Available online at
http://uppp.uitm.edu.my/online-issues.html

e-ISSN: 2689-4934

ESTEEM Academic Journal Vol 22, September 2025, 64-80

ESTEEM
Academic Journal
(EAJ)

Simulation-driven in robotic milling of soft material: Evaluating parallel and equidistant toolpath strategies using SprutCAM

Wan Nor Shela Ezwane binti Wan Jusoh[1], Mohamad Irwan Yahaya[1*], Shukri bin Zakaria[1], Mahamad Hisyam Mahamad Basri[1], Md Razak Daud[2], Noor Iswadi Ismail[1]

[1]*Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Mara, 13500 Permatang Pauh Pulau Pinang, Malaysia*
[2]*Mechanical Engineering Department, Politeknik Ibrahim Sultan, 81700 Pasir Gudang, Johor Darul Ta'zim, Malaysia*

ARTICLE INFO

Article history:
Received 15 May 2025
Revised 14 August 2025
Accepted 25 August 2025
Online first
Published 8 September 2025

Keywords:
robotic machining,
Sprutcam simulation,
toolpath strategies,
amplitude variations,
surface quality.

DOI:
10.24191/esteem.v21iSeptember.6483.g4961

ABSTRACT

The modern manufacturing industry is increasingly focused on robotic machining for soft materials, such as foam, due to its ability to provide precise automated operations. This study examines the effect of robotic movement parameters on soft material machining, considering material surface quality and machining time for strategy comparison. The testing of the Parallel and Equidistant machining methods revealed their operational capabilities and practical viability. The parallel method promotes robot motion stability and controlled amplitude, resulting in uniform machining outcomes. In contrast, the equidistant approach results in irregular robotic movement and oscillatory amplitude variations, which can lead to surface imperfections and reduced efficiency. The success of this research was driven by SprutCAM's comprehensive simulation capabilities, including its visualisation tools, which enabled prior to actual machining, reduced testing time, expanded operator options, and automatically aligned processes to enhance efficiency. Simulation data from SprutCAM has been proven instrumental in identifying key motion factors crucial for improving machining results. The findings highlight the indispensable role of simulation tools, such as SprutCAM, in robotic machining to ensure precision and consistency during the foam processing process. As a result, machining time is reduced, surface quality improves, and the performance of robot axis movement is refined alongside toolpath strategies. These results suggest that simulation-based process optimisation can significantly benefit modern manufacturing by providing essential principles for advancing robotic machining techniques.

[1*] Corresponding author. *E-mail address*: irwan352@uitm.edu.my
https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

1. INTRODUCTION

In recent years, foam has been used to replace various engineering materials in a variety of applications, primarily due to its beneficial mechanical properties, including light weight, high energy absorption, and ease of machining. The foam is widely used in industries such as automotive, aerospace, packaging and biomedical engineering, especially in the production of prototypes, insulation components, protective packaging and anatomical models. The foam materials are characterised by specific properties such as low density, high strength, low thermal conductivity, and exceptional sound insulation, making them suitable for a wide range of applications. The remarkable combination of impact resistance, environmental sustainability, and non-toxicity makes foam materials an ideal choice for numerous contemporary uses [1], [2]. The exceptional strength-to-weight ratio, along with their thermal and acoustic insulation properties, further sets foam materials apart from other engineering materials. Fig. 1 illustrates three main categories of foam types: closed-cell foams, open-cell foams, and honeycomb foams [3].

