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An Elaborative Review on Path Optimization using Force/Torque Sensor in Robotic Deburring Application on KUKA KR-6 Robot

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Abstract— Precision parts are now widely employed in many different industries, including machining, painting, advanced manufacturing, and the medical sector. High-precision machining is necessary to create fine surface roughness. Robot-assisted deburring procedures offer superior output and flexible working ranges over traditional deburring methods. As a result, it has been used increasingly frequently in difficult machining operations. To offer an overview of the evolution of the robot-control deburring technology, however, few review publications on the subject could be located. This study examines current developments in robot-assisted deburring. The summary of the research state of steady force and torque control for robot-control deburring comes after an overview of how robots are integrated with various machining processes. The output of standard robot-assisted deburring systems is then examined, along with the appropriate compensatory techniques. Finally, future directions for robot-assisted deburring development are highlighted. For scientists or engineers who have an interest in robot-assisted machining or deburring, this review is meant to serve as a road map.

Index Terms— KUKA KR-6, Force/Torque, Sensor, Robotic Deburring, Industrial Robot

I. INTRODUCTION

Robotic deburring has gained significant attention in manufacturing industries as a means to improve productivity, consistency, and worker safety. Deburring involves the removal of unwanted burrs or sharp edges from work pieces, typically after machining or casting processes. To achieve accurate and efficient deburring, precise control of the robot's tool path is crucial. Traditional approaches to path planning in robotic deburring rely on predefined trajectories, which may not be adaptable to work pieces with varying shapes or complex geometries. Additionally, these approaches often pass up the interaction forces between the components, leading to suboptimal deburring results.

To address these challenges, the integration of force/torque sensors and path optimization techniques has emerged as a promising solution for robotic deburring applications. Force/torque sensors provide real-time feedback on the Interaction forces experienced by the robot during deburring. By incorporating this information into the robot's control system, it can change tool path based on the detected forces, resulting in improved deburring performance.

Path optimization algorithms play a key role to enhancing the efficiency & effectiveness of robotic deburring. These algorithms aim to generate optimal tool paths that minimize deburring time while ensuring desired surface finish quality. By considering factors such as force distribution, material removal rates, and geometric constraints, path optimization techniques can significantly improve the overall deburring process.

One prominent approach to path optimization in robotic deburring is the utilization of the A*-Algorithm, which is widely employed in path planning problems. By representing the work piece surface as a graph, where each node represents a deburring point, the A*-Algorithm searches for the shortest path that connects all the points efficiently. The optimization process accounts for factors such as force distribution, minimizing redundant movements, and avoiding obstacles, resulting in time-optimal tool paths for deburring.

The integration of force/torque sensors and path optimization techniques offers several advantages in robotic deburring applications. Firstly, the real-time force feedback enables adaptive control, allowing the robot to adjust its movements to account for variations in work piece geometry and material properties. This adaptability improves the quality and consistency of the deburring process. Secondly, path optimization algorithms consider both force/torque requirements and geometric constraints, leading to optimized tool paths that minimize deburring time and enhance productivity.

In this review paper, we present a detailed exploration of path optimization techniques application of force/torque sensors in robotic deburring. We explore the use of route optimisation algorithms, such as to create time-optimal tool pathways as well as the integration of force/torque input into the control system. To evaluate the effectiveness and efficiency of the suggested approach, experimental assessments and case studies will be carried out. The output obtained from these experiments will demonstrate the potential benefits of incorporating force/torque sensing and path optimization in robotic deburring, paving the way for improved deburring processes in manufacturing industries.

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II. LITERATURE REVIEW:

MacMillan et al. [1] proposed the PIST planning method for pattern following in machining applications, which integrates force control and computer vision. In order to apply force control, the algorithm constructs offset manufacturing paths based on a straight part and a specified force direction. In order to establish a contour-following trajectory in image space and execute it in the robot's workspace, the PIST algorithm first uses a picture of the part, improves for perspective distortion, and defines the route in image space. A real-life instance including the deburring of metal parts serves as an illustration of the PIST algorithm's efficiency. The PIST method and conventional CAD/CAM software that employs CAD information and a laser reader for localisation are compared. The PIST planner outperformed the CAD/CAM precision from 1.2 mm, achieving a positional precision of nearly 1.7 mm. In order to achieve equivalent surface finishes for both planning trajectory methods, an admittance controller successfully corrected for the positional mistake. In comparison to conventional CAD/CAM methods, the PIST planner has a number of benefits, such as faster setup and processing times, flexibility to accommodate design changes and manufacturing flaws, and increased accuracy.

