Robot Grinding and Machining of Thin-Walled Blades: A Survey

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Abstract

Robotic grinding and machining, particularly of thin-walled blades, are pivotal in modern manufacturing, offering enhancements in precision and efficiency crucial for industries like aerospace and automotive. This survey examines the integration of robotic systems, highlighting advancements in error compensation, path optimization, and deformation control. Key challenges include dynamic errors, contact nonlinearity, and the limited rigidity of robotic arms, which impact machining accuracy. Innovations such as adaptive control strategies, machine learning integration, and advanced sensor technologies are explored to mitigate these issues. The survey underscores the importance of frameworks like flatness-based control for maintaining structural integrity during machining. Additionally, the role of custom grippers and real-time data utilization in enhancing precision is emphasized. Future research directions focus on adaptive methods, marker-free perception, and optimizing cutting parameters to further improve robotic machining capabilities. The survey concludes that ongoing innovation and interdisciplinary collaboration are vital for overcoming existing limitations and advancing the performance and reliability of robotic systems in dynamic manufacturing environments.

1 Introduction

1.1 Importance of Robotic Grinding and Machining

Robotic grinding and machining are essential in modern manufacturing, significantly boosting efficiency and precision, particularly for thin-walled blades where accurate contour tracking under dynamic uncertainties is critical [1]. The integration of robotic systems effectively addresses the challenges associated with deformable objects, enhancing manufacturing precision [2]. Additionally, these technologies lower product costs and increase work-cell flexibility, making them attractive for industrial applications [3].

In the aerospace sector, where precision is paramount, robotic machining enhances dynamic behavior analysis of axis systems, essential for meeting product specifications [4]. Although robotics adoption has been slow due to modeling and control challenges, recent advancements have improved integration into manufacturing environments [5]. Combining classical system identification with machine learning techniques has further refined estimation and control processes, underscoring the significance of these technologies in contemporary manufacturing [6].

Robotic machining's advantages include extensive operational reach, high flexibility, and cost-effectiveness compared to traditional CNC machines. Recent research focuses on optimizing process planning and control, enabling robots to manage substantial machining forces while ensuring accuracy. Ongoing studies also address issues such as vibration and error compensation, particularly in high-stakes fields like aerospace manufacturing, where precision is critical. As the demand for customized production rises, robotics in machining is set to play a transformative role in the manufacturing landscape [7, 3, 8, 5, 9].

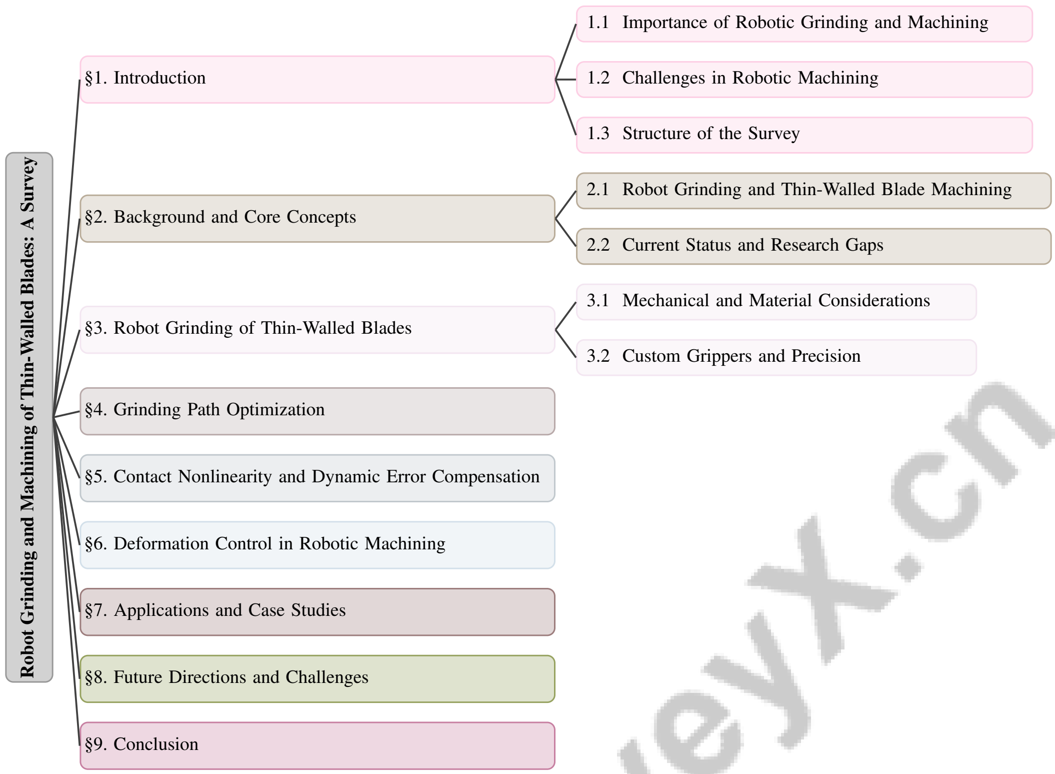

Figure 1: chapter structure

1.2 Challenges in Robotic Machining

Robotic machining faces several challenges that impede its effectiveness in industrial applications. A primary issue is the limited absolute positioning accuracy of industrial robots, typically achieving only millimeter-level precision, which is inadequate for high-precision tasks, particularly in aerospace manufacturing [8]. This limitation is compounded by the need for external measurement devices and complex calibration procedures to attain the necessary precision [4].

The rigidity of robotic arms also poses significant challenges to achieving high machining accuracy. Insufficient stiffness leads to vibration instabilities, or chatter, which severely affect milling operations [5]. The mechanical structure of industrial robots, characterized by rotational joints with lower stiffness, contributes to these instabilities, compromising machining precision [10]. Additionally, the low-frequency modes in robotic arms, which are less rigid than CNC machines, exacerbate mode coupling chatter, disrupting machining stability [11].