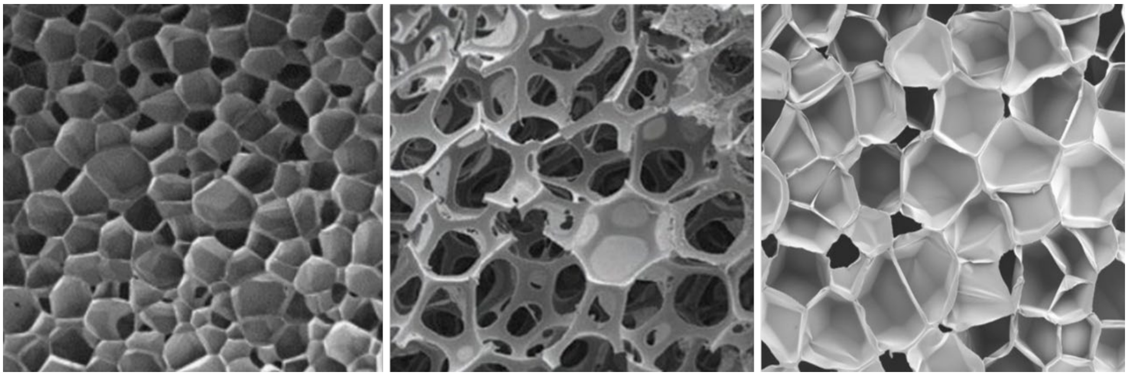

(a) (b) (c)

Fig. 1. Foam material types (a) closed-cell structures, (b) open-cell structures, (c) honeycomb structures [4]

Foam materials exist in various types, such as expanded polystyrene (EPS), extruded polystyrene (XPS), polyethene (PE), and polyurethane (PU) foams, each exhibiting distinct density, cell morphology, and mechanical performance [3], [5]. EPS and XPS foams are commonly used in packaging due to their lightweight and cushioning properties, while PE foams provide high resilience and flexibility. Polyurethane foams, particularly rigid closed-cell types, are often preferred for engineering and biomedical applications because of their high compressive strength, dimensional stability, and ease of machining [6-7]. Recent studies have highlighted the growing use of CNC and robotic milling for shaping foam components into precise geometries, enabling their application in prototypes, crashworthiness structures, and medical models [8-9]. This study focuses on machining polyurethane foam as a representative soft material, while acknowledging the diversity of foam types used in packaging and structural applications.

In machining applications, closed-cell foams are often favoured due to their superior mechanical properties of high density, rigidity, and dimensional stability that contribute to excellent structural durability and accuracy. These characteristics make them well-suited for demanding industries such as aerospace, automotive, biomedical, and marine, where lightweight yet strong materials are essential. The integration of robotic manufacturing technologies further enhances their machinability, offering improved precision, repeatability, and design flexibility for high-performance engineering applications [8-9].

Robotic milling is highly versatile, capable of processing a wide range of soft materials, shapes, and sizes, making it a valuable tool across diverse applications. The increasing use of robotic milling, particularly in polymer machining, has contributed significantly to the advancement of expertise in this

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

field [10]. Recent advancements in milling techniques have enabled the achievement of outstanding dimensional accuracy and improved surface quality. Insufficient heat dissipation during machining can cause material melting, and delamination problems further emphasise the importance of choosing the right tools and machining parameters [7].

Meeting specific user requirements often involves shaping foam components into complex three-dimensional models using CAM software and CNC milling. In this process, the selection of cutting parameters plays a crucial role, as it directly influences the geometric accuracy and surface finish of the final product. Key machining parameters are spindle speed, depth of cut, feed rate, and tool selection. Higher spindle speeds can lead to increased vibration, while the choice of tool path significantly affects surface quality. Achieving an optimal Material Removal Rate (MRR) and maintaining low surface quality depend on the correct adjustment of cutting depth. Furthermore, selecting a cutting tool with geometry suited to the material's characteristics helps minimise the risk of material damage and enhances surface quality. A thorough understanding of these parameters, as depicted in Fig. 2 is essential for selecting the appropriate settings, particularly when working with foam materials to achieve the desired surface finish required for various industrial applications [9], [11].