Shukla et al. [2] presented a study that attempted to identify the best welding procedures for employing WAAM technology to create narrow walls with smooth surfaces. When selecting process parameters in accordance with AWS standards, the research takes the microstructure and mechanical properties of final samples into account. The purpose of the study is to better understand temperature variation during weld bead deposition using a welding robot, a cold metal transfer power source, and WAAM technology. For the purpose of analysing how changed process parameters affected sample variations, mechanical tests such as bend tests and Vickers micro hardness tests were carried out. According to the findings, altering process variables little affects sample variance. The study comes to the conclusion that WAAM technology can be a more affordable option for additively manufacturing metal parts than laser or electron beam technologies.

Lloyd et al. [3] focused on modelling, calibration, and testing of the PSDM technique using a Denso VS-6556G manipulator for robotic deburring. Using a mathematical dynamic modelling technique called PSDM, the dynamic model may be evaluated in real-time and is provided in a regressive form for simple calibration. The paper gives a general description of the PSDM approach and shows how the design for the Denso manipulation was derived. The calculation of the calibration of the joint actuators model and the LuGre friction model for each joint is done experimentally. While overall rapid connectivity accelerating fitting captures 81-99% of the measured torque effects, the calibration findings are quite precise, catching 98-100% of motor, a gravitational and friction effects. The PSDM model's large performance advantage over the reverse Newton-Euler method may be seen through benchmarking. Overall, the PSDM technique demonstrates that dynamical analysis in robotic deburring systems can be done effectively and efficiently.

Bilal et al. [4] focuses on making sure that physical collaboration between people and robots is safe and reliable in order to avoid major harm. The researchers suggest a reasonably priced torque sensor system that can identify and quantify impacts among a robot and humans in order to do this. In order to promote stress dispersion and move high-stress spots, the design includes a perforated spoke structure. The sensor's sensitivity and reactivity to dynamic loads are improved by this improvement. By utilising finite element analysis, the researchers choose the design's ideal characteristics. They then run a number of simulations to check the design's functionality. The findings show that the suggested torque sensor design performs better than a sensor with a non-perforated spoke, offering greater performance in terms of safety and accuracy during human-robot collaboration.

Schmidt et al. [5] proposed a novel structure for smart grinding robotic units that can complete deburring operations with excellent quality and speed. A model-based supervision that uses a digital twin to determine the best order of processes and parameters to achieve the required quality is included in the system along with visual and metrological detectors to detect debris and work piece quality. A working model of a system has been created, and it creates verified codes for both the PLC and robots to carry out each operation.

Hu et al. [6] presented a robotic system for chamfering and deburring, two crucial production operations that are generally carried out physically by humans, especially for products with complex geometries. A manipulator, a force/torque instrument, pneumatic instruments with a tool changer, and pneumatically operated components make up the designed system. Two HMI's have been created to simplify the process. With the use of the first HMI, referred to as CAD-HMI, human operators may pick out desired characteristics on the computer-aided design (CAD) file and output them as tool trajectories for path development. Once the user installs the gear into the work cell, the second HMI, known as the primary HMI, acts to register the gear and calculate collision-free paths for the required operation. Control and operation capabilities for robots and tools are likewise included into the primary HMI. The authors provide evidence of the system's efficiency in managing intricate industrial items. Overall, the technology lessens the need for manual labour by improving the automated execution of deburring and cutting procedures in high-mix/low-volume production applications.

Onstein et al. [7] highlighted the difficulties in deburring cast components and demonstrates the limitations of manual deburring procedures, which put employees in danger. Although there are dedicated CNC machines for deburring, their significant investment costs make them unsuitable for operations with a high mix of low volume. Robotic instruments have been investigated as a less costly deburring option, although there have been few practical uses for them. The longer setup time, which raises the price of robotic deburring, is one explanation for this. With a particular emphasis on solutions for cast components, the study focuses on the present state and application of robotic manipulators in deburring applications. Examining the deburring process and its elements, special focus is placed on the development of more adaptable and automated deburring systems using sensors like lasers, vision technologies, and force control. The provided ideas are assessed in light of the difficulties that robotic deburring now faces and the necessary advancements to make it workable for high-mix, low-volume operations. In order to allow wider implementation of robotic deburring in industrial settings, the paper offers facts about the current state of the technology and emphasises areas that still need to be developed.

