Institute for Machine Tools and Industrial Management (iwb)
TUM School of Engineering and Design
Technical University of Munich

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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Supervised by Prof. Dr.-Ing. Michael Zäh
Institute for Machine Tools and Industrial Management (iwb)

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Acknowledgment

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Scope of Work

Title of the Master's Thesis:
Methodical Approach for Analyzing Process Parameters and Optimizing Boundary Conditions in Mutli-Axis Robot Programs

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

Author:	Jan Nalivaika	**Supervisor:**	Ludwig Siebert
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Motivation:
Computer-aided manufacturing (CAM) is used to automatically generate tool paths for computer numerically controlled machines. The CAM software considers the models of the raw and finished parts, 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. The definition of these constraints does not affect the relative tool path generated by the CAM software. 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. 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.

Objective:
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, and 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 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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Prof. Dr.-Ing. Michael F. Zäh	B.Sc. Jan Nalivaika

Abstract

Place your abstract here.

Zusammenfassung

Hier könnte Ihre Kurzzusammenfassung stehen.

Contents

Chapter 1

Introduction

1.1 Motivation

In the age of "Industrie 4.0", advanced technologies like digital twins, have greatly transformed industrial manufacturing [103]. 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 [39]. 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 [10, 102].
Computer-Aided Manufacturing (CAM) has been introduced as a crucial tool to improve productivity and accuracy in creating customized products [37]. CAM systems automate and optimize tasks such as machining, welding, and assembly [66]. 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 [31]. These capabilities play a significant role in achieving a carbon-neutral production process [94]. 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 [84].

Manufacturing machines are the backbone of modern industrial processes [9]. 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 [59].
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 [99]. They are cheaper to acquire and more flexible compared to CNC milling machines but have their own set of disadvantages [52]. One of the most important advantage is the wide adaptability. They allow for quick reconfiguration to produce different components or products, promoting flexibility in manufacturing [11]. Further, advancements in robotics and artificial intelligence (AI) have broadened their capabilities, enabling tasks that were once deemed too complex or hazardous for humans [41].

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 [38, 84].

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 [65, 76, 84, 110]. 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 (DoF) offer significant advantages in terms of flexibility and adaptability [4]. One example of a system with redundancy is a 6-DoF industrial robot with a rotary tilt table, which brings the system to eight DoF. However, these systems also present various conflict points that need to be carefully managed to ensure optimal performance [13, 75].

One of the critical challenges in manufacturing systems with redundant DoF is singularity avoidance [75]. Singularities occur when the robot manipulator loses control or achieves limited mobility due to certain configurations [77]. These configurations result in the loss of a DoF or make the system highly sensitive to small changes, leading to unstable or unpredictable behavior [79, 128]. Limiting the possible positions by adding artificial constraints can help to avoid this problem [36].

One significant aspect in manufacturing systems with redundant DoF 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 [32]. 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 [91]. Therefore, advanced control algorithms and motion planning techniques are necessary to optimize joint motion and minimize conflicts in joint acceleration and jerk [32, 111].

Extension control is another critical aspect that needs to be addressed in systems with redundant DoF. Redundant DoF can provide additional extension capabilities to industrial robots, allowing them to reach difficult-to-access areas [32]. However, managing and controlling the extension can be challenging, particularly when precise positioning or maintaining stability is required [71]. The robot must accurately determine the appropriate extension for each joint to avoid unnecessary overextension and collisions with the surrounding environment. The robot pose, which is the the combination of position and orientation in three-dimensional space, also has a significant effect on robot stiffness [121]. An increased number of joints can introduce more play and reduce overall system stiffness. This can affect precision, accuracy and stability. Robot orientation and its DoF must be carefully considered to ensure the desired level of stiffness and system rigidity [75, 100].

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 accuracy of position in the manufacturing process. Nevertheless, achieving and maintaining high accuracy and repeatability can be difficult due to the increased complexity and sensitivity to various factors [32]. Frequent changes in direction in the joints are another factor that affects precision. Due to the serial kinematics of industrial robots, the present play in the motor joints can add up the inaccuracies and impede the manufacturing process [19, 51]. 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 computationally intensive task [113]. Poor direction changes can result in prolonged and unnecessary movement times, ultimately hampering the overall productivity of the manufacturing process [93]. Minimizing production time is crucial for improving efficiency and throughput. Optimal path planning, motion optimization, and parallel processing techniques can be employed to reduce non-value adding movements while leveraging redundant DoF effectively [13].