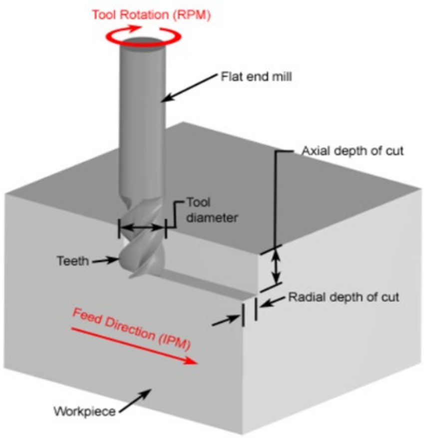


Fig. 2. Milling machining mechanism

Spindle speed and cutting speed are interconnected but serve distinct functions in machining. Spindle speed refers to the rotational speed of the spindle, measured in revolutions per minute (rpm) [12]. It governs the rotational velocity of either the cutting tool or the workpiece. On the other hand, cutting speed is the rate at which the cutting tool advances relative to the workpiece, typically expressed in meters per minute (m/min). This parameter indicates the material removal rate. The following equation (Eq. (1)) describes the relationship between spindle speed and cutting speed:

$$V_c = \pi D N \tag{1}$$

where V_c represents cutting speed (m/min), D represents the diameter of the cutting tool or workpiece (m), and N represents spindle speed (rpm)

Robotic milling necessitates frequent determination of spindle speed values, with the frequency being directly calculable from the spindle speed and the number of flutes. This relationship is reciprocal, where, for instance, when the Kuka KR120 R2700 robot provides the frequency, the researcher can compute the

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

corresponding spindle speed. The relationship between spindle speed and frequency (f_o) is expressed by the following equation (Eq. (2)) [13]:

$$f_o = \frac{1}{T}n = \frac{\omega}{60}n \tag{2}$$

where f_o represents frequency, T represents time, n represents the number of flutes and ω = represents spindle speed (rpm)

Feed rate and feed per tooth are related concepts, but they are applied in different contexts based on the specific study objectives and the desired output response. Feed rate refers to the linear speed at which the cutter moves along the workpiece [14], typically measured in millimetres per minute (mm/min). Feed per tooth, on the other hand, represents the amount of material removed by each tooth of the cutter during one revolution, usually expressed in millimetres per tooth (mm/tooth) or inches per tooth (in/tooth). The relationship between feed rate, feed per tooth, spindle speed, and the number of teeth on the cutter is given by the following equation (Eq. (3)):

$$f_r = f_t.Z.N \tag{3}$$

where f_r represents feed rate (mm/min), f_t represents feed per tooth (mm/tooth), Z represents the number of teeth on the cutter, N represents spindle speed (revolutions per minute, rpm).

Feed rate controls the machine's speed, affecting surface quality, while feed per tooth establishes the optimal values for both finishing and rough cutting operations. The type of material plays a critical role in determining the appropriate feed values. When soft materials are subjected to higher feed rates, tool damage can occur, whereas stiffer materials require lower feed rates to prevent such issues.

Depth of cut refers to the thickness of material removed by a cutting tool in a single pass, usually measured in millimetres (mm) [15]. This parameter is essential in machining processes, particularly in milling. The depth of cut influences key factors such as Material Removal Rate (MRR), cutting forces, and tool wear during machining. The relationship is expressed by the following formula (Eq. (4)):

$$MRR = d.f.V \tag{4}$$

where MRR represents material Removal Rate (mm³/min), d represents depth of cut (mm), f represents feed rate (mm/rev), and V represents cutting speed (m/min)

