Institute for Machine Tools and Industrial Management (iwb)
TUM School of Engineering and Design
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Methodical Approach for Analyzing Process Parameters and Optimizing Boundary Conditions in Mutli-Axis Robot Programs

Methodischer Ansatz zur Analyse von Prozessparametern und Optimierung von Randbedingungen in Mutli-Achs-Roboterprogrammen

Scientific work for obtaining the academic degree

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Scope of Work

Title of the Master's Thesis:
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Methodischer Ansatz zur Analyse von Prozessparametern und Optimierung von Randbedingungen in Mutli-Achs-Roboterprogrammen

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Motivation:
Computer-aided manufacturing (CAM) is used to automatically generate tool paths for computer numerical control (CNC) machines. The CAM software considers the models of the raw and finished part as well as the constraints of the machine, the tools, and the manufacturing technology. Together with user-configurable parameters, tool paths for 3-axis, 5-axis, and robot-based machine tools are generated. The growing demand for flexibility in machine tools, such as the use of multiple manufacturing technologies in one machine or automated loading and unloading, has led to many machine tools being equipped with additional mechanical axes. Examples include robots mounted on linear axes and rotary-tilt tables. The tool paths created in CAM programs are usually defined by five degrees of freedom. The first three are the translational axes X, Y, and Z. The tilting and inclining of the tool are defined by the A- and B-axes. Occasionally, an additional rotation of the tool (C-axis) around the Z-axis (e.g., for dragging a swivel knife) is defined. Machines with more degrees of freedom than those limited by the toolpath often need user-defined constraints. These constraints are necessary to fully specify the movements of the machine axes. An example is the alignment of a part using the rotary-tilt table so that the Z-axis of the tool always points in the direction of gravity. This is helpful in processes like fused deposition modeling (FDM) and wire arc additive manufacturing (WAAM). It is common practice to set the user-defined constraints based on experience. A preliminary literature review indicates that the configuration of these degrees of freedom has an impact on the energy demand and stability of the process.

Objective:
The definition of these constraints does not affect the relative tool path generated by the CAM software. As such, a methodical approach to optimize these constraints in terms of efficiency, speed, and energy demand of the machine is required. Currently, no literature provides a comprehensive analysis or methodology regarding this global optimization problem. This

work aims to attain a methodical approach that analyzes a set of constraints and evaluates the influence of those constraints on a set of defined process variables. It will focus on a 6-axis robot with a rotary-tilt table, whereby the results should also be transferable to other machines. Furthermore, the experiments and validations will be limited to the manufacturing processes of WAAM and milling. First, the influence of the constraints on relevant process variables (energy demand, joint turnover, speed and acceleration peaks, total joint movements) in a manufacturing process such as WAAM will be assessed. Subsequently, a process evaluation will be elaborated in the CAM software, by means of which the process quality can be determined. Depending on the respective process variables, approximation methods or machine learning methods will be investigated for the process evaluation. The process quality as a one-dimensional variable will be determined by weighting the process variables. Subsequently, a method for the optimization of the constraints will be elaborated. This task corresponds to an optimization problem in which the process quality will be maximized by selecting suitable constraints.

Procedure and working method: The following work packages are conducted within this thesis:

- Literature research
- Familiarization with WAAM, milling machines, and CAM software
- Selection of suitable process parameters
- Elaboration of the proposed method in a suitable programming language
- Verification and validation of the elaborated method
- Documentation of the work

Agreement:

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Garching, 29.03.2024

Prof. Dr.-Ing. Michael F. Zäh	B.Sc. Jan Nalivaika

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Chapter 1

Introduction

1.1 Motivation

In the age of "Industrie 4.0", advanced technologies like digital twins, have greatly transformed industrial manufacturing [30]. A considerable amount of data can be gathered from various processes, like milling or 3D printing. By analyzing this data, it is possible to find new and optimized methods for efficient manufacturing [12]. By doing so, a significant amount of resources, like time and money, can be saved while at the same time increasing the quality of the produced product [4, 29].
Computer-Aided Manufacturing (CAM) has been introduced as a crucial tool to improve productivity and accuracy in creating customized products [11]. CAM systems automate and optimize tasks such as machining, welding, and assembly [18]. One of the key strengths of CAM lies in its precision and consistency, ensuring that intricate components are produced with minimal error. Furthermore, CAM systems contribute to increased efficiency by minimizing material waste and reducing production time [9]. These capabilities play a significant role in achieving a carbon-neutral production process [26]. One of the most important areas of CAM is the calculation of the tool path for computer numerical control (CNC) machines as well as the movement and behavior of multi-axis industrial robots [23].

Manufacturing machines are the backbone of modern industrial processes [3]. These machines encompass a wide range of equipment, from CNC machining centers to 3D printers and automated assembly lines. Their primary ability lies in precision and efficiency. CNC machines, for instance, can repeatedly produce intricate parts with high accuracy, reducing human error and ensuring consistency [16].
Industrial robots are a dominant part in the area of manufacturing as they can perform multi-axis movements that are needed to fulfill the customers wishes for individualized products [27]. They are cheaper to acquire and more flexible compared to CNC milling machines but have their own set of disadvantages [15]. One advantage is the wide adaptability. They allow for quick reconfiguration to produce different components or products, promoting flexibility in manufacturing [5]. Further, advancements in robotics and artificial intelligence (AI) have broadened their capabilities, enabling tasks that were once deemed too complex or hazardous for humans [13].

Achieving efficiency and sustainability in the current fast-changing environment requires a thorough analysis of the interdependent relationships between the manufactured part, process parameters, and boundary conditions that govern multi-axis robot programs [23]. As the companies that work with industrial robots can place a strong emphasis on energy reduction, cycle-time minimization, or precision, optimizing these parameters is essential. CAM enables the simulation of the planned process, thus adapting any boundary conditions to fit the selected goals [17, 21, 23]. This thesis is focused on a methodical approach for analyzing process parameters and optimizing boundary conditions in multi-axis robot programs.