Beyond mechanical limitations, robotic machining grapples with sensory and computational complexities. Sensing deformation and managing the high degrees of freedom in soft bodies presents challenges, especially due to the complexities of non-linear deformation models [2]. The high non-linearity and sensitivity to local minima in existing methods further complicate deformation control, often resulting in suboptimal outcomes [12].

Cooperative control among multiple robotic systems introduces additional challenges, as tracking errors can complicate effective error management [13]. The manipulation of soft objects requires careful handling to avoid damage from excessive gripping forces, particularly with complex shapes sensitive to local strain [14].

Programming and operational challenges also persist, with issues such as mass programming for low material removal rate (MRR) operations and inadequate machining quality due to insufficient stiffness in high-MRR applications [9]. The limited robotics knowledge among potential users and the complexities of robot trajectory generation further hinder broader adoption of robotic machining technologies [3]. These multifaceted challenges underscore the need for ongoing research and

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innovation to enhance the capabilities and reliability of robotic machining systems in dynamic environments.

1.3 Structure of the Survey

This survey is structured to provide a thorough exploration of robotic grinding and machining of thin-walled blades, focusing on the intricate challenges and innovative solutions within this advanced manufacturing domain. It begins with an introduction that underscores the critical role of robotic machining in modern manufacturing, highlighting its potential to enhance efficiency and precision while addressing significant challenges to widespread adoption. The advantages of robotic machining centers, including cost-effectiveness and versatility, are discussed alongside the necessity for advanced modeling and process control to optimize performance across various applications such as deburring, milling, and polishing. The survey reviews three decades of research on robotic machining, identifying trends, operational categories based on material removal rates, and future innovation directions [5, 9].

Subsequent sections delve into mechanical and material considerations in robotic grinding of thin-walled blades, examining custom grippers and precision enhancement. Grinding path optimization is analyzed, focusing on methodologies and control strategies to improve machining efficiency and accuracy.

Contact nonlinearity and dynamic error compensation are addressed, highlighting techniques and recent innovations in error compensation methods. The survey further explores deformation control in robotic machining, discussing model-free and modal-based frameworks, as well as coupled offline and online learning approaches [14].

Real-world applications and case studies illustrate the practical implementation and effectiveness of these technologies in industrial settings [4]. The survey concludes with a discussion on future directions and challenges, emphasizing the need for continued research and innovation to overcome existing limitations and enhance the capabilities of robotic machining systems [6].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Robot Grinding and Thin-Walled Blade Machining

Robot grinding and machining of thin-walled blades represent sophisticated manufacturing techniques essential for industries prioritizing precision and efficiency. Central to these processes is the contour tracking capability of robotic systems, which must function reliably amidst dynamic uncertainties and potential actuator faults [1]. The precision required for machining intricate thin-walled structures underscores the importance of these capabilities.

The increasing adoption of industrial robots as machine tools is driven by their cost-effectiveness and large workspaces [10]. However, ensuring high rigidity and precision during milling operations necessitates a deep understanding of robotic arm dynamics [11]. Analyzing the dynamic behavior of six-axis industrial robots is critical for mitigating self-excited frequencies and vibrations that can compromise machining performance [4].

The framework for robotic grinding and machining encompasses key components such as gripper design, sensing, modeling, planning, and control [2]. These elements enable robotic systems to meet the complex demands of machining thin-walled blades, where deformation control and precision are crucial. Categorizing robotic machining into low and high material removal rate (MRR) operations aids in the analysis and optimization of machining strategies [9].

For deformation control, the manipulation of deformable objects like thin-walled blades involves advanced control theories, including the Euler-Bernoulli beam model for in-domain actuation management [15]. Optimal strategies, such as Cosserat-based methods, are essential for maintaining structural integrity during machining [12].

Integrating measurement and operation technologies in robotic machining forms a comprehensive framework to enhance precision and efficiency [7]. Addressing the multifaceted challenges in robot grinding and thin-walled blade machining is pivotal for advancing manufacturing capabilities.

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2.2 Current Status and Research Gaps

Research in robotic grinding and machining has made significant strides, yet challenges and gaps persist. A major issue is the slow adoption of robots for machining tasks, largely due to substantial process forces and complexities in modeling and control [5]. These factors hinder the integration of robotic systems into high-precision manufacturing processes.

Data acquisition limitations present another challenge, as high-quality data is crucial for training machine learning models that could improve robotic machining operations [6]. The scarcity of such data constrains the development of robust machine learning applications necessary for enhancing automation and precision.

In intelligent mechanical metamaterials, a significant challenge is computing gradients for back-propagation within unique physical architectures that differ from standard neural network methodologies [16]. This underscores the need for innovative computational techniques tailored to these materials' distinct characteristics.

Moreover, current measurement technologies often fail to provide accurate data in dynamic environments, negatively impacting machining precision, particularly with complex materials like composites [4]. The challenges of real-time control and accurate geometric modeling in manipulating deformable linear objects (DLOs) further complicate these issues [17].

Optimizing robotic machining systems, especially for high MRR operations, remains an area requiring further exploration [9]. The non-linear mapping from actuator space to operational space complicates performance evaluations, necessitating effective control strategies and coordination among joint axes to minimize contour error degradation [1].

Addressing these research gaps in robotic systems for complex manufacturing environments requires continuous innovation and interdisciplinary collaboration. This approach aims to enhance the precision, efficiency, and adaptability of robotic machining technologies, particularly in integrated measurement and operation contexts, where challenges such as error modeling and process control must be addressed. Enhanced collaboration across fields, including sensor technology and artificial intelligence, can lead to the development of robust robotic solutions tailored to meet the demands of customized and intricate manufacturing tasks [7, 5, 9, 3].

