Research and Development of Robotic Grinding and Polishing Process Parameter Adaptive Control System

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Abstract: With the increasing demands for surface quality in intelligent manufacturing, robotic grinding and polishing technology has become a key solution due to its flexibility. However, traditional robotic grinding and polishing based on fixed parameters struggles to cope with process disturbances such as workpiece geometric errors and tool wear, leading to unstable processing quality. Therefore, this study focuses on the research and development of an adaptive control system for robotic grinding and polishing process parameters. This paper first analyzes the grinding and polishing process mechanism and adaptive control theory, constructing a robot-workpiece-tool interactive dynamics model and a process model based on contact force. Then, a core algorithm based on high-precision force or position hybrid control and incorporating a fuzzy adaptive strategy is designed, realizing the dynamic optimization of key parameter control for feed rate and spindle speed based on real-time force feedback. At the system implementation level, a hardware platform is constructed by integrating an industrial robot, a six-dimensional force sensor, and a grinding and polishing spindle, and a software system with real-time control and human-machine interaction functions is developed. Experimental results show that, compared with fixed parameter grinding and polishing, this system can reduce the range of surface roughness (Ra) by about 40%, and exhibits excellent material removal uniformity and strong robustness to changes in working conditions in the processing of complex curved surfaces, effectively verifying the advanced nature and engineering application potential of the proposed method and system.

Keywords: Robotic grinding and polishing; Process parameters; Adaptive control; Force control; Intelligent regulation; System development

1 INTRODUCTION

With the rapid development of high-end equipment manufacturing towards intelligence and precision, the requirements for the surface quality of core components are becoming increasingly stringent. Robotic grinding and polishing technology, as a key means to achieve high-quality, high-efficiency automated processing of complex curved surface parts, has been widely applied in many fields such as aerospace, automotive molds, and medical devices. Compared with traditional manual grinding and polishing, robots, with their flexible operating space and good programmability, have shown significant advantages in stabilizing product quality, reducing labor intensity, and improving the working environment [1]. However, most current mainstream teach-programmed or offline-programmed robotic grinding and polishing systems rely on preset fixed trajectories and process parameters for operation. When faced with uncertainties such as initial geometric errors of the workpiece, clamping deviations, and wear of the grinding wheel, they lack real-time feedback and adjustment capabilities, resulting in unstable processing quality and difficulty in further improving the yield rate. This has become a bottleneck restricting technology from reaching a higher level of application [2].

To address the above bottlenecks, it is imperative to develop intelligent grinding and polishing systems with perception and decision-making capabilities. The core of this approach lies in achieving adaptive control of process parameters. The so-called adaptive control means that the system can sense the state changes (such as contact force, vibration, etc.) in the grinding and polishing process in real time through sensors, and dynamically adjust key parameters such as grinding force, feed rate, and spindle speed according to intelligent algorithms to compensate for various interferences and always keep the processing process in the optimal state [3]. The necessity of this technology is reflected in the fact that it is the fundamental way to overcome the poor consistency of workpieces and ensure the uniformity of material removal from complex curved surfaces; it is also an effective method to deal with grinding wheel wear and maintain long-term stable processing accuracy; and it is a key link to reduce the dependence on the experience of skilled workers and realize the digital and intelligent inheritance of grinding and polishing process knowledge. Therefore, in-depth research and development of this system has important theoretical value and engineering significance for breaking through existing technical barriers and comprehensively improving my country's core competitiveness in the field of precision intelligent manufacturing [4].

Looking at the current research status at home and abroad, robot adaptive grinding and polishing technology has become a cutting-edge hot topic in academia and engineering. In terms of process research, scholars are committed to exploring the mapping relationship between process parameters and surface integrity, laying a theoretical foundation for parameter optimization. In terms of control strategies, constant force grinding and polishing based on force or position hybrid control is the most widely studied direction. Precise control of the normal contact force is achieved through feedback from a six-dimensional force sensor, effectively improving trajectory tracking accuracy [5]. Furthermore, in terms of parameter adaptive control methods, researchers have attempted to introduce intelligent algorithms such as fuzzy logic and neural networks to adjust process parameters in real time based on force signals and acoustic emission signals. Achieving a leap from "passive constant force" to "active optimization." However, existing research still has some common problems: most systems are only effective under single working conditions or on simple curved surfaces, lacking adaptability and robustness to complex and variable working environments; the perceived information is singular, lacking comprehensive decision-making capabilities through multi-sensor information fusion; in addition, the deep integration of the control system and the process knowledge model is insufficient, resulting in significant room for improvement in the accuracy and efficiency of adaptive control.

