Abstract

This dissertation explores trajectory planning and optimization techniques specifically designed for redundant robotic systems operating in advanced industrial manufacturings. Developed in collaboration with EFORT Intelligent Robot Co., Ltd.—a leading manufacturer of industrial robots—and Politecnico di Torino, this research brings together innovative technologies to tackle key challenges in modern manufacturing, with a particular emphasis on laser cutting and other robotic machining applications. Focusing on practical applicability, this study systematically tackles the demand for precise, smooth, and efficient trajectory planning and optimization, which are essential for achieving superior industrial outcomes.

The dissertation begins by introducing a novel conic posture optimization method specifically designed for through-hole laser cutting, a process extensively utilized in the automotive industry. This method models the laser tool's posture using conical geometry and employs a robust multi-objective optimization algorithm to balance machining accuracy, energy efficiency, and processing speed. The proposed approach effectively mitigates taper error, a challenge from this novel conic cutting, while significantly enhancing machining performance. The simulation and practical experiments conducted on complex B-pillar components validate the method's efficacy, demonstrating substantial improvements in overall operational efficiency. These results highlight the technique's technical strengths and its promising potential for widespread use in industrial applications.

Subsequently, the dissertation proposes an advanced trajectory optimization method integrating graph-based search algorithms with reinforcement learning techniques. This hybrid approach specifically addresses the critical industrial challenge of generating smooth and collision-free robot trajectories within complex and constrained machining environments. The two-stage optimization strategy effectively leverages redundancy provided by an additional translational standoff axis, a com-

mon feature for laser cutting machines. The first stage employs a comprehensive graph-based optimization algorithm to generate initial collision-free orientations and trajectories, systematically exploring feasible configurations to mitigate collision risks. The second stage utilizes reinforcement learning, refining the generated paths to further enhance trajectory smoothness and dynamic stability. Experimental outcomes validate this methodology's efficacy, demonstrating its ability to ensure continuous, collision-free motion even in highly complex manufacturing setups, significantly enhancing robotic system reliability and machining quality.

Furthermore, the research advances trajectory smoothness optimization through minimizing jerk (the derivative of acceleration), utilizing sophisticated B-spline modeling combined with quadratic programming techniques. This innovative approach addresses the persistent industrial challenge posed by abrupt joint movements, frequently resulting in detrimental mechanical vibrations, increased tool wear, compromised machining precision, and heightened risk of system damage. The jerk-minimizing optimization method proposed in this dissertation effectively smooths multi-axis robotic motions, substantially reducing mechanical shocks and enhancing operational stability. Additionally, an iterative collision detection strategy is incorporated, ensuring operational safety without compromising trajectory quality. Empirical validations on industrial robotic platforms underscore the method's capability to deliver significant improvements in motion smoothness and machining precision, facilitating more consistent and high-quality manufacturing outcomes.

Lastly, the dissertation introduces a cutting-edge feedrate scheduling method employing B-spline modeling and blending transition techniques to achieve time-optimal trajectories for 6-DOF industrial robots. This approach comprehensively manages discrete trajectory segments by seamlessly integrating smooth transition curves, explicitly considering critical robotic kinematic constraints such as velocity, acceleration, and jerk limitations. The proposed methodology optimizes overall machining cycle time while preserving trajectory continuity and machining quality. Simulation experiments rigorously validate the effectiveness and efficiency of the approach, demonstrating marked reductions in machining cycle time, improved operational throughput, and enhanced production stability. Consequently, this innovative trajectory planning approach represents a significant advancement in robotic machining technology, promising considerable benefits for high-volume and precision-critical manufacturing industries.

The collective findings and advancements presented in this dissertation contribute significantly to both academic research and industrial applications in robotic manufacturing. The methodologies developed enhance the performance and reliability of robotic systems, addressing critical challenges in trajectory optimization. The practical implications of this research are closely related to industry, particularly in sectors such as automotive manufacturing, where precision and efficiency are paramount. Overall, this dissertation not only advances the theoretical foundations and methodological approaches in robotic trajectory optimization but also effectively bridges the gap between academic research and industrial practice.