別紙４－１（課程博士（英文））

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Abstract (Doctor)

Title of Thesis	Spline-Based Approaches to Time-Optimal, Smooth, and High-Accuracy Trajectory Generation for Industrial Machines

Approx. 800 words

Computer numerical control machines and industrial manipulators are extensively used in modern manufacturing industries to perform various tasks with complex profiles that require high-speed, high-accuracy, and repeatability. Tasks are represented as a geometric profile in the Cartesian workspace. Generally, complex profiles are separated into a series of linear segments by the computer-aided manufacturing system. To avoid discontinuous motions at the sharp corners of two linear segments, the machine has to completely stop the motion for each segment, which consumes energy and machining time. If the continuous feed rate is considered to transverse between segment trajectories, discontinuities of resulting trajectories induce mechanical wear and large tracking errors by the controllers.

To enhance productivity, the main objective is to complete the tasks in the minimum motion time. Consequently, research has explored to simultaneously improve the contradictory objectives of motion time, such as smoothness, consumed energy, and accuracy of the workpiece. Therefore, the Pareto optimal solution, which contributes a trade-off between contradictory objectives is getting attention by the decision makers nowadays. Due to the access limit of the original controllers and the complexity of the control structure, the advanced controllers are still difficult to implement for improving the desired objectives of industrial machines. Therefore, the optimal reference trajectory generation becomes a key driver for its simplicity. Most importantly, the reference motion trajectories must accurately represent the geometric path, be at least continuous in acceleration, and satisfy the kinematic and dynamic limits of the machines for all horizons.

In literature, the optimal control problems are solved by direct transcription methods, where the machine limits are considered as discrete constraints on grid points for calculation along the trajectory. As a drawback, constraint violations may occur in-between the determined grid points. For complex paths with frequently changed derivatives, a large number of grids are typically required for constraint satisfaction; thus, the problem becomes computationally expensive, and the optimization solver may fail to find a feasible solution. Therefore, this process is not straightforward for users. This thesis presents several approaches for single and multi-objective smooth optimal trajectory generations for industrial machines by control parameterization of splines, guaranteeing kinematic constraints for the entire horizon regardless of the grid points. Two main approaches are analyzed in this study: decoupled, in which the optimal control problem is solved with two steps of geometric path planning and trajectory optimization, and coupled, in which the problem is solved in a single step of optimization. Literature review and preliminaries for this thesis are discussed in Chapter 1 and 2.

Chapter 3 and 4 provide the decoupled trajectory generations, assuming the geometric paths

are predefined by a parametric curve or a set of via-points. The control parameterization is implemented in terms of B-splines to provide acceleration and jerk continuities. Chapter 3 presents the bi-objective optimization problem between the total motion and the jerk square integral of motion trajectories in the time domain. Guaranteed kinematic constraints are proposed based on the spline convex hulls and the maximum geometric derivatives along the path. The Pareto front comprising the significant trade-off solutions is explored by the combinations of normalized normal constraint and divide and conquer algorithms. The simulations and experimental results validate that the proposed method provides an approximately 3% faster and 21.57% lesser average axial tracking errors than the conventional linear reparameterization method. Chapter 4 discusses the time optimal control problem in the parameter domain using the nonlinear transformation of optimization variables. The time dependency is excluded, and the optimal motion time for each segment trajectory is independently achieved. The guaranteed kinematic constraints are determined based on the spline convex hulls that limit the maximum geometric derives between the locally affected intervals; therefore, it is more relevant to apply on complex geometric paths. Comparison with the jerk-limited time-optimal trajectory generation shows that the proposed method is more robust with the problem grid size and gives a smoother time-optimal trajectory, which reduces the average axial tracking errors by approximately 12%.

Chapter 5 presents coupled optimal trajectory generations by parameterization of B-splines. Time-optimal contour reshaping of the complex workpieces comprising straight-line, circle, and spline contour segments is discussed in the first part. The velocity and acceleration continuity between segment trajectories, fitting accuracy of the geometric path, and kinematic constraints using spline convex hulls are considered as constraints in the problem formulation. The optimization results prove that the proposed method can represent various G-code segments by considering the trade-off between the time-optimality and fitting accuracy of the workpiece. The second part discusses the smooth trajectory generation for reduced impact motion. Motion optimization is considered for the smooth catching of a flying object with a similar velocity by minimizing the residual impact force between the object and the industrial machine. The optimization results confirm that the resulting trajectories are bounded by kinematic and workspace limits and satisfy the required velocity for the smooth catching operation. Finally, the conclusions for proposed spline-based decoupled and coupled optimal trajectory generations are drawn, and the expected future works are discussed in Chapter 6.