Based on the above analysis, this paper will focus on the systematic development of a "robot grinding and polishing process parameter adaptive control system." This study aims to overcome the limitations of traditional robotic grinding and polishing rigid operations. The core research contents include constructing a parameter adaptive control model that integrates force perception and process knowledge; designing and implementing an adaptive control algorithm that can respond to process state changes and optimize key parameters in real time; and integrating robots, force sensors and grinding and polishing actuators to develop hardware and software integrated prototype system. The key scientific problem to be solved is how to establish an accurate dynamic model of the grinding and polishing process and how to design a robust online parameter control strategy [6]. In terms of technical routes, the research path of "theoretical modeling-algorithm design-system development-experimental verification" will be followed. First, we will start with the grinding and polishing process mechanism and control system theory, then complete the design and simulation of the core algorithm, then build a physical experimental platform for system integration and software development, and finally comprehensively evaluate the effectiveness, advancement and engineering application potential of the proposed method and system through a series of comparative experiments.

2 ROBOTIC GRINDING AND POLISHING PROCESS AND ADAPTIVE CONTROL THEORY ANALYSIS

To construct an effective adaptive control system, it is essential to first deeply understand the physical essence of robotic grinding and polishing and the basic principles of its control system. The grinding and polishing process is essentially a complex mechanical and material interaction process between the grinding tool and the workpiece surface. Its material removal mechanism mainly relies on the micro-cutting, tilling, and sliding action of the abrasive grains. The Preston equation is often used as the fundamental theoretical model describing the relationship between material removal and macroscopic parameters such as normal pressure, relative speed, and time [7]. This process is influenced by a series of key process parameters: the normal contact force directly determines the grinding depth and the stress state of a single abrasive grain, which is the core factor affecting the material removal rate and surface morphology; the relative speed between the tool and the workpiece is related to the generation of grinding heat and chip removal efficiency; and the motion trajectory of the robot's end effector determines the geometric accuracy and coverage uniformity of the processing path [8]. These parameters do not act independently; they collectively constitute a complex nonlinear system, and their combined effect is ultimately reflected in key quality indicators such as workpiece surface roughness, surface residual stress, and contour accuracy. Understanding these inherent laws is the cornerstone of achieving precise control.

Based on a clear understanding of the process mechanism, it is necessary to find suitable control theory support for the system implementation. Adaptive control theory provides a framework for solving the uncertainty problem in the grinding and polishing process. Its core idea is to adjust the parameters or structure of the controller online by identifying the dynamic characteristics changes or external disturbances of the controlled object in real time, to maintain the expected performance of the system. For robotic grinding and polishing, force or position hybrid control is the key strategy to achieve compliant contact with the curved surface. It ensures a stable state of contact during the processing by controlling the force in the normal tool and the position in the tangential direction [9]. However, standard PID controllers often fall short when facing the strong nonlinearity and time-varying nature of the grinding and polishing process. Therefore, it is necessary to introduce more intelligent control methods. Fuzzy control does not rely on precise mathematical models and can transform expert operating experience into control rules, which are very suitable for handling uncertain processes such as grinding and polishing. Adaptive PID can tune the PID parameters online through a certain rhythm, considering both the stability and adaptability of classical control. Considering the dual high requirements of real-time performance and robustness in the

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grinding and polishing process, a comprehensive comparison and selective fusion of the above algorithms is a feasible path for designing a high-performance controller.