Energy use is also a significant concern in manufacturing systems employing redundant DoF [29]. 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 [13, 14].

While redundant DoF may introduce potential conflicts and require special attention, they can also significantly enhance performance in manufacturing systems [7]. The added DoF 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 of DoF, manufacturing systems can enhance their performance, increase efficiency, and exhibit greater flexibility in handling diverse tasks [13].

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.

Chapter 2

State of Science and Technology

The following chapter gives a overview of manufacturing technologies, CAM, and various algorithms for optimization problems. Special attention is given to the comparison of optimization problems in manufacturing with redundant degrees of freedom.

2.1 Manufacturing Technologies

Manufacturing technologies encompass a wide range of processes that are used to transform raw materials into finished products. Two major categories within this field are subtractive and additive manufacturing [53]. Subtractive manufacturing involves removing material from a workpiece to shape it into the desired form [117]. This is commonly achieved through techniques like cutting, drilling, milling, or grinding. On the other hand, additive manufacturing, also known as 3D printing, involves building up layers of material to create an object. This process offers greater design flexibility and the ability to create complex geometries [25]. Both subtractive and additive manufacturing play crucial roles in various industries, revolutionizing production methods and offering new possibilities for customization and innovation [8, 112].

2.1.1 Subtractive Manufacturing

Subtractive manufacturing, also referred to as subtractive fabrication or machining, is a precise and efficient method utilized in contemporary manufacturing processes [116]. This approach entails the removal of material from a solid block or workpiece, resulting in the formation of a desired shape or product [18]. In contrast to additive manufacturing techniques, like 3D printing, where material is applied layer by layer, subtractive manufacturing always starts from a block of material [1].

Subtractive manufacturing involves various techniques such as milling, turning, drilling, and grinding that are mostly performed by using CNC machines [64]. Such machines are programmed to precisely control the cutting tool movement to clear material from the workpiece based on a predetermined design [3].

The versatility and precision of subtractive manufacturing is one of its significant advantages. A CNC machine can process a diverse array of materials, such as metals, plastics, and composites, with high level of precision and surface quality, allowing for the creation of intricate and complex components [109, 122]. As a result, it finds applications in industries where precision and quality are critical, such as aerospace, automotive, and medical.

The process of subtractive manufacturing starts with the drafting of the intended component using computer-aided design (CAD) software. Subsequently, CAM software is used to generate instructions that are used to guide the CNC machine (see chapter 2.2 for more details) . The machining process begins with the machine operator setting up and securing the workpiece in the machine and starting the execution of the generated instructions [81].

The cutting tools then perform various operations, including drilling holes, creating pockets or slots, and shaping the external contours of the part, by following the predetermined movements. In a typical 3-axis machine, the degrees of freedom are along the X, Y, and Z axes. Additionally, recent research is trying to extend the machines possibilities by adding advanced abilities like constantly monitor and adjusts the cutting parameters to ensure the most efficient cutting speed, feed rate, and tool engagement while minimizing errors [108].

Subtractive manufacturing provides numerous advantages over alternative manufacturing techniques. This method allows for the creation of intricate and highly customizable components with tight tolerances and complex geometries [57]. In addition, it results in exceptional surface finish, dimensional accuracy, and consistency, guaranteeing uniform quality across production runs. Moreover, it is cost-effective for small to medium production volumes as it does not necessitate the use of costly molds or tooling [42].

One of the disadvantages of the process is the possibly long cycle time. Particularly for intricate designs, and can result in significant material waste [35]. Furthermore, it may not be appropriate for high hardness or brittle materials, which can lead to excessive tool wear or breakage [48]. In summary, subtractive manufacturing offers a wide range of applications but should be carefully considered for each situation. CNC technology in combination with subtractive manufacturing has become indispensable across a variety of industries. Nonetheless, it is crucial to evaluate its restrictions and suitability for specific design needs and material characteristics.

One common issue in CNC machining is tool vibration. Tool vibration, also called Chatter, refers to the unwanted oscillation or movement of the cutting tool during the machining operation [126]. This phenomenon can have detrimental effects on the quality of the finished part and can lead to various problems, such as poor surface finish, reduced dimensional accuracy, increased tool wear, and even tool breakage [5].