Nguyen and Melkote [8] discussed how the kinematics of a robot arm, where a forces/torque sensor is installed on its flange, can lead to skewed force sensor results. The development of an inverse filter to correct for this distortion depends on the sensor's Frequency Response Function (FRF). However, correct modelling is required since the sensor's FRF varies depending on where a robot's end effector is positioned. The research suggests a Gaussian Process Regression model-based method to estimate the FRF of a force sensor installed on an industrial robot with six degrees of freedom in order to solve this. At various robot locations, impact hammer tests are used to characterise the force sensor FRF. From the impact hammer data, GPR models are created to forecast the size of certain frequency bins. Cross-evaluation measures are used to assess the GPR modelling strategy's efficacy. This method provides distortion compensation and boosts the accuracy and reliability of measurement of force in industry robot applications by properly forecasting the FRF of a force sensor at varied robot locations.

Pérez et al. [9] examines the rise in popularity of robotic machining applications including milling and drilling due to their benefits over CNC machines in terms of flexibility, programming ability, and cost-effectiveness. The authors give a summary of recent developments in robotic manufacturing and lay forth a theoretical foundation for the method, stressing its advantages and disadvantages. The poor toughness of robots, which has an adverse effect on machining precision and can cause vibration, is one of the major problems addressed in the research. In order to address these problems, researchers want to make robots stiffer. The most recent advances in robotic machining may be categorised into many study fields, such as method modelling and control, robot workspace optimisation, redundancies evaluation, vibrations and chattering analysis, and novel designs and approaches for machining enhancement. In order to make robots a competitive alternative to CNC machines, research is being done to increase the process' accuracy and efficiency. Using force/torque control, which enables the system to collect feedback and make use of an enhanced stiffness matrix to fix faults and increase machining accuracy, the authors are presently working on characterising various robot-assisted milling procedures.

Caesarendra et al. [10] centred on using sensors data evaluation as a tool to measure and link the grinding stage with the quality of the surface finish during the production of aeronautical components. After boring out whole operations, deburring is a crucial finishing step to eliminate burrs from work coupons. In order to extract features from sensor data, the study uses signal processing techniques, notably wavelet reduction and Welch's spectrum estimation. Then, these traits are sent into a system for adaptive neuro-fuzzy inference (ANFIS) for analysis. The ANFIS classifies the deburring operation stage and forecasts the top surface condition terms of head hole chamfer length. The experimental findings show a tendency towards decreasing vibrations indication, which is qualitatively connected to the deburring phase and the growth of chamfer length through the deburring process. The study demonstrates how sensor analysis of information and ANFIS can measure and forecast the quality of the surface finish produced during the deburring process, offering important insights for streamlining manufacturing procedures in the aerospace sector.

Abele et al. [11] This research suggests a method for creating time-reducing tool path for a robotic deburring operation of interior contours using the A*-Algorithm. The goal is to reduce the total deburring time by optimising both the deburring procedure itself by using acceptable deburring tools with proper settings and the robot's path between the various sites. To automatically create a graph according to the work piece information in the STL file, the authors use the simulation software Open RAVE with a Matlab interface. On this graph, the travelling salesman problem is solved to find the robot's trajectory's shortest path. The strategy takes into account both the tool choice and the robot's route planning in order to optimise the deburring operation.

Kuss et al. [12] have put out a workable method to identify form irregularities in work components for robotic deburring operations to automatically adjust to. The method derives potential variants of a work piece geometric model from the manufactured part's dimensional tolerance parameters and employs a matching technique among point clouds to assess shape similarity. Then, for further trajectory preparation and work piece localisation, the geometry model with the highest similarity is employed. The suggested approach's efficacy and viability in industrial applications, which results in improved deburring quality, are demonstrated through experimental validation.

Leo Princely and Selvaraj [13] have defined a novel Vision-Guided Robotic System (VGRS) approach that intends to overcome the limitations of conventional "Teach" or offline programming techniques while deburring work pieces in large-scale manufacturing settings. The VGRS approach collects the shape of every two-dimensional work item and uses that information along with information on the finishing state to automatically construct a robotic language programme. The suggested approach has been experimentally confirmed, and it is demonstrated to offer a small, reasonably priced completing robot system that cuts down on programming time.

