission gaps (such as gear meshing errors), and flexible deformations (elastic deformation of links during high-speed movement). These factors cannot be ignored in micron-level precision control.

(3) External disturbances: such as workbench vibration, thermal deformation caused by environmental temperature changes, and dynamic interference caused by load changes (such as grabbing workpieces of different masses).

The dynamic equation of the robotic manipulator can be expressed as:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F_f(q,\dot{q}) = \tau + \tau_d$$

Where: $M(q)$ is the inertia matrix (symmetric positive definite matrix), reflecting the inertial characteristics of the manipulator in different poses; $C(q,\dot{q})\dot{q}$ is the Coriolis and centrifugal force term, describing the additional force generated by joint rotation; $G(q)$ is the gravity term, related to the manipulator's pose and gravitational acceleration; $F_f(q,\dot{q})$ is the friction term, including nonlinear factors such as Coulomb friction and viscous friction; τ is the joint driving torque (control input); τ_d is the external disturbance torque (such as vibration, load changes).

Through the Jacobian matrix $J(q)$, the motion in the joint space $(q,\dot{q},\ddot{q})$ can be converted to the motion in the Cartesian space of the end effector $(x,\dot{x},\ddot{x})$, i.e., $\dot{x}=J(q)\dot{q}$, which provides a key mapping relationship for end trajectory tracking control in precision manufacturing

3. Design of Advanced Control Algorithms for Robotic Manipulators

3.1 Robotic Manipulator Control Algorithm Based on Improved PID Control

Traditional PID control is widely used in industrial control due to its simple structure and easy implementation, but it has limitations in precision manufacturing scenarios (such as difficulty in handling nonlinear friction and parameter variations). To this end, this paper designs a PID control algorithm with friction compensation, whose core is to introduce a friction model into the traditional PID framework to offset the impact of nonlinear friction on accuracy.

The output of the improved PID controller is:

$$\tau(t) = K_p e(t) + K_i \int e(\tau)d\tau + K_d \dot{e}(t) + F_f^*(q,\dot{q})$$

Where: $e(t)=q_d(t)-q(t)$ is the joint position error (q_d is the desired position, q is the actual position); K_p,K_i,K_d are proportional, integral, and derivative gains respectively; $F_f^*(q,\dot{q})$ is the friction compensation term, calculated based on a preset friction model (such as the LuGre model) to offset the impact of actual friction F_f.

Through offline parameter identification and online fine-tuning, this algorithm can improve the "stick-slip effect" (causing end jitter) of traditional PID during low-speed movement to a certain extent and enhance trajectory tracking accuracy. However, its robustness is still insufficient in dealing with parameter variations (such as load changes) and unknown disturbances.

3.2 Design of Advanced Algorithm Based on Adaptive Robust Control

To solve the problems of parameter uncertainty and external disturbances in precision manufacturing, this paper proposes an adaptive robust control algorithm, whose core is to dynamically adjust the control strategy by real-time estimating model parameters and disturbance boundaries, achieving high-precision tracking and strong anti-interference capability. The algorithm design is divided into the following steps:

(1) Parameter Estimation Module

The recursive least squares (RLS) method is used to online estimate unknown parameters in the dynamic model (such as coefficients of the inertia matrix $M(q)$ and gravity term $G(q)$). Define the parameter vector $\theta \in \mathrm{R}^n$ (including all parameters to be estimated), then the dynamic equation can be linearly expressed as:

$$M(q)\ddot{q}_d + C(q,\dot{q})\dot{q}_d + G(q) = Y(q,\dot{q},\dot{q}_d,\ddot{q}_d)\theta$$

Where $\mathrm{Y}(\cdot)$ is the regression matrix. The parameter estimation value $\hat{\theta}$ is updated through the RLS algorithm:

$$\hat{\theta}(k) = \hat{\theta}(k-1) + P(k)Y(k)\left[\tau(k) - Y(k)^T\hat{\theta}(k-1)\right]$$

$$P(k) = P(k-1) - \frac{P(k-1)Y(k)Y(k)^T P(k-1)}{\lambda + Y(k)^T P(k-1)Y(k)}$$

Where $\lambda \in (0,1]$ is the forgetting factor, used to enhance the tracking capability for time-varying parameters.