1.2 Problem Formulation

Manufacturing systems that incorporate redundant degrees of freedom offer significant advantages in terms of flexibility and adaptability [1]. One example of a system with redundant degrees of freedom is a 6-DoF industrial robot with a rotary tilt table, which brings the system to eight degrees of freedom. However, these systems also present various conflict points that need to be carefully managed to ensure optimal performance [6, 20].

One of the critical challenges in manufacturing systems with redundant degrees of freedom is singularity avoidance [20]. Singularities occur when the robot manipulator loses control or achieves limited mobility due to certain configurations [22]. These configurations result in the loss of a degree of freedom or make the system highly sensitive to small changes, leading to unstable or unpredictable behavior [31]. Limiting the possible positions by adding artificial constraints can help to avoid this problem.

One significant conflict point in manufacturing systems with redundant degrees of freedom is joint acceleration and jerk, which is the rate of change of acceleration. The robot must allocate accelerations effectively among its joints to achieve smooth and coordinated motion. Failure to do so can result in jerky or erratic movements, which not only compromise precision but also impact the efficiency of the manufacturing process [10]. Rapid changes in acceleration and jerk can cause mechanical stress, decrease system lifespan, and compromise precision. Additionally, the joints can be limited in their ability to keep up with the required speed due to limitations in power [24]. Therefore, advanced control algorithms and motion planning techniques are necessary to optimize joint motion and minimize conflicts in joint acceleration and jerk [10].

Extension control is another critical aspect that needs to be addressed in systems with redundant degrees of freedom. Redundant degrees of freedom can provide additional extension capabilities to industrial robots, allowing them to reach difficult-to-access areas [10]. However, managing and controlling the extension can be challenging, particularly when precise positioning or maintaining stability is required [19]. The robot must accurately determine the appropriate extension for each joint to avoid unnecessary overextension and collisions with the surrounding environment.

Robot orientation also has a significant effect on robot stiffness. A increased number of joints can introduce compliance and reduce overall system stiffness. This can affect precision, accuracy and stability. Robot orientation and its degrees of freedom must be carefully considered to ensure the desired level of stiffness and system rigidity [20, 28].

Precision is a crucial element in manufacturing systems closely tied to its stiffness. The robot needs to have precise control over the movement of each joint to achieve the desired precision in the manufacturing process. Nevertheless, achieving and maintaining high precision can be difficult due to the increased complexity and sensitivity to various factors [10]. Frequent changes in direction in the joints are another factor that affects precision. The present play in the motor joints can add up the inaccuracies and impede the manufacturing process [14].

Mechanical stress, decreased precision, and increased energy consumption can result from abrupt and frequent direction changes.

Furthermore, effectively coordinating the movement of multiple joints to execute rapid direction changes can prove to be a difficult and time-consuming task. Poor direction changes can result in prolonged transfer times, ultimately hampering the overall productivity of the manufacturing process [25]. Minimizing transfer time is crucial for improving production efficiency and throughput. Optimal path planning, motion optimization, and parallel processing techniques can be employed to reduce transfer time while leveraging redundant degrees of freedom effectively [6].

Energy use is also a significant concern in manufacturing systems employing redundant degrees of freedom [8]. The presence of additional joints and their non-optimal usage can require more power to operate, potentially leading to increased energy consumption. As energy efficiency becomes a priority in modern manufacturing, efficient energy management strategies are necessary to mitigate the increased power demand [6, 7].

While redundant degrees of freedom may introduce potential conflicts, they can also enhance performance in manufacturing systems [2]. The added degrees of freedom increase flexibility and adaptability, enabling the robot to carry out complex tasks more efficiently. Redundancy enables multiple approaches to achieve a desired end-effector position or orientation. By effectively utilizing the surplus degrees of freedom, manufacturing systems can enhance their performance, increase efficiency, and exhibit greater flexibility in handling diverse tasks [6].

Currently, there is no integrated system that can evaluate a computed tool path based on the chosen objective, such as minimizing movement or maximizing stiffness, in conjunction with available CAM systems. Additionally, there is no option to provide an optimal or near optimal solution for defining the necessary constraints for a specific goal, like for example, minimizing energy usage.

1.3 Objective

The definition of the redundant constraints, mentioned in chapter 1.2, does not affect the relative tool path as generated by the CAM software. As such, a methodical approach to optimize these constraints, without altering the toolpath, in terms of efficiency, speed, and energy demand of the machine is required. Currently, no literature provides a comprehensive analysis or methodology regarding this global optimization problem. This work aims to attain a methodical approach that analyzes a set of constraints and evaluates the influence of those constraints on a set of defined process variables. It will focus on a 6-axis robot with a rotary-tilt table, whereby the results should also be transferable to other machines. Furthermore, the experiments and validations will be limited to the manufacturing processes of WAAM and milling.

First, the influence of the constraints on relevant process variables (energy demand, joint turnover, speed and acceleration peaks, total joint movements) in a manufacturing process such as WAAM will be assessed. Subsequently, a process evaluation will be elaborated in the CAM software, by means of which the process quality can be determined. Depending on the respective process variables, approximation methods or machine learning methods will be investigated for the process evaluation. The process quality as a one-dimensional variable will be determined by weighting the process variables. Subsequently, a method for the optimization of the constraints will be elaborated. This task corresponds to an optimization problem in which the process quality will be maximized by selecting suitable constraints.

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I hereby declare that this thesis is entirely the result of my own work except where otherwise indicated. I have only used the resources given in the list of references.

Garching, March 15, 2024

(Signature)