Winkler and Suchý [14] while industrial robots primarily using position control, addressed the significance of force/torque sensor for production activities. The authors provide examples of difficult setup and breakdown tasks completed by manipulators using widely available commercial robot controllers. They draw attention to the constraints introduced on force/torque control by the limitations of control structures and parameters. 6Two particular tests have been provided to show force-controlled robot assembly. The first test involves using a hybrid position/force control on a single robot to mount a nut on a threaded bolt. In the second experiment, two collaborating robots use force/torque control to assemble a screw fitting. The tasks are broken down into smaller tasks in both situations, and the proper controllers design and parameters are chosen. The cases have been effectively verified through real-world tests, and outcomes are provided. The paper emphasises the necessity to modify controller topologies and settings for various circumstances by demonstrating the actual use of force/torque control for assembly jobs using conventional commercial robot controllers.

Domroes et al. [15] have concentrated on the creation and evaluate of force-controlled machining procedures using a readily accessible setup. Deburring and grinding are the two main applications for robot machining that are covered in this study. While the grinding use-case employs an axial force (pressure) control, the deburring use-case uses a force-dependent feed-rate control. In addition to discussing the impact of both general machining settings and robot-specific factors, the research assesses both methodologies. In general, the paper sheds light on the creation and assessment of force-controlled machining procedures.

Z. Wang et al. [16] presents the design and research assessment of a fully pre-stressed, double-layered, six-axis force/torque sensor. The sensor's construction is contrasted with that of the standard Stewart platform-based force sensors. An ideal design strategy is put forth based on the provided measurement range, trying to reduce the stresses placed on the measure limbs while yet meeting the intended job requirements. To accomplish the goal, structural characteristics are optimised. The creation of a sensor prototype and the creation of a calibration system follow. The calibrated experiment is carried out, proving the excellence of the sensors structure and certifying the efficiency of the best possible design approach. The thoroughly pre-stressed six-axis force/torque sensors is designed, manufactured, and calibrated in this paper, with an emphasis on its benefits over conventional alternatives and the accomplishment of the optimal design methodology.

Y. Wang et al. [17] have looked into the best way to plan a train's route given restrictions and a set maximum arrival time. The paper includes arbitrary speed limits, variable grade profiles, tunnels, and curves, as well as variable line resistance. A trade-off between consumption of energy and riding comfort is the goal function. The paper develops the issue of optimal control as a MILP issue and represents the non-linear train models by a piece-wise affine model. The approach performs well in a case study and can be solved effectively by existing solvers.

Liao et al. [18] in this research, a novel modelling and control strategy for a dual-purpose compliance tool head-based automated polishing and deburring process is presented. The tool head has a pneumatic spindle that three pneumatic actuators may extend and retract to provide tool compliance. The tool head can deburr and polish surfaces by incorporating a linear encoder and a pressure sensor. The suggested control strategy uses a PID controller, which is used for pressure tracking during polishing and organising the tool force according to the part geometry. The tool length is additionally controlled using a separate PID controller for deburring control using tool extension sensing. The efficacy of the suggested techniques has been validated by experimental testing and use on a polishing/deburring robot. Overall, this method offers a practical option for accurate and regulated cleaning and deburring operations employing a flexible compliant tool head.

Kim et al. [19] a new present pneumatic tool and an effective robotic deburring technique. The approach incorporates tool dynamic and a control strategy that takes into account data on the deburring process, as well as the motion in tool, manipulator, and the work piece. In order to offer compliance and lessen chatter brought on by air compressibility, an active pneumatic technology tool is built with only one pneumatic operator and a passive chamber. A coordination control approach is devised, utilising a two-level hierarchy system of control founded on an organisation scheme. For example, static and Kinetic friction, irregular conformance of the pneumatic technology cylinder owing to air compressibility, and other external disturbances are all reduced to a minimum by using robust feedback linearization. The accuracy and speed of deburring are two metrics by which experimental results show the efficiency of the established coordination control method. Overall, this method provides an effective and dependable response to robotic deburring operations.

Ziliani et al. [20] concentrates on the use of a mechatronic technique for the robotic deburring purposes of planar work parts of uncertain forms utilising an industrial manipulator. The method is based on a specially crafted deburring tool and a mix force/velocity control rule. The efficiency of the approach employing a SCARA industrial robot manipulator with two degrees of freedom is demonstrated by experimental findings. The research demonstrates the practical viability of the mechatronic technology by highlighting its successful use in producing accurate and effective robotic deburring purposes of planar work parts.