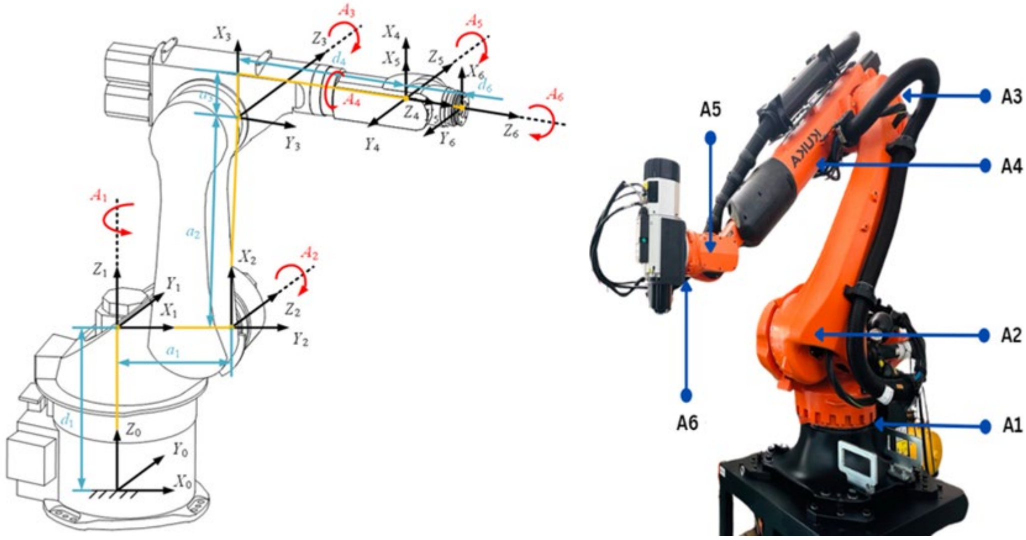
The depth of cut is primarily influenced by the material being processed. Softer materials, such as plastic, foam, and wood, can usually handle greater depths; however, excessive depth may lead to a poor surface finish. In contrast, harder materials like metal, alloys, and titanium require smaller depth values to reduce cutting forces and minimise tool wear. To minimise friction, coolants and advanced tools like ceramics and carbides are commonly used. [16-17].

A practical cutting strategy is essential for flat-face milling operations using a 6-degree-of-freedom (6-DOF) robotic arm, as it impacts both dimensional accuracy and the optimal force interaction between the robot and the manufacturing process. Evaluating the flat-face machining method involves assessing parameters that integrate dimensional accuracy with process stability, as well as the system's compatibility with both face and tangential milling techniques. Various studies have shown that robotic systems produce excellent results in terms of surface flatness and process stability during face milling operations [18-19].

In a typical 6-axis KUKA KR120 R2700 [20] robotic arm shown in Fig. 3, each joint (A1 to A6) has its own link frame that facilitates the calculation of the robot's movements and the transformations between different frames, enabling precise control over the robot's actions during tasks such as milling machining.

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

Each axis serves a specific purpose: A1 and A2 facilitate basic rotation, A3 and A4 manage the main arm movements, and A5 and A6 enable complex machining angles. These capabilities allow the robot to process materials at various cutting angles, including soft material where the focus is on achieving precise tolerances and surface quality. Surface quality is a crucial quality metric that determines whether a product meets its functional requirements. The machining process directly impacts surface quality, which in turn affects the product's overall functionality. When designing surfaces with improved adhesion properties or ensuring compatibility between interacting materials, surface topography becomes a crucial factor. Surface quality metrics are standard tools used for evaluating the conditions of container surfaces. To maintain high machining efficiency and achieve the desired surface quality, it is essential to optimise machining parameters [21]. The final surface quality is influenced by two key factors outlined by Hafner et al. [2] namely, the intrinsic properties of the material being foamed, such as density, viscosity, and thermal conductivity, which significantly influence the foaming process. Similarly, milling machining parameters, including cutting speed, feed rate, depth of cut, and tool geometry, play a crucial role in shaping the material, impacting its final quality and performance [6].



(a) (b)

Fig. 3. (a) Link frame of the KUKA Robot [22], (b) KUKA KR120 R2700 [23]