Several factors contribute to tool vibration in CNC machining. One of the primary factors is the cutting parameters, which include the cutting speed, feed rate, and depth of cut. When these parameters are not optimized, excessive cutting forces can be generated, causing the tool to vibrate. It is crucial to find the right balance between material removal rates and minimizing tool vibration to ensure optimal machining outcomes [40].

The tool holder and spindle system also influence tool vibration. A rigid and stable tool holder and spindle are necessary to minimize vibrations and maintain accuracy during machining [114]. Any excessive play or misalignment in these components can contribute to tool vibration. To mitigate tool vibration in CNC machining, various strategies can be employed. Optimizing cutting parameters, such as adjusting the cutting speed, feed rate, and depth of cut, can help minimize vibrations [82].

In conclusion, tool vibration is a common challenge in CNC machining that can negatively impact part quality. Thus it is paramount to ensure stiffness for high precision operations. Chapter 2.1.3 gives a more in-depth look regarding the stiffens in machining operation executed with industrial robots.

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2.1.2 Additive Manufacturing

AM processes involve the conversion of CAD-files into physical objects by building them layer by layer. This layering approach offers several advantages. Firstly, it allows for the creation of complex geometries that would be extremely challenging or impossible to produce using traditional manufacturing methods [90]. The ability to fabricate intricate structures with internal cavities, undercuts, and overhangs opens up new possibilities in engineering and design [1].

Various AM technologies utilize different methods to build the layers. Fused Deposition Modeling (FDM), for example, involves extruding molten thermoplastic filament through a heated nozzle, which solidifies as it cools, creating the desired shape [118]. Stereolithography (SLA) employs a liquid photopolymer resin that is solidified by a UV laser, while Selective Laser Sintering (SLS) uses a high-power laser to selectively fuse powdered materials, such as plastics or metals [78, 115].

The compatibility of AM with a wide range of materials is another scientific advantage [15]. It enables the production of components with diverse properties, including strength, flexibility, conductivity, and heat resistance. AM can accommodate various plastics, such as ABS, PLA, and nylon, as well as metals like titanium, aluminum, and stainless steel. Additionally, ceramics and even biomaterials, like hydrogels or living cells, can be used in AM processes. New materials specifically tailored for AM are continuously developed expanding the possibilities for unique applications [6].

The design freedom offered by AM is a significant scientific breakthrough. Traditional manufacturing methods often have design constraints due to limitations in tooling and manufacturing processes. With AM, designers have greater flexibility to create complex and organic shapes, lightweight structures, and intricate internal features. This freedom leads to optimized performance and improved functionality [89].

However, AM also poses scientific challenges. Post-processing requirements, such as smoothing, polishing, or heat treatment, may be necessary to achieve the desired surface finish or material properties [56]. Additionally, certain applications may have limited material options, particularly in terms of high-temperature or high-strength applications. Production speed can also be a constraint for large or complex parts, as AM processes can be time-consuming compared to traditional manufacturing methods [25].

As AM technologies continue to advance, they have the potential to transform supply chains. The concept of distributed manufacturing, where products are produced closer to the point of use, becomes feasible with AM [56]. This reduces transportation costs, lowers carbon emissions, and enables on-demand manufacturing, leading to shorter lead times and increased sustainability [44].

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Wire Arc Additive Manufacturing

Wire Arc Additive Manufacturing (WAAM) is a specific type of additive manufacturing process known as Directed Energy Deposition (DED) [107]. According to the DIN EN ISO/ASTM 52900 standard, DED involves using focused thermal energy to melt the starting material during the application process [26]. In the case of WAAM, an electric arc is used to generate the necessary energy for melting. This is achieved by utilizing standard welding technology, such as gas-shielded metal arc welding, in combination with precise spatial movement of the welding torch [22]. This allows for the construction of components layer by layer.

WAAM offers several advantages over other additive manufacturing techniques. One major advantage is its high deposition rate, which range up to 6kg/h. This high deposition rate enables the construction of large components in a relatively short amount of time. Components can be produced within a single workday, providing a significant time advantage compared to techniques like Powder Bed Fusion (PBF), which typically operates at much slower deposition rates [54].