As advancements in robotic grinding technology continue to evolve, it is imperative to understand the underlying considerations that drive these innovations. In particular, the mechanical and material aspects play a crucial role in optimizing the grinding process for thin-walled blades. Figure 2 illustrates the hierarchical structure of these key considerations and advancements, highlighting the significant impact of custom grippers in enhancing both precision and adaptability in machining operations. This visual representation not only encapsulates the complexities involved but also serves to emphasize the interconnectedness of various factors that contribute to the efficacy of robotic grinding systems.

3 Robot Grinding of Thin-Walled Blades

3.1 Mechanical and Material Considerations

Achieving precision and stability in robotic grinding of thin-walled blades necessitates addressing mechanical and material considerations. Industrial robots often face challenges such as instability during milling tasks due to lower joint stiffness, leading to excessive vibrations and chatter [10]. This instability is particularly problematic for thin-walled structures, where the lack of rigidity can compromise accuracy [4]. Analyzing dynamic behavior, as seen in studies on the KUKA KR240-2, highlights variations in stiffness and vibration responses across configurations, underscoring the need for comprehensive understanding to optimize machining processes [11].

Custom grippers tailored for specific deformable objects are crucial in mitigating these challenges. These grippers must exhibit human-like dexterity to handle delicate thin-walled structures without deformation [2]. Advanced sensing technologies, such as accelerometers, play a vital role in measuring dynamic responses and enhancing coordination among robotic axes during machining tasks [1].

Evaluations in tasks like circular milling emphasize the need for improved stiffness and real-time monitoring to enhance machining quality and stability [3]. Existing methods often fail to establish

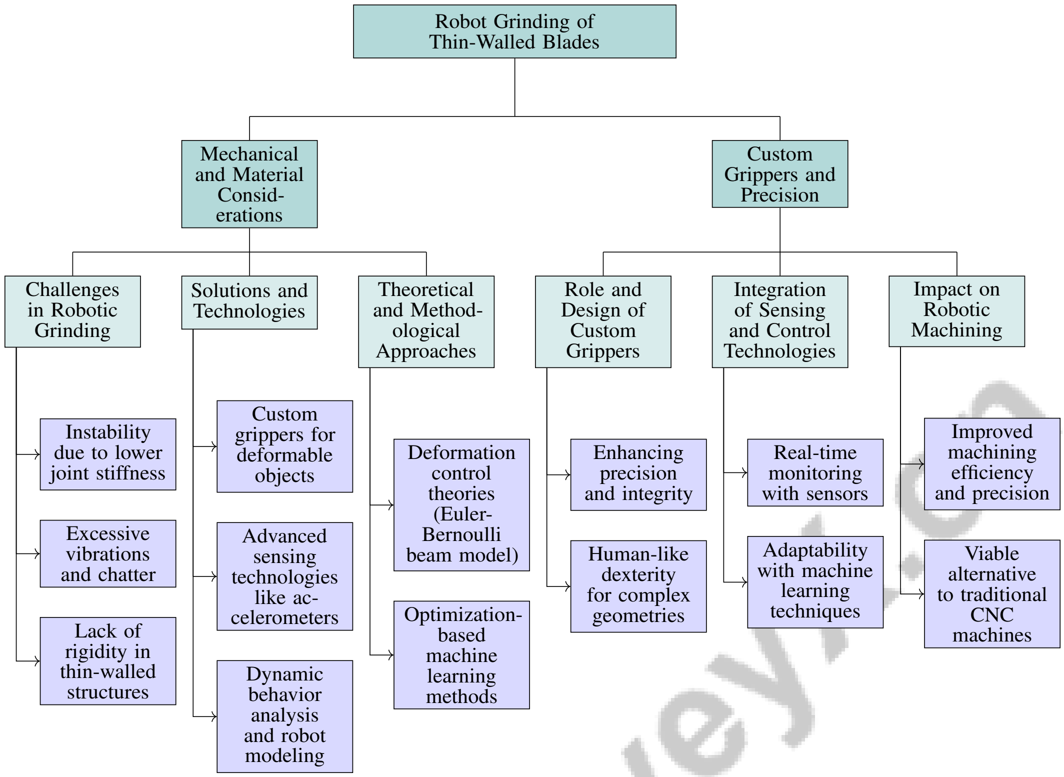


Figure 2: This figure illustrates the hierarchical structure of key considerations and advancements in robotic grinding of thin-walled blades, focusing on mechanical and material considerations, and the role of custom grippers in enhancing precision and adaptability in machining operations.

accurate working models due to factors like manufacturing errors and environmental conditions [8]. Therefore, integrating dynamic behavior analysis and robot modeling is essential for enhancing robotic machining capabilities [5].

Deformation control theories, such as the Euler-Bernoulli beam model, provide a framework for managing deformation in microbeams, analogous to thin-walled structures in robotic machining [15]. Optimization-based machine learning methods can improve state estimation where data gathering is costly, benefiting mechanical and material considerations of thin-walled structures [6]. Addressing these considerations enhances the precision and efficiency of robotic grinding operations on thin-walled blades, advancing manufacturing capabilities [9].

3.2 Custom Grippers and Precision

Custom grippers are instrumental in enhancing precision and integrity during robotic grinding of thin-walled blades. These grippers are designed to address challenges associated with machining deformable structures, where maintaining precision is crucial [2]. Their human-like dexterity is essential for manipulating complex geometries without deformation, preserving accuracy throughout the grinding operation.

Advanced sensing capabilities integrated within custom grippers enable real-time monitoring and adjustments during machining tasks. Sensors such as force-torque sensors and accelerometers provide feedback on dynamic responses, allowing robotic arms to adaptively modify their grip and path to minimize errors [1]. This integration enhances coordination among robotic axes, crucial for achieving high precision in contour tracking and mitigating dynamic uncertainties [5].

Machine learning techniques further improve precision by optimizing control and path planning strategies for custom grippers. Data-driven approaches enhance adaptability and responsiveness to changes in the machining environment, improving overall grinding accuracy [6]. These advancements contribute significantly to the efficiency and precision of robotic grinding operations, enabling effective machining of thin-walled blades in various industrial applications [9].