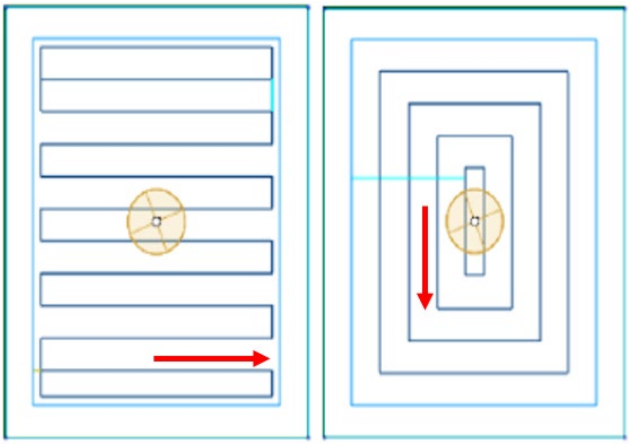
The redundancy characteristic in robotic systems involves the use of a 6-DOF robot, although only 5-DOF are essential for defining the tool's pose during the milling operation. The axis not involved in determining the tool's pose is known as the redundant axis, which enhances the flexibility of the robot's end-effector in milling tasks. This redundant axis is aligned along the tool axis. The homogeneous transformation matrix, which defines the tool's coordinate system relative to the robot base coordinate system, is given by the following expression (eq. (5)) [22]:

$$T_{bt} = \begin{bmatrix} -cos\theta_r & sin\theta_r & 0 & P_x \\ sin\theta_r & cos\theta_r & 0 & P_y \\ 0 & 0 & -1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

where T_{bt} represents transformation matrix, $P(P_x, P_y, P_z)$ is the position coordinate of the tool coordinate system in the robot base coordinate system, and θ_r represents the rotation angle around the redundant axis, which adds flexibility to the tool's movement in the milling task.

Several toolpath strategies are available in CAM-based robotic milling, such as Equidistant Legacy, Deep High-Performance Cutting, and High-Performance Cutting. However, this study specifically focuses on comparing the parallel and equidistant toolpath strategies, as illustrated in Fig. 4, since these two approaches represent the most contrasting patterns in terms of machining time, robot axis movement, and surface quality. The selection criterion focused on maintaining the direction and magnitude of the cutting force vector as consistently as possible. This method improves the accuracy and realism of predictive outcomes by minimising discrepancies between the cutting force model and the robot's dynamic behaviour. The study also focused on comparing the Equidistant and Parallel strategies, assessing their impact on machining time, variations in axis movement on each robot axis, and surface quality. Table 1 presents a comparison of the Equidistant and Parallel machining strategies.



(a) (b)

Fig. 4. Machining tool path: (a) Parallel (b) Equidistant

Table 1. Comparison of Parallel and Equidistant Machining Strategies

Machining Parameter	Parallel Strategy	Equidistant Strategy
Machining Time [24]	Reduces machining time by maintaining a more linear and efficient toolpath.	This leads to increased machining time due to continuous tool engagement and complex trajectory adjustments.
Surface Quality [25]	Produces a more consistent surface finish with minimal tool overlap, reducing machining artefacts.	Achieves a uniform material removal process, though tool marks may appear due to continuous engagement.
Robot Axis Movements [26]	Maintains smoother and more consistent axis transitions, minimising robotic stress and power consumption.	Produces intricate and frequent axis movements, increasing mechanical wear and energy consumption.

The parallel and equidistant toolpath strategies have been widely discussed in machining literature. Parallel toolpaths generate linear passes across the workpiece surface, which result in stable cutting forces, shorter machining time, and smoother surface finish [27]. In contrast, equidistant toolpaths maintain a constant offset from the previous pass, enabling uniform material removal but often introducing higher tool engagement, complex robot motions, and longer processing times [25], [28]. Recent studies confirm that parallel paths are particularly efficient for large flat areas, while equidistant strategies are more suitable for

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

complex geometries where consistent step-over is required [26]. These findings support the focus of this study, which evaluates the operational differences between the two strategies in robotic milling of foam.