Another advantage of WAAM is its capability to construct large components without limitations on part size. The production volume is only constrained by the working range of the kinematics employed. For example, in the case of an articulated-arm robot, the range is defined by its minimum and maximum reach. This means that WAAM has the potential to create components of various sizes without compromising its effectiveness [69].

However, it is important to note that WAAM components may have some inherent defects. These include residual stresses and deformations that persist after the production process, as well as relatively low geometric precision and modest surface quality. These limitations should be taken into consideration when utilizing WAAM for manufacturing purposes [119].

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WAAM-Process and Cold Metal Transfer

The operating principle of WAAM involves the generation of an arc through electrical discharge between an electrode and the workpiece. This arc transfers energy to the workpiece, causing melting in the fusion zone [83]. Additionally, if a welding filler material in the form of a wire is introduced into the arc, it also melts and can be used to deposit welds onto a metallic substrate [22]. To ensure a continuous weld seam, a wire feed system can be employed [27].

The industrial manufacturing of components using WAAM involves a kinematic system that allows movement of the welding torch. This can be achieved using robot-configurations or gantry systems [95]. Alternatively, a spatially fixed welding torch, combined with robotic kinematics or rotary-tilt table, can be used to move the component [80]. The WAAM process builds up the component layer by layer, following a predefined path.

Cold Metal Transfer (CMT) welding is a sophisticated process that merges the advantages of multiple welding techniques [33]. It functions based on the principle of controlled short-circuiting, wherein the welding torch generates a short circuit between the electrode and the workpiece. This short circuit triggers the wire melt and detach. The detachment is assisted by a retraction of the wire. This process is generating a sequence of droplets that transfer to the weld pool with remarkable precision [97, 106].

CMT welding provides superior heat control with lower heat input than conventional methods. The controlled arc and droplet transfer reduce the risk of overheating and distortion, making it suitable for thinner materials and heat-sensitive applications [96]. The process minimizes spatter formation, resulting in cleaner and smoother welds and reducing the requirement for post-weld cleaning [106]]. This process stands out for its exceptional weld quality. Its precise control over heat input and metal transfer results in improved fusion, reduced porosity, and an enhanced appearance of the weld bead. CMT welding is ideal for applications that require the highest weld quality which includes structural fabrication and automotive manufacturing [20].

For dependable weld quality, CMT welding typically integrates advanced process control systems, which utilize adaptive control and real-time monitoring to consistently adjust welding parameters based on sensor feedback. This enhances the precision and dependability of the welding process [88].

A CMT cycle consists of three phases [97]:
1st pulse phase: a high current pulse leads to the ignition of the arc, which melts the wire electrode. A droplet begins to form at the tip of the wire. The wire is moved forward in the direction of the workpiece.
2nd arc phase: The arc is kept burning at a lower current. burning at a lower current. This prevents the melt droplet from detaching early and from detaching prematurely and transferring to the workpiece.
3d short-circuit phase: as soon as the wire comes into contact with the substrate, the voltage drops to 0 V and the wire feeder is signaled to withdraw the wire. is signaled to withdraw the wire. This supports the droplet detachment from the wire into the molten bath.

Figure 2.1 shows the three Phases of a CMT cycle. The voltage is constant in the first two phases and drops to zero in the short circuit phase. The spike of current is clearly visible in the first phase which is also the shortest.

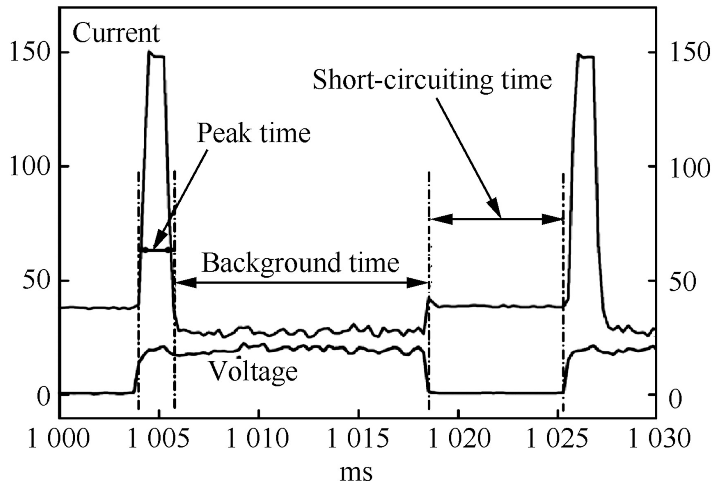

Figure 2.1: Current and Voltage wave forms of a CMT process [97]

In summary, WAAM and CMT are highly sophisticated processes that enable the creation of 3D printed parts with specifically designed parameters. CMT achieves precise welds with low heat input and minimal spatter. It is ideal for thinner materials and applications requiring high weld quality. Advanced process control systems enhance the reliability of CMT welding [87, 92].