Zhang et al. [21] handled the pre-chroming deburring and polishing procedure needed for cast aluminium wheels. Due of the time-consuming and repetitive nature of manual deburring and polishing, industrial robots are being investigated for use in these situations. However, the previous approach of producing wheel route programming for robots was time-consuming, lasting 8 to 10 weeks due to the necessity for accurate determination of the deburring tool's orientation and position based on the wheel's curvature. The authors created a workable technique for creating 6 DOF robot routes utilising a hybrid pressure and visual servoing approach to get around this problem. While the visual servoing directs the tool to follow a designated route on the wheel while capturing position and orientation data, the force servoing provides regular touch among the robot tool and the the wheel surface. Robot pathways are then created using the recorded data. The created method can automatically design precise 6 DOF robot pathways for deburring aluminium alloys in less than an hour, according to experimental data, which greatly reduces programming time. According to the authors, this technique provides a flexible option for robot route development because it may be used for various production processes like welding and strip painting.

Pires et al. [22] in manufacturing. Robotic applications have emphasised the significance of force/torque sensing. In order to properly accomplish autonomous operations, the article argues that force/torque sensor are required for accurate monitoring of the forces that result from interaction between tools and components. The paper focuses on a particular class of force/torque sensors and offers instructions on how to employ and incorporate them in robot force/torque control applications. An industrial example that highlights the significance of regulate for task accomplishment serves as the paper's conclusion.

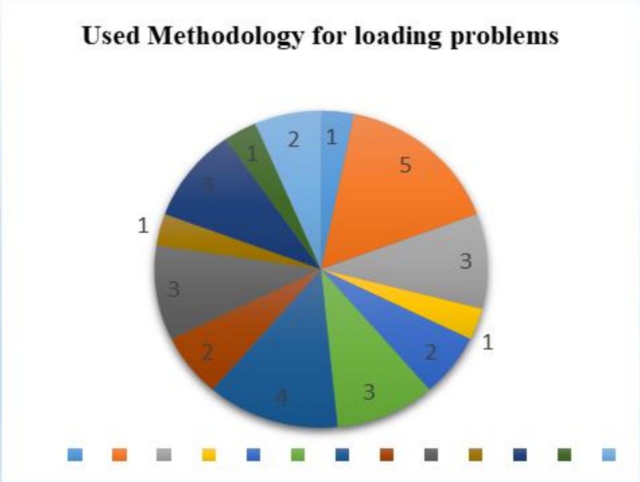
Schimmels [23] this two-part research describes a technique to increase a robotic manipulator's effective stiffness and positioning capacity through multiple directions compliance and constraint. The method uses a manipulator compliant that offers a particular kind of unidirectional couplings in force-deflection mapping together with an end-effector attached jig to generate a frame of reference based on multiple-point interaction with the work component. Even in the case of infinite positional errors, the directional coupling maintains contact preservation during edge tracking and allows for multipoint contact during insertion. The enhanced manipulator placement in the setting of work part surface deburring is demonstrated in the study. Overall, by using multidirectional compliance and constraint, this approach provides a way to improve the relative positioning and stiffness of robotic manipulators, hence optimising their performance.

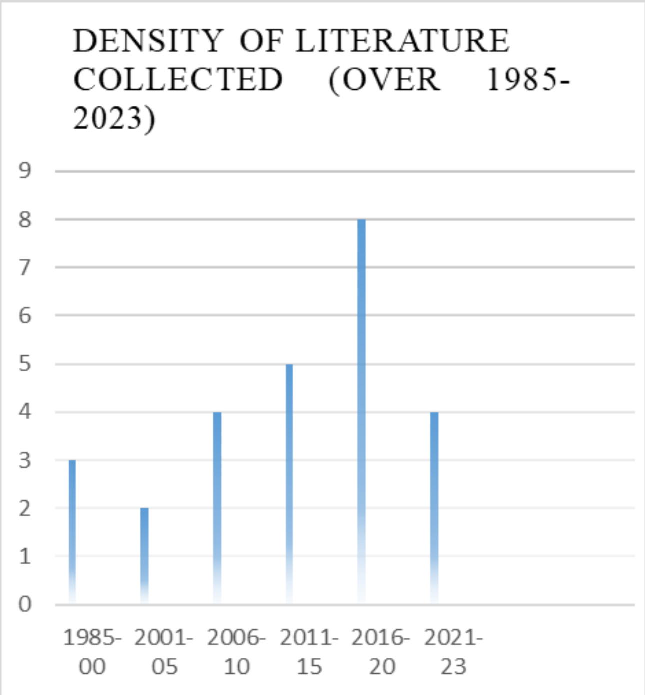
Chen and Tung [24] This two-part research describes a technique to increase a robotic manipulator's effective stiffness and positioning capacity through multiple directions compliance and constraint. The method uses a manipulator compliant that offers a particular kind of unidirectional couplings in force-deflection mapping together with an end-effector attached jig to generate a frame of reference based on multiple-point interaction with the work component. Even in the case of infinite positional errors, the directional coupling maintains contact preservation during edge tracking and allows for multipoint contact during insertion. The enhanced manipulator placement in the setting of work part surface deburring is demonstrated in the study. Overall, by using multidirectional compliance and constraint, this approach provides a way to improve the relative positioning and stiffness of robotic manipulators, hence optimising their performance. The suggested approach is illustrated by conducting precise deburring and cutting on work parts with unknown shapes utilising a Cartesian robot arm and firmly mounted grinding tool. The manipulator effectively deburrs the edges of objects with unexpected geometrical configurations while keeping the cutting force at the necessary level, demonstrating the viability and usefulness of the suggested technology. The results of this study help to improve the accuracy and automation of robotic deburring procedures for work items with arbitrary shapes.