Integrating custom grippers with advanced sensing and control technologies represents a breakthrough in robotic machining, enhancing the precision and adaptability required in modern manufacturing environments. This advancement addresses challenges such as optimizing process planning and control, allowing robots to efficiently handle diverse tasks—including deburring, milling, and polishing—while managing substantial process forces. As industrial robots become more cost-effective and multifunctional, their adoption in machining operations rises, offering manufacturers a viable alternative to traditional CNC machines, often limited by higher costs and single-function capabilities [5, 9].

4 Grinding Path Optimization

Optimizing the grinding path in robotic machining is a complex challenge that necessitates a thorough understanding of path planning and control strategies. Table 1 presents a comparative analysis of path planning methodologies and control strategies, illustrating their roles in optimizing grinding paths within robotic machining. The precision and efficiency of robotic machining are directly influenced by these methodologies, addressing critical challenges such as error sources, process forces, and the integration of advanced technologies like sensors and artificial intelligence [3, 5, 7, 9]. This review explores path planning methodologies essential for robotic grinding operations, emphasizing their role in accommodating the dynamic behavior of robotic systems, followed by an examination of control strategies that refine path optimization to meet modern manufacturing demands.

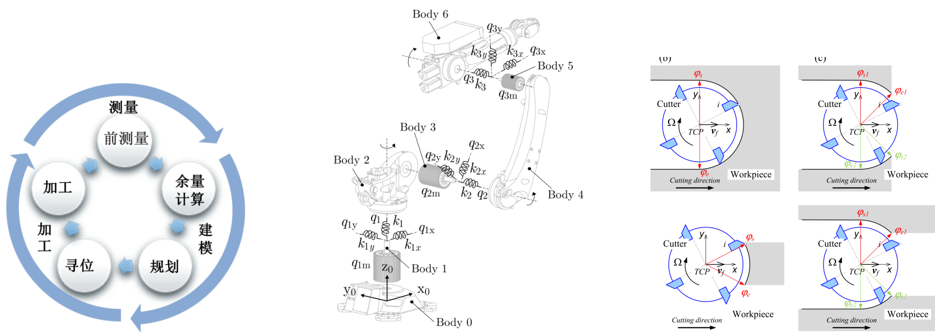
4.1 Path Planning Methodologies

Path planning methodologies are crucial for optimizing robotic grinding tasks, ensuring both efficiency and accuracy. These methodologies are categorized based on process requirements and the capabilities of the robotic systems employed [5]. Effective path planning involves predicting and accommodating the dynamic behavior of the robotic arm under varying conditions, achievable through multi-body dynamics models that incorporate joint compliance for accurate predictions during milling tasks [10].

The integration of sensors and accelerometers in path planning provides real-time data on the robot arm's dynamic response, aiding in characterizing stiffness under various conditions and enabling precise adjustments to the grinding path [11]. Leveraging these technologies allows robotic systems to dynamically adapt paths, minimizing errors and enhancing machining precision.

Advanced path planning methodologies increasingly incorporate machine learning techniques to optimize the robot's trajectory and control strategies. This integration enhances accuracy and adaptability in complex tasks such as deburring, milling, and polishing, allowing robots to effectively respond to varying process forces and environmental conditions. These methodologies improve operational efficiency and expand the potential applications of robots in precision machining processes [7, 5]. Data-driven approaches enable robotic systems to learn from previous operations, enhancing adaptability to new tasks and environments, ensuring path planning meets modern manufacturing's precision requirements.

As illustrated in Figure 3, optimizing grinding paths is crucial for enhancing efficiency and precision in modern manufacturing and robotics. The visual aids exemplify different approaches to path planning. The first image presents a circular flowchart symbolizing a continuous process cycle, with six interconnected circles labeled in Chinese characters, denoting distinct workflow steps. This visual underscores the systematic and iterative nature of path planning in industrial processes. The second image showcases a sophisticated robotic arm comprised of multiple bodies and joints, highlighting the complexity and flexibility required in path planning. This representation emphasizes the importance of joint coordination and movement precision for achieving optimal paths. Lastly, the third image depicts a CNC machine's operation, illustrating the workpiece's position relative to the cutter and emphasizing the need for precise control and planning to ensure desired outcomes. Together, these images provide a comprehensive overview of methodologies employed in path planning, stressing the importance of strategic optimization for enhancing operational efficiency and accuracy in manufacturing and robotics [7, 10, 3].



(a) The image depicts a circular flowchart with six interconnected circles, each representing a step in a process. The circles are labeled with Chinese characters and arrows indicating the flow of information or steps.[7]

(b) A robotic arm with multiple bodies and joints[10]

(c) Cutting Direction and Workpiece Position in a CNC Machine[3]

Figure 3: Examples of Path Planning Methodologies

4.2 Control Strategies for Path Optimization

Control strategies are vital for optimizing grinding paths in robotic machining, enhancing both precision and efficiency. These strategies often integrate advanced control algorithms that adapt to the dynamic behavior of robotic systems, especially when addressing the complex geometries of thin-walled blades [5]. A key focus is developing control systems capable of managing the non-linearities and uncertainties inherent in robotic machining environments [12].

Model predictive control (MPC) is an effective approach, allowing real-time adjustments to the grinding path based on predictive models of the robot's behavior [1]. MPC can incorporate constraints related to the robot's kinematics and dynamics, optimizing the grinding path while minimizing errors and ensuring adherence to desired contour specifications [10].

Integrating machine learning techniques into control strategies offers a promising avenue for enhancing path optimization. By utilizing data from past operations, machine learning algorithms can improve the robot's ability to predict and compensate for dynamic changes in the machining environment, refining the grinding path in real-time [6]. This adaptability is crucial for maintaining high precision amidst external disturbances and variations in material properties.