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2.1.3 Industrial Robots

Industrial robots are advanced machines designed to perform various tasks in manufacturing and industrial settings. They come in different types, each with its own set of capabilities and advantages. They crucial to modern manufacturing and automation, transforming production methods and repetitive task performance across diverse industries. Since their inception in the mid-20th century, these machines have undergone significant advancements, evolving into highly adaptive and sophisticated devices that promote productivity, accuracy, and safety within manufacturing processes [58]. At their core, industrial robots are programmable machines designed to execute tasks with a high degree of accuracy and efficiency. They can carry out repetitive actions consistently, which enhances productivity and reduces the risk of human error [101].

One common type of industrial robots is the articulated robot. These robots have rotary joints that allow them to move like a human arm, with multiple links and joints. They can perform a wide range of tasks, such as welding, material handling, or assembly operations [46, 55]. Another type is the Cartesian robot, also known as gantry robots. These robots move along three linear axes (X, Y, and Z) to perform tasks. They are commonly used for pick and place operations or in applications that require precise positioning [62]. SCARA robots, on the other hand, are designed for fast and precise movements in assembly operations. They have a selective compliance assembly robot arm that allows them to move quickly while maintaining accuracy [24]. Delta robots are used for high-speed pick and place applications, such as packaging or sorting. They are known for their rapid movements and high throughput [12]. Collaborative robots, or cobots, are designed to work safely alongside humans. They have built-in safety features, such as force sensors or vision systems, that allow them to interact with humans without causing harm. Cobots are often used in tasks that require human-robot collaboration, such as assembly or inspection operations [73].

Industrial robots are based on articulated robots and have a wide range of applications across various industries. They can be used for assembly operations, where they can perform tasks like fastening, welding, or soldering components together. Robots are also commonly used for material handling tasks, such as lifting, moving, and stacking materials in warehouses or production lines. Inspection tasks can be automated with robots equipped with sensors or cameras, allowing them to inspect products for defects or perform quality control checks [43].

Industrial robots offer several benefits. Firstly, they increase productivity by working continuously, without breaks or fatigue. This leads to higher production rates and shorter cycle times. Additionally, robots can perform tasks with high precision and accuracy, reducing errors and defects, thereby improving product quality [63]. Safety is another important aspect of industrial robots. They are designed to handle dangerous or hazardous tasks, keeping human workers safe. Robots can work in environments with high temperatures, toxic substances, or heavy loads, minimizing the risk of injury to humans [49]. While the initial investment in industrial robots can be high, they offer long-term cost savings. Robots can reduce labor costs by automating repetitive tasks and increasing efficiency. They also offer flexibility, as they can be reprogrammed or reconfigured to perform different tasks, allowing for greater adaptability in manufacturing processes [61].

When comparing industrial robots to CNC machines, there are a few notable disadvantages for industrial robots. Firstly, industrial robots generally have lower positional accuracy and repeatability compared to CNC machines. CNC machines are purpose-built for precise machining operations and can achieve high levels of accuracy and repeatability [116]. Secondly, industrial robots typically have a longer cycle time compared to CNC machines for similar tasks. The complex movements and computations involved in robot control can result in slower overall operation speeds, which may not be ideal for high-volume production environments [60]. Additionally, industrial robots can be more complex to program and set up than CNC machines. CNC machines follow a predefined set of instructions, whereas programming industrial robots often requires more advanced programming skills and can be time-consuming [124]. Lastly, industrial robots may have limitations when it comes to handling heavy loads or performing heavy-duty machining operations. CNC machines are specifically designed for heavy-duty cutting, milling, and drilling tasks, whereas industrial robots are better suited for lighter material handling and assembly operations [120]. These differences should be considered when deciding between industrial robots and CNC machines for specific manufacturing applications.