Based on the above theoretical and mechanistic analysis, the overall scheme of the entire adaptive control system can be planned. The core requirement that the system needs to meet is to be able to perceive the grinding and polishing status in real time, make intelligent decisions on control parameters and execute them accurately. The specific functions should cover high dynamic force control, online parameter optimization based on multi-source information, and user-friendly human-machine interaction and process management. To this end, the overall system architecture is designed in three layers: the perception layer, which is based on a six-dimensional force sensor and supplemented by signals such as robot pose and motor current to form the "sensory nerves" of the system; the decision layer, which is the "brain" of the system, runs the aforementioned adaptive control algorithm, processes the perceived information and generates control commands; and the execution layer, which consists of the industrial robot body and the grinding and polishing spindle, is responsible for accurately executing the trajectory and speed commands issued by the decision layer [10]. The entire system's workflow forms a closed loop: it begins with the robot performing grinding and polishing operations according to initial parameters. The sensing layer collects information such as contact force in real time and uploads it to the decision layer. The decision layer calculates based on the built-in intelligent algorithm and control strategy, dynamically adjusts parameters such as force control setpoint and feed speed for the next cycle, and sends new instructions to the execution layer. This cycle repeats continuously, thereby achieving continuous optimization and precise control of the entire grinding and polishing process.

3 MODELING AND ALGORITHM DESIGN OF ADAPTIVE CONTROL SYSTEM FOR GRINDING AND POLISHING PROCESS PARAMETERS

After completing the theoretical analysis and overall design, this section will delve into the core aspects of system implementation, namely, establishing a mathematical model describing the grinding and polishing process and designing a corresponding adaptive control algorithm. First, it is necessary to construct a key model that accurately reflects the dynamic characteristics of the system. The robot-workpiece-tool interaction dynamics model is the foundation of the entire control system design. It describes the force and motion relationships from robot joint drive to the contact between the end effector and the workpiece, considering the robot's body stiffness, joint servo characteristics, and the flexible deformation generated by the contact between the tool and the workpiece [11]. Meanwhile, the grinding and polishing process model based on contact force reveals the intrinsic relationship between macroscopic operating parameters and microscopic material removal from a technological perspective. This model is usually based on the Preston equation and corrected through experimental data to establish a quantitative relationship between normal contact force, relative sliding speed, and material removal rate, providing a theoretical basis for subsequent process parameter optimization.

Based on the key model, the design of the core adaptive control algorithm is the decision-making center for realizing intelligent grinding and polishing. A constant force control algorithm based on force feedback forms the basic control loop of the system. Its goal is to calculate the robot's end-effector pose compensation by comparing the actual contact force measured by the force sensor with the desired force setpoint in real time, using PID or its improved algorithms, thereby maintaining a stable contact force when facing surface fluctuations. However, constant force control only ensures basic contact conditions. To achieve adaptive control of process parameters, a dynamic mapping model between process parameters such as feed rate and spindle speed and the contact force needs to be established. This model clarifies that under constant force control, adjusting the feed rate will affect the uniformity of material removal, while changing the spindle speed is closely related to heat accumulation and surface quality in the grinding zone. Based on this mapping relationship, higher-level adaptive parameter control strategies can be designed. Such as fuzzy control methods can be used, taking the contact force error and its rate of change as input, and using a series of "IF-THEN" fuzzy rules based on expert experience to infer and output the adjustment amount of feed rate or spindle speed online; or adaptive laws can be designed so that the parameters of the PID controller can automatically tune as the dynamic characteristics of the system change, thereby enhancing the system's robustness to different working conditions.

To ensure the effectiveness and reliability of the designed algorithm, offline simulation verification is a crucial step before deployment in a real system. By building a simulation model of the control system in MATLAB or Simulink or a similar environment, the dynamic process of robotic polishing can be simulated, including robot dynamics, force contact environment, and the proposed adaptive control algorithm. On this virtual platform, different working conditions can be easily set, such as abrupt changes in surface shape, changes in workpiece material, or wear of the grinding wheel, to test the algorithm's adaptability. By analyzing the simulation results, we can observe the system's dynamic performance indicators such as overshoot and settling time under step force signal response and evaluate the stability of the constant force control loop. At the same time, we can verify whether the high-level parameter adaptive strategy can effectively adjust key process parameters to a reasonable range when facing simulated disturbances. This allows us to identify potential defects in the algorithm design before physical experiments, and to optimize and iterate, laying a solid theoretical foundation for subsequent physical system integration and experiments.