Decentralized control architectures can enhance coordination among multiple robotic systems, facilitating more efficient path optimization in collaborative machining scenarios [13]. This approach helps mitigate tracking errors and enhances overall stability during grinding processes, particularly when dealing with complex and deformable objects [14].

Investigating advanced control strategies for path optimization in robotic grinding is essential for enhancing the performance and versatility of robotic machining systems, particularly in addressing challenges of precision and adaptability in various tasks such as deburring, milling, and polishing. By leveraging the advantages of robotic systems—cost-effectiveness, flexibility, and capability to handle complex geometries—research in this area aims to overcome limitations related to robotic rigidity and machining accuracy, ultimately facilitating broader adoption of robots in high-precision industrial applications [7, 5, 9]. Addressing challenges associated with dynamic environments and complex geometries can significantly enhance the precision and efficiency of manufacturing processes involving thin-walled blades.

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Feature	Path Planning Methodologies	Control Strategies for Path Optimization
Optimization Technique	Multi-body Dynamics	Model Predictive Control
Technological Integration	Sensors And ML	Machine Learning
Adaptability	Dynamic Path Adjustments	Real-time Compensation

Table 1: Comparison of path planning methodologies and control strategies for path optimization in robotic machining, highlighting key features such as optimization techniques, technological integration, and adaptability. The table provides a concise overview of the mechanisms employed for enhancing precision and efficiency in robotic grinding operations.

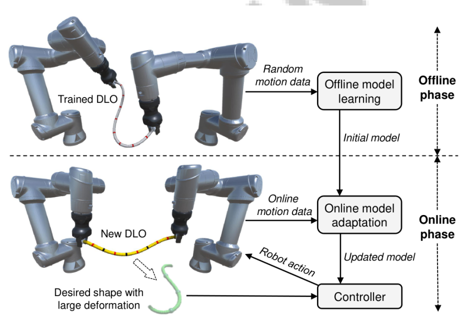
5 Contact Nonlinearity and Dynamic Error Compensation

5.1 Dynamic Error Compensation Techniques

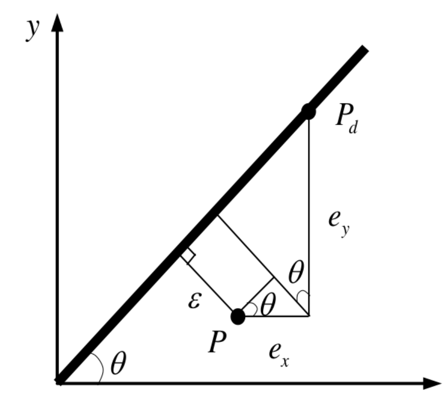
Dynamic error compensation is vital for enhancing the precision of robotic grinding, especially with complex geometries like thin-walled blades. Techniques such as Adaptive Non-singular Terminal Sliding Mode Control (ANTSMC) integrate contour error compensation with joint trajectory tracking to significantly improve machining precision [17, 1]. Multi-body dynamics models, exemplified by the KUKA KR90, incorporate flexible joints to predict dynamic variations during milling, assisting in process planning to reduce vibrations [10, 11]. The variability in robot arm stiffness necessitates adaptable compensation strategies.

External measurement systems are crucial for improving absolute positioning accuracy in dynamic environments, enabling effective online error compensation [8]. The Dynamic Behavior Analysis method identifies crucial frequencies affecting machining, allowing for precision-enhancing adjustments [4]. Flatness-based control stabilizes deformation, supporting accuracy maintenance during operations [15]. Despite the importance of addressing dynamic behavior and compliance-induced errors, many studies overlook these complexities [5]. The OMLE method demonstrates how prior knowledge and regularization can improve model performance and error compensation [6].

These techniques are essential for advancing robotic machining precision, addressing dynamic environment challenges, and enhancing grinding operation precision through optimized process planning and control mechanisms [7, 5].



(a) Robotic Manipulator with DLO and Model Adaptation[17]



(b) A diagram illustrating the relationship between a point P and its coordinates in a Cartesian coordinate system[1]

Figure 4: Examples of Dynamic Error Compensation Techniques

As depicted in Figure 4, the integration of contact nonlinearity and dynamic error compensation is crucial in robotics and control systems. The first image showcases a robotic manipulator with a deformable link object (DLO) and model adaptation, highlighting its operational adaptability. The second diagram illustrates the geometric relationship in a Cartesian coordinate system, essential for correcting positional errors through vector analysis. These examples emphasize the importance of dynamic error compensation in improving robotic accuracy and responsiveness, particularly in addressing contact nonlinearity challenges [17, 1].

5.2 Innovations in Error Compensation Methods

Recent advancements in error compensation for robotic machining focus on integrating sophisticated control systems to enhance precision and adaptability. One notable innovation is combining an external closed-loop control system with a PID algorithm, allowing real-time compensation for positional errors and significantly improving accuracy [8]. This system enables continuous adjustments based on feedback from external sensors, mitigating dynamic disturbances and enhancing machining stability.

Machine learning techniques show promise in improving adaptability and precision by addressing various error sources, including measurement inaccuracies and motion errors, thus enhancing machining quality and efficiency [6, 7, 3]. By using historical data and predictive analytics, machine learning dynamically optimizes control parameters, ensuring responsiveness to environmental changes and reducing reliance on manual calibration.

Advancements in sensor technologies and control systems have greatly improved error compensation by enabling real-time monitoring and adjustment of positioning inaccuracies, particularly in tasks like aircraft assembly gasket polishing [7, 8, 3]. High-resolution sensors detect minute deviations, providing essential data for real-time correction. When integrated with robust algorithms, these sensors maintain high accuracy even with complex geometries and material inconsistencies.