Industrial robots can be programmed using different methods. One common method is using a teach pendant, where operators manually move the robot to record positions and actions. Offline programming is another approach, where programs are created and simulated on a computer before being transferred to the robot. Sensor-based programming allows robots to respond to sensor inputs or interact with the environment [47]. More information regarding the control of robots is described in chapter 2.2.

Serial kinematics is a widely used configuration in industrial robots, where the robot arm is constructed as a sequential chain of joints and links. Each joint provides one degree of freedom (DOF), enabling the robot to move and position its end-effector in a controlled manner. The joints can be of various types, including revolute, prismatic, spherical, and cylindrical, providing rotational, linear, and combined movements. The motion of the robot arm is controlled using forward kinematics and inverse kinematics. Forward kinematics calculates the position and orientation of the end-effector based on the joint angles, while inverse kinematics determines the joint angles required to achieve a desired end-effector pose [104]. Serial kinematics robots have significantly contributed to automation processes, enhancing productivity, efficiency, and flexibility in manufacturing industries.

In summary, the robots performance relies on sophisticated control algorithms and feedback systems that allow them to adapt to dynamic conditions, adjust movements in real-time, and maintain a consistently high level of accuracy [72]. This improves both the quality of the final product and the safety of the manufacturing process, as robots can navigate complex paths without risking collisions or accidents [16]. As technology continues to advance, industrial robots will play an even more prominent role in shaping the future of manufacturing and automation [30]

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Redundancy in robotic systems

Industrial robots with redundant degrees of freedom are robotic systems that have been designed with more degrees of freedom (DOF) than are necessary for a specific task [75]. This extra DOF allows the robots to perform additional joint movements or configurations beyond what is required for basic movement or manipulation.

The primary advantage of these redundant robots is their increased flexibility and adaptability [32]. Robots with more DOF can access a wider range of positions and orientations, making it possible for them to complete complex tasks in constrained environments that would have been difficult or impossible otherwise. With this added flexibility, they can avoid obstacles and work around them without disrupting their duties. In industrial settings, redundant manipulators provide significant advantages. Their additional degrees of freedom enable them to improving accessibility to hard-to-reach areas and enhancing overall operational capabilities [100].

Redundancy can take on many different forms in robotic systems. One option is to increase the number of joints in the serial kinematics of an articulated robot [79]. Another approach to redundancy is the addition of a rotary tilt table, which is commonly used in WAAM in combination with a 6-DoF robot [125]. This combined system enables the robot to manipulate the workpiece from various angles, enhancing the manufacturing process.

Furthermore, the inclusion of a linear axis that the robot base can traverse on is yet another form of redundant DoF. This additional linear motion provides the robot with extended reach and the capability to access a larger workspace, making it suitable for tasks that require movement along a specific axis [14].

Additionally, redundancy can also be observed when using a generic 6-DoF system for operations that only necessitate 5 or fewer DoF [46, 75]. Although the system possesses more flexibility than required for the specific task, it allows for adaptability and versatility in accommodating different operations without the need for reconfiguring the robot.

In summary, redundancy in robotic systems can be achieved through various means such as increasing joint numbers, incorporating rotary tilt tables, including linear axes, or using a higher DoF system for tasks that demand fewer DoF. These redundant features enhance the capabilities and versatility of the robot, enabling it to perform a wide range of complex tasks efficiently.

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While redundancy in industrial robots can provide increased flexibility and adaptability, it also comes with certain disadvantages. One major drawback is the increased complexity and cost associated with redundant systems [45]. The addition of extra joints, axes, or mechanisms adds to the overall complexity of the robot, requiring more sophisticated control algorithms and hardware [32]. This complexity not only increases the initial cost of the robot but also adds to the maintenance and troubleshooting efforts [2]. Additionally, the presence of redundant DoF can make the robot more prone to mechanical failures, as more components are involved. This can result in increased downtime and higher maintenance costs. Moreover, the increased complexity of redundant systems can make programming and calibration more challenging, requiring specialized skills and expertise [34]. Therefore, while redundancy can offer advantages in certain scenarios, careful consideration must be given to the cost, complexity, and maintenance implications before implementing it in industrial robotics applications.