2. METHODOLOGY

This study evaluates the effects of machining using parallel and equidistant toolpath strategies, emphasising SprutCAM software's role. The comparison focuses on differences in machining time, material surface quality, and robotic axis movement (A1-A6) through robotic machining techniques. The study analyses the relationship between the two toolpath strategies under identical machining parameter settings, including controlled spindle speed, feed rate, and depth of cut, to ensure consistent and repeatable results. The evaluation of surface quality was conducted using visual inspection of the machined samples and Scanning Electron Microscopy (SEM) to observe surface texture, cell wall integrity, and the presence of machining defects such as debris or tearing. This qualitative approach provides valuable insights into the machining behaviour of foam. It highlights the influence of toolpath selection on the final surface characteristics, which is critical for applications requiring smooth finishes and structural reliability.

2.1 Simulation setup

Fig. 5 illustrates the SprutCAM software, which is used for CAD design [26]-[30], programming setup [31] that support toolpath planning and collision detection to ensure smooth and optimised tool engagement during machining [32]. The software enables adaptive control of machining parameters such as spindle speed, feed rate, depth of cut, and tool orientation, minimising errors [28]. The simulation of toolpath selection can provide accurate trajectory predictions at machining time. It also evaluates the movement distances of each robotic axis (A1-A6) to analyse amplitude trends based on the selected toolpath. This virtual simulation approach reduces the reliance on trial-and-error methods in physical experiments, improving machining efficiency and surface finish quality. Furthermore, the integration of SprutCAM with KUKA robotics demonstrates advanced programming flexibility and accuracy in robotic manufacturing operations.

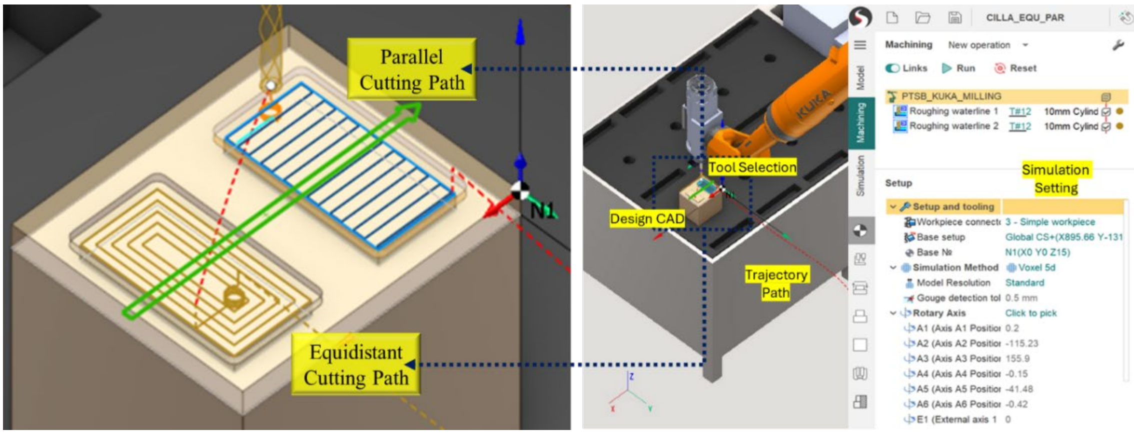


Fig. 5. SprutCAM simulation and programming setup

To enhance operational safety and machining accuracy, measures were implemented to prevent the robot from entering singularity zones or configurations that could compromise control. Real-time trajectory simulations, as suggested by Qiao et al. [33], were utilised to identify potential singularities and collision points. This allowed for immediate adjustments to the trajectory, ensuring smooth robotic movement and

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

optimal performance [34]. The control program also accounted for the linear axes and the workpiece positioning device's axes within the robot's operational space. Munasypov et al. [10] emphasized the importance of factoring in joint rotation limits and collision avoidance in control program development. Accordingly, strategic trajectory planning was applied to maintain continuous control, prevent singularities, and achieve optimal machining outcomes. The process involved several key steps, as depicted in Fig. 6, including trajectory generation, collision detection, singularity analysis, and program optimisation [35], [36]. These steps ensured precise, reliable, and safe robotic machining operations.

