別紙４－１（課程博士（英文））

Date of Submission (month day, year) : 07/03/2023

Department of Mechanical Engineering		Student ID Number	D209105	Supervisors	Naoki Uchiyama Kentaro Takagi
Applicant's name	Mathias Sebastian Halinga				

Abstract（Doctor）

Title of Thesis	Time and Energy Optimal Trajectory Generation for Coverage Motion of Industrial Machines.

Approx. 800 words

In the manufacturing industry, industrial machines including Computer Numerical Control (CNC) and industrial robots are widely used because of their accuracy, flexibility, and high production rates to meet the demands for precise products. Coverage motion is one of the dominant motions of industrial machines for manufacturing tasks such as milling, polishing, painting, additive manufacturing, laser cutting, and inspection. To achieve high accuracy, these tasks require precise motion; on the other hand, the tasks are repetitive and are performed for a long time, which leads to high energy consumption. Energy saving is needed given the current worldwide situation of high energy costs, environmental effects, and the depletion of energy sources. In addition, shorter operating times are key for industrial machines to meet high production demands and guarantee profits. To attain shorter operation times, machines are typically operated at higher velocities, thus leading to high energy consumption and low precision. Precise motion is vital for machines to manufacture high-quality products. Therefore, the industrial sector is driven by a high need for machines with accurate motion, shorter operation times, and energy saving.

Coverage motion optimization is one of the methods that play a major role in reducing time and energy consumption and increasing the accuracy of the machine. It is a feasible and less costly method that does not require replacing existing machine components with new ones or modifying the control law. Motion optimization is categorized into geometric path optimization and trajectory generation while considering objective functions such as smoothness, time, cost, and energy consumption. In the literature, many studies focused on motion optimization and implemented the two processes separately: simultaneous path optimization and trajectory

generation are relatively unexplored. By integrating geometric path optimization and trajectory generation, industrial machines can realize high-quality products with higher machine performance and ensure environmental sustainability. Due to the high demand for environmental sustainability and reducing production costs, the objective functions of time and energy consumption are considered. Moreover, time and energy are two conflicting objectives; the trade-off between time and energy is determined. This thesis discusses several approaches of industrial machines coverage motion optimization for accuracy and performance enhancement using trajectory (velocity) optimization with simultaneous geometric path optimization. The proposed approaches can be used for machine operations such as milling, laser cutting, inspection, gluing, and polishing that execute point-to-point motions.

To enhance machine performance in terms of time and energy consumption while achieving accurate motion in industrial machines, the proposed optimization approaches are described as follows in this thesis: Introductory remarks are presented in chapter 1 followed by a literature review in chapter 2 describing the related studies in motion optimization, optimization methods, and industrial feed drive systems. Chapter 3 presents the method for simultaneous path and trajectory (velocity) optimization used to improve machine efficiency in a coverage motion for industrial machines by ensuring the smoothness and satisfaction of the machine constraints. The multi-objective path and trajectory optimization are proposed to obtain a trade-off between time and energy consumption for coverage motion. The jerk limited acceleration profile (JLAP) describes the trajectory where the velocity profiles generated for each linear segment attain desirable velocities. The energy model of an industrial two-axis feed drive system is used to solve the optimization problem. The non-dominated genetic algorithm II (NSGA II) generates a Pareto front for trade-off time and energy consumption solutions. The simulation results of the proposed method are validated through experiments using the industrial two-axis feed drive system. Experimental results show the effectiveness of the proposed approach where time reduction and energy saving are 10.05% and 2.10%, respectively. Furthermore, the optimized path has a lower maximum error of 76.6% compared to the optimized path with constant commanded velocity.

An energy optimization approach for the coverage motion of industrial machines, which simultaneously integrates trajectory generation and geometric path optimization is presented in chapter 4. The modified S-curve profile describes the trajectory along a linear segment with harmonic motion employed for smooth jerk continuity to enhance the motion accuracy. An energy consumption model of the industrial feed drive system is used to achieve optimal energy. A genetic algorithm (GA) is applied for the optimization. Experimental validation of the simulation results is carried out using the industrial two-axis feed drive system. Simulation and experimental results show that the energy saving of the feed drive system is achieved under machine kinematic limits that ensure smooth motion, which is approximately 14.6% energy saving compared to an unoptimized solution.

Chapter 5 describes an approach that proposes optimal motion planning by simultaneous path and velocity optimization to achieve the trade-off between time and energy consumption. The multi-objective optimization model for minimizing time and energy consumption is solved by the NSGA II. The modified S-curve profile describes the trajectory, which ensures smooth jerk continuity. To validate the effectiveness of the proposed approach, simulation and experiments are carried out using the industrial two-axis feed drive system, and the motion accuracy is compared to that of JLAP. Experimental results reveal that the best trade-off trajectory of the proposed approach achieves respectively 13.9% and 3.5% of time reduction and energy saving. The mean tracking error is reduced by 16.2% and 14.9% for the x and y axes, respectively, compared to the JLAP. Last, chapter 6 presents the concluding remarks of this thesis and prospective future works.