Continuous-path mode

In the context of industrial robotics, continuous and smooth paths of a tool, plays a crucial role in achieving precise and smooth movements of robotic arms along a defined trajectory [59]. This ensures that the robot can execute complex tasks with accuracy and efficiency. By incorporating continuous paths mode into industrial robot programming, manufacturers can optimize production processes and improve the quality of manufactured products [127].

Continuous path mode refers to a mode of operation in high-speed CNC machines where the goal is to achieve a smooth and uninterrupted movement of the machine along a toolpath. In this mode, the machine is expected to follow a path without any sudden changes in velocity, acceleration, or curvature. The purpose of continuous path mode is to minimize jerk spikes, machine vibrations, and other undesirable effects that can occur when there are discontinuities in the toolpath [59, 123].

Continuous-path mode in CNC machining is a crucial aspect when it comes to processing parts with rapidly varied geometric features. These types of components, often found in high-end equipment, pose challenges due to their intricate structures and strict requirements. The presence of rapidly varied geometric features, coupled with the continuous-path running characteristic, gives rise to trajectory errors during the machining process, which severely hampers the overall machining accuracy of such parts [98]. This becomes even more critical in high-feed-speed machining scenarios, where existing studies struggle to effectively reduce this error without compromising machining efficiency [68].

In CNC machines, toolpaths are typically composed of lines and arcs [74]. At the transition points between these elements, careful consideration is required to ensure that the physical limits of the machine are not exceeded. For example, when the machine is moving at a constant feedrate, a sudden change in velocity can occur when two successive non-tangent linear moves meet. This can lead to undesirable effects on the machine and the quality of the cut [17]. Similar issues arise at transitions between lines and arcs or between two arcs, where curvature discontinuities need to be addressed.

Contouring errors are caused by factors such as servo lag, dynamics mismatch, external disturbances, and more. Reducing contouring errors is essential for improving the performance of CNC motion systems and achieving high-speed and high-precision machining [59].

To overcome these challenges and achieve a smooth and continuous toolpath, path smoothing techniques are necessary. Many path smoothing methods have been proposed in the literature, but most of them are limited to linear toolpaths. However, in high-speed CNC machines and industrial robots, the toolpaths often consist of both lines and arcs. Therefore, there is a need for a path smoothing method that can handle both line-to-line transitions and transitions involving arcs [98].

To address this issue and enhance both the processing efficiency and precision, various estimation and compensation methods have been proposed for trajectory error in high-feed-speed continuous-path machining. The actual reachable feed speed is determined based on the geometry and drive constraints of the CNC machine tool. The continuous-path running trajectory error is estimated by approximating the desired toolpath using spline curves. Furthermore, a combination of mirror compensation and Taylor's expansion compensation can be employed as an error compensation approach [59].

One notable advantage of this proposed approach is its ease of estimation and compensation for continuous-path running trajectory errors by analyzing and modifying the NC codes. This implies a high level of feasibility for free-form toolpaths. Experimental results have demonstrated the favorable performance and effectiveness of these methods. By reducing the trajectory error in multi-axis high-speed machining, this study offers an effective approach to enhance the machining precision and efficiency of parts with rapidly varied geometric features in engineering applications. [105]

One approach to achieving continuous path mode is by using biclothoid fillets. These fillets are used for corner smoothing and can be fitted between two arcs or a line and an arc. The main advantage of using biclothoid fillets is that they result in a smoother curvature profile compared to other methods such as Bezier fillets. This smoother curvature profile allows for higher feedrates and shorter cycle times, ultimately improving the overall performance of the CNC machine [98].

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2.2 Computer-Aided Manufacturing

2.2.1 CAM Software

Computer-aided manufacturing (CAM) software is a type of computer software used to automate and optimize the manufacturing process. CAM software takes the design data from computer-aided design (CAD) software and converts it into instructions that control machines and tools to produce the desired product. It plays a critical role in modern manufacturing, helping to streamline production, improve efficiency, and reduce errors.

CAM software enables manufacturers to generate toolpaths and machining instructions for a variety of manufacturing processes, including milling, turning, drilling, and 3D printing. It takes into account factors such as material properties, tool capabilities, and manufacturing constraints to generate the most efficient and accurate instructions for the machines. CAM software can also simulate the machining process to detect any potential collisions or issues before the actual production begins, saving time and resources.