The development of integrated measurement-operation technology and online error correction systems marks significant progress in enhancing robotic machining precision. These innovations address measurement errors, coordinate transformation inaccuracies, and motion errors, improving absolute positioning accuracy and machining quality in applications like aerospace manufacturing [7, 8, 5, 9]. By overcoming challenges related to dynamic errors and contact nonlinearity, these advancements facilitate more efficient and accurate manufacturing processes, particularly in machining thin-walled blades.

6 Deformation Control in Robotic Machining

6.1 Model-free and Modal-based Deformation Frameworks

Deformation control frameworks are essential in robotic machining to ensure precision, especially when handling complex and deformable objects. These frameworks employ local and global modeling techniques to interpret the relationship between sensor data and robot motion, allowing for adaptive responses to environmental changes without extensive pre-established models [2]. Model-free controllers leverage physical interpretations of modal features for linear parameterization, enabling real-time adaptability and maintaining precision despite the lack of comprehensive model data [18]. Modal-based frameworks complement this by using tactile feedback and controlled contact forces to manipulate deformable objects, minimizing unintended deformations through reduced gripping [14]. These frameworks aim to minimize distance errors to desired shapes and internal elastic energy, preserving object integrity throughout machining [12].

The continuum deformation cooperative control (CDCC) strategy innovatively manages deformation by allowing robotic units to maintain formation while adapting to deviations from tracking errors [13]. Adaptive control mechanisms within CDCC enhance precision and stability in complex deformation scenarios. Together, model-free and modal-based frameworks advance robotic machining by reducing reliance on intricate models, thus enhancing flexibility and adaptability. This is crucial for addressing dynamic environments and complex geometries, improving precision and efficiency in tasks like milling, deburring, and polishing [7, 5, 10, 9]. Industrial robots, despite their larger operational workspaces and lower costs compared to traditional machine tools, face challenges in rigidity and stability that can compromise accuracy. Optimizing process planning and control is vital to mitigate vibration and chatter, facilitating more effective robotic machining applications.

6.2 Coupled Offline and Online Learning for Deformation Control

Integrating coupled offline and online learning methods enhances deformation control in robotic machining, particularly for thin-walled blades with complex geometries. The Coupled Offline and

Online Learning Method (COOL) employs neural networks for real-time adaptation, crucial for managing dynamic machining environments [17]. This method develops a foundational model through offline learning, refined via online learning to accommodate real-time changes and disturbances. The neural network framework allows continuous updates and optimization of control strategies based on sensor data, maintaining high precision in deformation control. This dynamic adjustment of control parameters enhances contour accuracy and responsiveness to material variations and external forces during machining. Advanced control strategies, such as closed-loop systems with real-time visual feedback, enable immediate error correction and robust performance [1, 18, 5, 12]. Techniques like adaptive non-singular terminal sliding mode control further refine contour tracking by compensating for dynamic uncertainties and actuator faults.

Insights from the CDCC strategy can improve learning-based deformation control methods. Future research should enhance CDCC robustness by integrating error bounds into leader trajectory designs and exploring complex formations [13]. Such advancements could lead to greater stability and precision, enhancing robotic machining effectiveness. Investigating integrated offline and online learning for deformation control marks a significant advancement in robotic machining, addressing the complexities of modeling and controlling material deformation during processes. Data-driven methods enhance robotic systems' adaptability and precision, enabling them to manage significant process forces and achieve high-quality outcomes in tasks like milling, polishing, and deburring [7, 8, 5, 17, 9]. Harnessing neural networks and adaptive learning provides the flexibility and precision needed to tackle challenges posed by dynamic environments and complex geometries, advancing robotic systems' capabilities in modern manufacturing.

7 Applications and Case Studies

7.1 Real-World Applications and Dataset Utilization

Benchmark	Size	Domain	Task Format	Metric
CNC-RBM[3]	5,000	Machining	Circular Milling	Circularity

Table 2: The table presents a representative benchmark dataset utilized in robotic machining processes, highlighting key characteristics such as size, domain, task format, and metric. Specifically, it details the CNC-RBM benchmark, which is employed in machining applications with a focus on circular milling tasks and circularity metrics. This dataset is essential for evaluating the efficiency and precision of robotic systems in real-world manufacturing scenarios.

Robotic machining is increasingly prevalent in industries requiring high precision and efficiency, notably in aerospace, automotive, and medical device manufacturing. In aerospace, robotic systems are integral for machining turbine blades, prioritizing accuracy and surface quality, thus overcoming traditional manufacturing limitations and reducing production times [1]. The automotive industry benefits from robotic machining for producing lightweight components with precise contouring, enhancing efficiency in handling diverse materials and complex geometries [2]. In medical device manufacturing, robotic systems ensure precision and repeatability, complying with strict regulatory standards.

Utilizing comprehensive datasets is crucial for optimizing robotic machining processes. These datasets capture the dynamic behavior of robotic systems under varying conditions, essential for training machine learning models to enhance adaptability and precision [6]. High-quality data supports advanced control strategies like model predictive control and machine learning-based optimization, crucial for achieving optimal machining outcomes. Table 2 provides an overview of a key benchmark dataset used in robotic machining, illustrating its relevance and application in enhancing precision and adaptability in industrial processes.

Simulation environments that generate synthetic datasets further boost the flexibility of robotic machining development. They allow modeling complex scenarios and testing control strategies without extensive physical trials, accelerating innovation and reducing costs [5]. Integrating real-world data with simulation-generated datasets strengthens the robustness of robotic systems, ensuring their effectiveness across diverse industrial applications.

Robotic machining's implementation in manufacturing highlights its transformative impact, characterized by increased cost efficiency, flexibility, and multifunctionality. Over the past decades, industrial robots have become prominent for tasks like milling, polishing, and deburring, offering significant advantages over traditional CNC machines, including lower operational costs and broader reach. Despite challenges like reduced rigidity and sensitivity to vibrations, ongoing research and technological advancements continue to enhance robotic capabilities, paving the way for more customized and efficient manufacturing solutions [3, 5, 7, 9]. By leveraging comprehensive datasets and advanced control strategies, industries can achieve notable improvements in precision, efficiency, and adaptability, fostering further advancements in robotic machining.