(2) Design of Adaptive Robust Control Law

The goal of the control law is to make the end trajectory tracking error $e = x_d - x$ converge to zero while suppressing disturbances. Based on Lyapunov stability theory, the control law is designed as:

$$\tau = Y\hat{\theta} + K_v\dot{e} + K_p e + \mathrm{sat}\left(\frac{\hat{\rho}e}{\epsilon}\right)$$

Where, K_v,K_p are positive definite gain matrices, used to ensure error convergence; $\mathrm{sat}(\cdot)$ is the saturation function, avoiding excessive control input; $\hat{\rho}$ is the estimated value of the disturbance boundary, updated in real-time through the adaptive law $\dot{\hat{\rho}}=\gamma\|e\|$ ($\gamma>0$ is the adaptive gain); ϵ is a small positive number, used to balance control accuracy and chattering.

4. Results

In this study, experiments were conducted to verify the effectiveness and practicability of the designed control algorithms, especially their ability to improve the operational accuracy of robotic manipulators in precision manufacturing scenarios and adapt to complex environments. First, a typical robotic manipulator model was constructed, and the adaptive control algorithm was implemented in the control system. The robotic manipulator was required to perform a series of standard actions, move to specific positions, and track predetermined paths. These actions were designed to simulate common operation tasks in precision manufacturing, covering different difficulty levels from simple to complex, such as precise grabbing of microelectronic components and assembly trajectory tracking of precision instrument parts.

To evaluate the effect of the control algorithms, data on the tracking control of the robotic manipulator were collected, including position error, trajectory accuracy, response time, and stability during task execution. The simulation results of the manipulator's tracking control trajectory are shown in Figure 1.

Experimental results show that the robotic manipulator adopting the adaptive control algorithm exhibits higher control precision in most test tasks. Especially in complex precision assembly tasks and scenarios with environmental interference (such as micro-vibration, temperature fluctuations), the adaptive algorithm can adjust the control strategy more quickly to cope with these uncertain factors. During fine operation tasks, such as assembling parts with a diameter of less than 0.5mm, the robot manipulator with adaptive control shows smaller position errors (usually within the micron range) and more stable motion trajectories, effectively avoiding assembly failures caused by micro-offsets that may occur with traditional control methods.

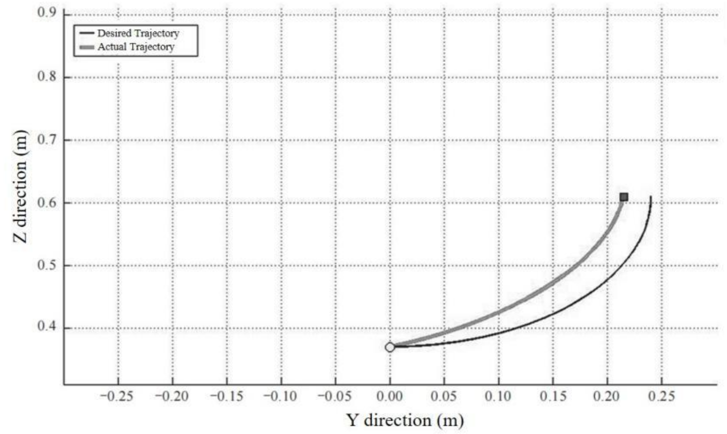

Figure 1. Simulation results of manipulator tracking control trajectory

The response speeds of the robotic manipulator before and after adding adaptive control are shown in Figure 2 and Figure 3. Among them, Algorithm 1 uses a traditional PID controller for robotic manipulator control, and Algorithm 2 adds an adaptive feedback link based on traditional PID control.