One of the key features of CAM software is its ability to optimize the machining process. It can automatically optimize toolpaths to minimize machining time, reduce material waste, and improve surface finish. By analyzing the geometry of the part, the software can determine the most efficient toolpath strategies, such as contouring, pocketing, or adaptive machining. It can also optimize tool selection, toolpath sequencing, and cutting parameters to achieve the best possible results.

CAM software also offers advanced features such as multi-axis machining and support for complex geometries. It can generate toolpaths for machines with multiple axes of motion, allowing for more intricate and precise machining operations. It can handle complex geometries, including freeform surfaces and curved profiles, and generate toolpaths that accurately follow the desired shape.

Furthermore, CAM software often integrates with other manufacturing software systems, such as computer-aided engineering (CAE) and enterprise resource planning (ERP) systems.

This integration enables seamless data exchange, improves collaboration between different departments, and ensures that the manufacturing process is aligned with the overall production goals.

In summary, CAM software is a crucial tool for modern manufacturing. It automates and optimizes the manufacturing process, generating toolpaths and machining instructions based on CAD data. It enables manufacturers to improve efficiency, reduce errors, and achieve higher-quality products. With features such as optimization, simulation, multi-axis machining, and integration with other systems, CAM software empowers manufacturers to stay competitive in today's fast-paced and complex manufacturing environment.

2.2.2 Path Planning

Path planning and path generation are essential components of computer-aided manufacturing (CAM) software. These processes involve determining the optimal toolpaths for machining operations, ensuring efficient and accurate production.

Path planning refers to the process of determining the best possible sequence of movements for the machining tool to follow while producing a part. It involves considering various factors such as the geometry of the part, tool capabilities, machining constraints, and desired machining parameters. The goal of path planning is to minimize machining time, reduce material waste, and improve the overall quality of the finished product.

Path generation, on the other hand, involves the actual generation of the toolpath based on the planned movements. CAM software uses algorithms and mathematical models to calculate the position and orientation of the tool at each point along the toolpath. The generated toolpath should accurately follow the desired shape and contour of the part while considering factors like cutting direction, feed rate, and tool engagement.

To achieve efficient path planning and path generation, CAM software utilizes a range of techniques. One common approach is contouring, where the tool follows the boundaries of the part's geometry, ensuring a smooth and continuous cut. Pocketing is another technique used to remove material from within closed areas, such as pockets or slots, by following an optimized toolpath.

Another important aspect of path planning and generation is adaptive machining. This technique allows the CAM software to dynamically adjust the toolpath and cutting parameters based on the material properties, tool wear, and other factors. By continuously monitoring and adapting the machining process, adaptive machining ensures consistent and accurate results, even in challenging manufacturing conditions.

Multi-axis machining is another advanced feature that CAM software offers for complex geometries. It enables the tool to move along multiple axes simultaneously, allowing for more intricate cuts and shapes. This capability is particularly useful for machining curved surfaces, freeform shapes, or parts with undercuts.

Simulation plays a crucial role in path planning and generation. CAM software often includes simulation tools that allow users to visualize and verify the toolpath before actual production. These simulations help detect and resolve potential collisions, interferences, or errors that could arise during machining. By identifying and addressing these issues early on, manufacturers can avoid costly mistakes and ensure safe and efficient production.

In conclusion, path planning and path generation are vital components of CAM software. They involve determining the best sequence of movements and generating toolpaths to optimize machining operations. Techniques such as contouring, pocketing, adaptive machining, and multi-axis machining are used to achieve efficient and accurate results. Simulation tools enable users to visualize and verify the toolpath before production, ensuring error-free and safe machining processes. With path planning and generation capabilities, CAM software empowers manufacturers to enhance efficiency, reduce errors, and produce high-quality products.

Chapter 3

Methodology

WHAT IS A PROCESS PARAMETER AND WHAT IS A BOUNDARY CONDITION

3.1 Selection of Process Parameters

3.2 Optimization of Boundary Conditions

3.3 MAGIC

3.4 MAGIC

Chapter 4

Implementation and Validation

4.1 Implementation

4.2 Testing and Validation

4.3 Analysis and Discussion of the results

4.3.1 Analysis

4.3.2 Discussion

Chapter 5

Conclusion

5.1 Summary

5.2 Outlook

Chapter 6

Appendix

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Disclaimer

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)