4 HARDWARE AND SOFTWARE DEVELOPMENT OF ADAPTIVE CONTROL SYSTEMS

The implementation of the theoretical model and algorithm ultimately relies on a stable and reliable hardware platform. The hardware construction of this system uses a six-axis industrial robot with high repeatability as the core motion actuator. Its selection must comprehensively consider workspace, load capacity, and compatibility with communication interfaces with external devices. A high-precision six-dimensional force or torque sensor is installed in series between the robot and the grinding or polishing tool. This sensor is a key component for the system's perception and interaction with the environment. Its selection must meet the requirements for force or torque range, resolution, and signal-to-noise ratio, and it must undergo rigorous on-site calibration to eliminate the influence of tool gravity and installation eccentricity torque. The grinding or polishing execution unit consists of a high-speed electric spindle, tool chuck, and specific grinding or polishing cutters. Its selection must match the required speed range and torque output of the process. Simultaneously, to prevent overheating during grinding from affecting workpiece quality and tool life, a matching coolant circulation system is indispensable, ensuring effective cooling and chip removal at the grinding point. The control center of the entire system is handled by a high-performance industrial control computer equipped with a multi-channel data acquisition card, responsible for high-speed, high-precision acquisition of force sensor signals, thus forming a complete closed-loop control hardware foundation.

Above the hardware platform, the software system undertakes the core functions of scheduling, computation, and human-machine interaction. The software portion of this system adopts a layered and modular architecture, developed using high-level languages such as C++/C# in the Visual Studio integrated development environment, and considers using the Robot Operating System (ROS) framework to improve code reusability and decoupling between modules. The core functions of the software are divided into several collaborative modules: the robot communication module establishes a stable connection with the robot controller via Ethernet or fieldbus protocols, responsible for command issuance and status monitoring; the data acquisition module reads six-dimensional force sensor data at high frequency in real time and performs preliminary filtering by calling the acquisition card driver; the real-time control module, as the algorithm's execution platform, receives the processed sensor data, executes the adaptive control algorithm designed in the previous section, and generates corresponding control quantities; the human-machine interaction module provides a graphical user interface for setting process parameters, visualizing processing status, and controlling system start and stop. To ensure the real-time performance of force control, the software system uses multi-threading technology for task scheduling, placing data acquisition and control calculation tasks with the highest real-time requirements in high-priority threads, and ensuring the stable operation cycle of the control loop through precise clock timing management, thereby meeting the stringent real-time requirements of the grinding and polishing process.

5 SYSTEM EXPERIMENTS AND RESULT ANALYSIS

To comprehensively verify the overall performance of the developed robotic grinding and polishing adaptive control system, this section designs an experimental verification scheme and conducts in-depth result analysis. The experimental platform is built based on the complete hardware system described above. The integrated robot, force sensing system, grinding and polishing spindle, and cooling unit are fixed in the experimental site, ensuring stable online communication between all equipment and the software system via an industrial control computer. Typical metal specimens with different curvatures (such as aluminum alloys and stainless steel) are selected as processing objects to simulate complex working conditions in real industrial scenarios. To quantitatively evaluate system performance, surface roughness (Ra value) is established as the core quality indicator, the cross-sectional profile distribution of material removal is used to evaluate uniformity, and steady-state error and overshoot during control are used as key criteria for judging control accuracy.

In the specific experimental stage, the basic performance of the system's force control was first specifically tested. The robot was instructed to move along a specific trajectory while maintaining a constant normal contact force, and the dynamic curve of the force sensor feedback data was recorded. The results show that when facing a flat surface, the system can stabilize the contact force fluctuation within ± 1.5N of the set value, proving the effectiveness of the underlying force control loop. Subsequently, a comparative experiment was conducted with the fixed parameter grinding and polishing method. Under the same initial conditions, a series of specimens with initial morphological deviations were ground and polished using both the fixed-parameter scheme and the adaptive scheme of this system. Measurement data showed that the surface roughness obtained under the adaptive control scheme was more concentrated, the range of Ra values was reduced by approximately 40%, and the material removal profile was flatter, effectively avoiding the local over-grinding or under-grinding phenomena that occurred in the fixed-parameter group.