7.2 Experimental Manipulation and Deformation Studies

Experimental manipulation and deformation studies in robotic machining provide critical insights into effective deformation control strategies, especially for thin-walled blades. These studies evaluate the efficacy of control algorithms and sensor integration techniques in real-world environments, focusing on manipulating deformable objects where precise deformation prediction and control are vital [14].

Tactile feedback systems are a key approach, enabling precise control of contact forces during machining. By integrating tactile sensors, researchers can monitor deformation in real-time, adjusting parameters to minimize errors and maintain structural integrity [12]. This real-time feedback is crucial for managing the non-linearities and uncertainties of machining processes, allowing systems to adapt to dynamic changes.

Continuum deformation cooperative control (CDCC) strategies have been explored to enable coordinated deformation control through adaptive mechanisms [13]. These strategies are beneficial for collaborative machining tasks, facilitating synchronized movements and reducing tracking errors.

Incorporating machine learning in experimental studies enhances robotic adaptability. By analyzing extensive datasets from trials, machine learning algorithms optimize control strategies and improve deformation control precision, leading to more efficient machining operations [6].

Experimental manipulation and deformation studies are pivotal in advancing robotic machining. By exploring advanced control strategies and integrating innovative sensor technologies, these studies significantly contribute to developing versatile and resilient robotic systems. These systems tackle contemporary manufacturing challenges, ensuring improved performance in tasks like polishing, milling, and assembling complex components [7, 5, 9, 2].

8 Future Directions and Challenges

8.1 Future Directions in Deformation Control

Advancements in deformation control for robotic machining are poised to benefit from adaptive control strategies and enhanced robotic stiffness, which are essential for optimizing machining performance [5]. Future research should prioritize the development of adaptive methods that dynamically adjust to changing conditions, aligning with the OMLE framework to refine regularization techniques for improved adaptability and precision [6].

Innovative approaches include the integration of marker-free perception methods, such as tactile and visual feedback, alongside advanced planners to enhance deformation control versatility in complex tasks involving deformable objects. This involves using model-free frameworks and adaptive controllers that incorporate modal analysis and real-time feedback for effective deformation management, thus improving stability and performance across diverse applications [18, 17, 14, 12]. Eliminating external markers enhances robotic flexibility in dynamic environments. Furthermore, refining adaptive tuning methods, like the Adaptive Non-singular Terminal Sliding Mode Control (ANTSMC), can improve performance in non-smooth path tracking scenarios.

Expanding the characterization of rigidity in robotic arms across various platforms and examining additional factors impacting dynamic stability during machining are crucial for optimizing performance. This includes enhancing techniques for joint parameter identification and employing sophisticated control strategies to stabilize operations, addressing challenges like vibration instabilities and ensuring optimal performance under varying process forces. These advancements aim to leverage the cost-efficiency and flexibility of robotic machining while overcoming stiffness limitations compared to traditional machine tools [10, 7, 6, 5, 9].

A comprehensive approach to manipulating soft robots and deformable objects is vital, as progress in this area could significantly enhance robotic autonomy and broaden applications in industrial, service, and healthcare sectors. The complexities of deformable object manipulation (DOM) require breakthroughs in hardware design, sensing, modeling, planning, and control for effective interaction with significantly deformable objects [7, 14, 2]. Enhancing adaptive control algorithms and integrating additional sensory modalities will improve manipulation robustness and versatility.

Research should also focus on optimizing cutting parameters and exploring the relationship between cutting forces and dynamic behavior. Developing accurate predictive models can lead to more efficient machining processes. Incorporating additional actuators into deformation control systems can enhance resolution and accuracy, crucial for manipulating deformable objects. This aligns with ongoing research to improve robotic capabilities in applications requiring precise manipulation of soft materials. Leveraging advancements in hardware design, sensing technologies, and control strategies will further optimize these systems to address challenges posed by non-rigid objects, leading to more effective and autonomous robotic operations [7, 14, 13, 2].

To achieve significant advancements in accuracy, optimizing measurement systems and integrating sophisticated algorithms is essential, particularly in robotic machining applications where errors such as measurement inaccuracies and robotic motion errors can negatively impact machining quality [7, 3]. Integrating vision and force feedback, alongside spline-based representations for load estimation, will enhance precision and robustness in robotic machining operations. These advancements are expected to push the boundaries of deformation control, leading to more sophisticated and capable robotic systems in manufacturing.

8.2 Enhancements in Measurement and Stability

Enhancements in measurement techniques and stability improvements are critical for increasing the precision and reliability of robotic machining, especially for complex geometries like thin-walled blades. Current research focuses on refining measurement systems to provide precise, real-time data essential for optimizing control strategies and improving machining performance. This includes the development of integrated measurement-operation-machining technologies that address various error sources, such as measurement errors and robotic motion discrepancies, thereby enhancing machining quality. These advanced systems have shown promise in tasks like polishing aircraft assembly gaskets, significantly improving the efficiency and accuracy of robotic machining processes [7]. The integration of high-resolution sensors capable of detecting minute deviations in position and orientation is crucial for real-time error correction, enabling robotic systems to maintain high accuracy even in dynamic environments.

A significant challenge in achieving stability in robotic machining is the potential for compounded errors due to communication delays and disturbances, which can hinder robotic units' ability to maintain desired positions [13]. Addressing these issues requires robust communication protocols and control algorithms that can mitigate disturbances, ensuring adaptive responses to changes in the machining environment.

Future research will also enhance benchmarks for evaluating robotic performance, particularly regarding dynamic variations in cutting forces [3]. Exploring the performance of parallel robots in machining tasks may yield improved stability and precision compared to traditional robotic systems. By incorporating these advancements, robotic machining processes can achieve greater consistency and accuracy, ultimately leading to more efficient and reliable manufacturing operations.