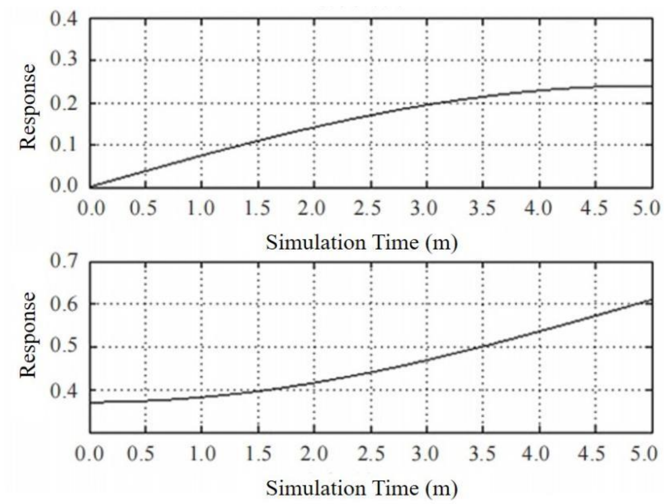

Figure 2. Response speed curve of robotic manipulator (Algorithm 1)

Comparing the response speed curves of Algorithm 1 and Algorithm 2, it can be seen that in scenarios requiring fast response in precision manufacturing, the robotic manipulator with adaptive control added has a faster response and smaller overshoot, and its robustness is significantly enhanced. It can maintain stable high precision in operations with frequent starts/stops and trajectory switches, which further proves that adaptive control technology can effectively improve the control precision of robotic manipulators in precision manufacturing. Through continuous technical optimization and algorithm iteration, it is expected that this technology will play a more important role in precision manufacturing fields such as semiconductor packaging and optical instrument manufacturing, where high precision is required.

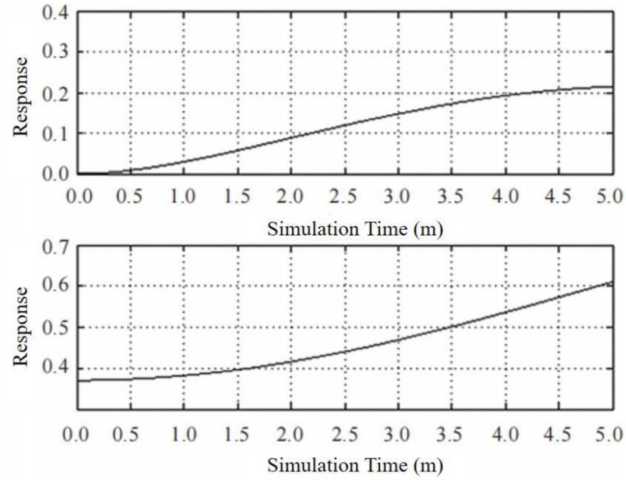

Figure 3. Response speed curve of robotic manipulator (Algorithm 2)

5. Conclusions

This study focuses on the high-precision control requirements of robotic manipulators in precision manufacturing, addresses the performance limitations of traditional control algorithms under parameter variations, external disturbances, and complex constraints, develops advanced control algorithms, and verifies their effectiveness. The improved PID control algorithm with friction compensation effectively improves the "stick-slip effect" of traditional PID during low-speed movement by introducing a friction model, enhancing trajectory tracking accuracy, but its robustness is still insufficient in dealing with parameter variations and unknown disturbances. The adaptive robust control algorithm, by online estimating model parameters through the recursive least squares method and designing the control law based on Lyapunov stability theory, realizes dynamic adjustment to parameter uncertainty and external disturbances, and shows better performance in experiments. In scenarios such as precision assembly and micro-part operations, the trajectory tracking accuracy reaches the micron level, with faster response speed, smaller overshoot, and significantly better robustness than traditional PID control. In conclusion, the control algorithms proposed in this study provide new solutions for high-precision control of robotic manipulators in the field of precision manufacturing, help promote the further integration of control theory and advanced manufacturing technology, and have important application potential in high-precision manufacturing scenarios such as semiconductor packaging and optical instrument manufacturing in the future.

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