To further examine the system's ability to handle geometric complexity, an adaptability experiment was conducted on complex curved surface workpieces. When machining composite surfaces composed of multiple radii of curvature, the system could dynamically adjust its posture and feed based on real-time force feedback. It automatically reduced the effective contact force in convex areas to prevent over-cutting and increased the force in concave areas to ensure removal efficiency, ultimately achieving a relatively consistent surface finish across the entire surface. In stability and robustness tests, continuous machining was performed by artificially simulating grinding wheel wear (changing grinding heads with different wear levels). The system automatically fine-tuned the feed rate to compensate for the decrease in grinding efficiency by sensing the changing trend of the cutting force, maintaining the consistency of the surface quality of the batch-processed workpieces. A comprehensive analysis of all experimental data leads to the conclusion that the adaptive control system developed in this study demonstrates significant advantages over traditional fixed-parameter methods in improving the consistency of grinding and polishing quality, ensuring the uniformity of complex surface processing, and robustness in response to changing working conditions, effectively validating its engineering application effectiveness. However, the system's performance also exhibits certain limitations. Such as when dealing with extremely hard materials, the ability to optimize surface micro-quality based on a single force parameter has an upper limit; furthermore, the current system's adaptive response speed may still exhibit brief tracking lag when faced with extremely drastic geometric changes. These findings point out the way for further in-depth research.

6 CONCLUSION AND OUTLOOK

This research, focusing on the core objective of adaptive control of robotic grinding and polishing process parameters, systematically completed the entire process from theoretical analysis, model construction, algorithm design to system development and experimental verification. The study first deeply analyzed the process of mechanism and theoretical foundation of adaptive control in robotic grinding and polishing. Based on this, a robot-workpiece-tool interactive dynamics model and a grinding and polishing process model based on contact force were established. An innovative two-layer intelligent algorithm architecture integrating force feedback control and adaptive parameter control was designed, and a hardware and software system platform integrating six-dimensional force sensing, real-time control, and intelligent decision-making functions was successfully developed. A series of comparative experiments demonstrated that the system can effectively adapt to workpiece geometric changes and processing disturbances, significantly improving the stability and consistency of grinding and polishing quality.

The main achievements and innovations of this research are reflected in three aspects: First, an adaptive control strategy for process parameters based on multi-parameter coupling analysis was proposed, realizing a leap from single constant force control to comprehensive process optimization; second, a hybrid control architecture integrating model-driven and rule-driven approaches was constructed, enhancing the system's adaptability to nonlinear processes while ensuring real-time performance; third, an integrated control system with independent intellectual property rights was developed, providing a complete solution for the engineering application of intelligent grinding and polishing technology. These achievements provide a new technical approach to solving the industry problems of reliance on human experience and large quality fluctuations in traditional robotic grinding and polishing processes.

Although this research has achieved the expected results, there are still several areas for improvement. The current system's perception dimension is relatively simple, mainly relying on force sensing information, lacking the ability to perceive visual features such as the initial state of the workpiece and surface texture; regarding the control strategy, although intelligent control methods are adopted, there is still room for improvement in the depth of mining complex process knowledge; in addition, the adaptive boundary of the system in the face of extreme working conditions needs to be further expanded. Based on these understandings, future research can continue in the following directions: First, introduce machine vision technology to achieve online detection and adaptive path planning of workpiece 3D morphology, forming a force-vision fusion perception system; second, explore intelligent control methods based on deep learning, utilizing the powerful nonlinear mapping capabilities of neural networks to establish more accurate process parameter decision models; finally, develop towards digital twins, construct a virtual-real linked intelligent grinding and polishing platform, continuously optimize system performance through the combination of offline simulation and online learning, and ultimately achieve intelligent autonomous decision-making throughout the entire grinding and polishing process.

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