The investigation of advancements in measurement techniques and stability enhancement in robotic machining is a vital research domain, addressing error sources that significantly impact machining quality. By developing integrated measurement-operation-machining technologies, researchers aim to optimize process control and improve the precision of robotic machining tasks, such as polishing and milling, leveraging the inherent flexibility and cost-effectiveness of industrial robots in various manufacturing applications [7, 5, 9, 3]. Addressing challenges associated with dynamic environments and complex geometries will significantly enhance the capabilities of robotic systems in modern manufacturing settings.

9 Conclusion

Robotic grinding and machining have emerged as transformative forces in advanced manufacturing sectors, notably aerospace and automotive, where the precision machining of thin-walled blades is crucial. The integration of robotic systems in these domains has markedly improved precision, efficiency, and flexibility, effectively addressing the limitations inherent in traditional manufacturing methods. Developments in error compensation, including advanced control strategies that minimize positioning and angular errors, underscore the potential of robotic systems to enhance machining accuracy. The flatness-based control method, among others, is pivotal for maintaining structural integrity during the machining of complex geometries, emphasizing the importance of continued research into dynamic stability and advanced control systems to mitigate challenges posed by robot compliance and dynamic environments.

The survey highlights key findings, such as the identification of error sources and the successful implementation of integrated robotic machining for customized parts, which are crucial for advancing manufacturing capabilities. Comparative analyses of various robotic machining studies reveal significant differences in effectiveness between low and high material removal rate operations, highlighting the need for tailored strategies to optimize machining processes. Proposed methods for controlling deformable linear objects demonstrate enhanced accuracy and adaptability, signifying the ongoing need for research to address limitations in dynamic scenarios. These insights collectively affirm the critical role of robotic grinding and machining in modern manufacturing and underscore the necessity for continued innovation to improve the performance and reliability of robotic systems in complex manufacturing environments.

References

[1] Zhu Dachang, Du Baolin, Cui Aodong, and Zhu Puchen. Adaptive non-singular terminal sliding mode fault-tolerant control of robotic manipulators based on contour error compensation. *arXiv preprint arXiv:2110.08705*, 2021.

[2] Jihong Zhu, Andrea Cherubini, Claire Dune, David Navarro-Alarcon, Farshid Alambeigi, Dmitry Berenson, Fanny Ficuciello, Kensuke Harada, Jens Kober, Xiang Li, et al. Challenges and outlook in robotic manipulation of deformable objects. *IEEE Robotics & Automation Magazine*, 29(3):67–77, 2022.

[3] Alexandr Klimchik, Alexandre Ambiehl, Sébastien Garnier, Benoit Furet, and Anatol Pashkevich. Efficiency evaluation of robots in machining applications using industrial performance measure. *Robotics and Computer-Integrated Manufacturing*, 48:12–29, 2017.

[4] Claudiu-Florinel Bisu, Medhi Cherif, Alain Gérard, and Jean-Yves K'Nevez. Dynamic behavior analysis for a six axis industrial machining robot, 2012.

[5] Alexander Verl, Anna Valente, Shreyes Melkote, Christian Brecher, Erdem Ozturk, and Lutfi Taner Tunc. Robots in machining. *CIRP Annals*, 68(2):799–822, 2019.

[6] Fredrik Bagge Carlson. Machine learning and system identification for estimation in physical systems, 2019.

[7] , , , and . Research on robotic measurement-operation-machining technology and its application. *China Mechanical Engineering*, 31(1):49–56, 2020.

[8] Hui Zhang, Xin Pan, Haiwei Li, Jie Du, Qingxun Meng, and Gang Zhang. Dynamic continuous online compensation method for processing robot path based on external measurement. In *Advances in Machinery, Materials Science and Engineering Application*, pages 285–297. IOS Press, 2022.

[9] Wei Ji and Lihui Wang. Industrial robotic machining: a review. *The International Journal of Advanced Manufacturing Technology*, 103:1239–1255, 2019.

[10] Hoai Nam Huynh, Hamed Assadi, Edouard Rivière-Lorphèvre, Olivier Verlinden, and Keivan Ahmadi. Modelling the dynamics of industrial robots for milling operations. *Robotics and Computer-Integrated Manufacturing*, 61:101852, 2020.

[11] Jean-Yves K'Nevez, Mehdi Cherif, Miron Zapciu, and Alain Gérard. Experimental characterization of robot arm rigidity in order to be used in machining operation, 2012.

[12] Azad Artinian, Faiz Ben Amar, and Veronique Perdereau. Optimal cosserat-based deformation control for robotic manipulation of linear objects, 2024.

[13] Matthew Romano, Prince Kuevor, Derek Lukacs, Owen Marshall, Mia Stevens, Hossein Rastgoftar, James Cutler, and Ella Atkins. Experimental evaluation of continuum deformation with a five quadrotor team, 2019.

[14] Yuhao Guo, Xin Jiang, and Yunhui Liu. Deformation control of a deformable object based on visual and tactile feedback, 2021.

[15] Amir Badkoubeh, Jun Zheng, and Guchuan Zhu. Flatness-based deformation control of an euler-bernoulli beam with in-domain actuation, 2015.

[16] Jiaji Chen, Xuanbo Miao, Hongbin Ma, Jonathan B. Hopkins, and Guoliang Huang. Intelligent mechanical metamaterials towards learning static and dynamic behaviors, 2024.

[17] Mingrui Yu, Kangchen Lv, Hanzhong Zhong, Shiji Song, and Xiang Li. Global model learning for large deformation control of elastic deformable linear objects: An efficient and adaptive approach, 2022.

[18] Bohan Yang, Bo Lu, Wei Chen, Fangxun Zhong, and Yun-Hui Liu. Model-free 3d shape control of deformable objects using novel features based on modal analysis, 2023.

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