Asokan and Singaperumal [25] concentrated on the use of impedance control, a technique for force and position control, in robotic tasks requiring dynamic contact with the environment. The research offers an impedance control technique that carries out such tasks using an electrohydraulic servo system. The method entails integrating an active degree of freedom into a trajectory-controlled manipulation using an electrohydraulic servo system. The required efficiency at the interface among the robot and its surroundings is achieved by modifying the manipulator's impedance utilising the electrohydraulic system. The researchers built a model of the entire system and investigated its stability and responsiveness traits. The specific use of the impedance-control approach for robotic deburring is taken into consideration, and both modelling and experimental results are presented in this study. The study sheds light on the use and efficiency of impedance control for robotic operations, notably in the context of deburring jobs, employing an electrohydraulic servo system.

Lee [26] draws attention to the improvements made in robotics force/torque sensors during the previous ten years, especially in research labs. Despite these advancements, however, the expensive cost and complicated system software of such devices has prevented their widespread practical use outside of the lab. This problem is demonstrated in the study by showing how force/torque sensors are used in a variety of robotic applications, such as grinding/deburring, drilling, and assembling, in both industrial and military settings. The article also covers the use of force/torque sensor for overload detecting and their use in robot programming. The study attempts to close the gap between laboratory developments and industrial acceptance of force/torque sensor in robotics by demonstrating real-life instances and practical applications.

The main criteria for choosing the appropriate form of modelling for a given application, particularly when it comes to the loading issues of robotic deburring applications, are precision, results acceptability and flexibility, computational time and cost.





- PIST (Planar Image-Space Trajectory)
- WAAM (Wire Arc additive manufacturing)
- PSDM (Physical and statistical detection model)
- Smart grinding robotic unit. (2)
- Force/Torque with CAD-HMI
- CNC deburring processes (2)
- F/T with frequency response function
- Adaptive neuro-fuzzy inference system.
- STL formation with Ai- algorithm (2).
- Vision Guided robotic system.
- Force control machining procedure.
- Pre-stressed force/torque sensor calibrated.
- Mixed integer linear programming.
- Proportional-integral-differential method.
- Mechatronics technology.
- Wheel route programming approach.
- Multidirectional compliance and constraint (2).
- Impedance control technique.
- The gap between laboratory developments and industrial acceptance.

III. CONCLUSION

For the purpose of improving robotic deburring processes, path optimisation algorithms with the incorporation of force/torque sensors have a lot of promise. The accuracy, efficacy, and productivity of deburring operations may be improved by manufacturers by utilising actual response from force sensors and applying route optimisation techniques.

Force/torque sensors are used to enable adaptive control, allowing robot tool trajectory modifications depending on contact forces. As a result of the tool paths being able to be adjusted in response to the pressures experienced during deburring, this adaptive control capacity enhances the consistency and standard of the surface finish.

The A* algorithm and other comparable path optimisation techniques are essential components of this integrated method. These algorithms provide force- and geometry-constrained tool paths that are labor-efficient Deburring time may be cut down by tool path optimisation, increasing production rates.

Investigations and experimental evaluations are used in the study in this area to further show the advantages of integrating force/torque sensor with route optimisation techniques. These studies demonstrate the benefits of an integrated strategy for deburring operations that result in higher results.

The use of force/torque sensor and route optimisation techniques is becoming more and more important as industries continue to look for ways to optimise deburring processes. These technologies are essential for advancing robotic deburring because they help manufacturers get better outcomes and broaden the use of robotic deburring across a variety of sectors.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Nil

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