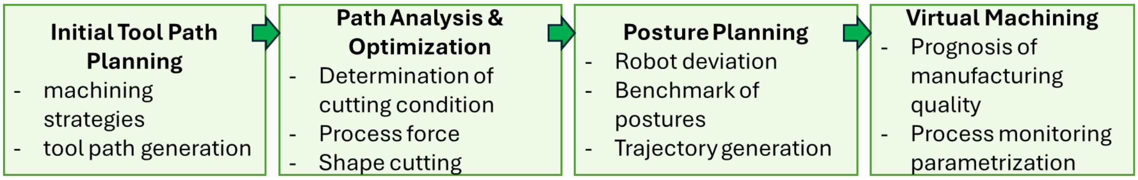


Fig. 6. Robot machining process planning using simulation-based techniques

Optimising processing parameters in SprutCAM is critical for developing accurate robot control programs. The relationship between the defined mathematical accuracy and the maximum linear deviation determines the number of interpolation points along the robot's motion trajectory. These points represent the coordinates in space that define the cutting tool path, where a greater number of points results in smoother motion but may increase the robot's processing load. Gao et al. [37] highlighted that accurate trajectory tracking necessitates the control scheme's dynamic model to faithfully represent the robot's real dynamic behaviour. Correct alignment of this model improves motion precision, stability, and overall machining performance in robotic applications. When machining highly soft material such as foam for prototyping purposes, the robotic arm showed remarkable performance, exhibiting qualities comparable to those of high-precision machine tools [38]. Table 2 presents the tool parameters and cutting conditions from the robotic milling experiment, including two machining strategies: Parallel Path and Equidistant Path, each offering different material removal behaviours.

Table 2. Tool settings and cutting parameters for the robotic milling experiment

	Material	**High Speed Steel (HSS)**
Tool Parameters	Number of teeth	2
	Diameter (mm)	10
Milling Condition	Spindle Speed (rpm)	18000
	Feed Rate (mm/min)	1500
	Depth of Cut (mm)	1
	Workpiece material	Foam
	Machining Strategies	Parallel Path
		Equidistant Path

2.2 Experiment setup

This experimental study evaluates the effects of machining parameters (spindle speed, feed rate, and depth of cut) on machining time, material surface quality, and robot axis movement. The workpiece material used was closed-cell rigid polyurethane foam (PUF), with machining dimensions of 50 mm × 100 mm and a total material size of 150 mm × 180 mm × 140 mm. Table 3 details the material's mechanical and physical properties. A two-flute carbide flat end mill (10 mm diameter, 70 mm total length) was utilised for the face cutting test. Robot machining was performed using a 6-axis KUKA KR120 R2700 milling robot, employing

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

two strategies: parallel and equidistant toolpaths, to assess their impact on the foam material. After machining, the surface quality of the foam samples was evaluated visually and further examined using a TM3030 Tabletop Scanning Electron Microscope (SEM) with SwiftED3000. The SEM analysis provided detailed observations of surface morphology, microstructural features, and evidence of machining-induced defects, such as tear or debris.

Table 3. Foam material characteristics [7]

Description	Properties
Density	50 kg/m^3
Thermal Conductivity	0.020 WmK
Compressive Strength	350 Kpa
Dimensional Stability	
@ -20 °C	0.3%
@100 °C	0.3%
Close Cell Content	93%
Water Absorbed (Max)	2%
Storage	Keep Dry

The foam used in this study is categorised as closed-cell rigid polyurethane foam (PUF), which is widely applied in protective packaging, insulation, and structural components. Polyurethane foam is preferred in machining studies due to its dimensional stability, high compressive strength, and uniform cell morphology, which allows consistent experimental evaluation [6-7]. Other packaging foams, such as expanded polystyrene (EPS), extruded polystyrene (XPS), and polyethene foams, exhibit different cell structures and mechanical behaviours [4], this study focuses on polyurethane foam as a representative closed-cell foam material.

The experiment was conducted under controlled conditions, where machining parameters such as robot spindle speed, feed rate, and depth of cut were carefully regulated to minimise variability and ensure accurate results. Parallel and equidistant toolpath strategies were used to evaluate the effect of these parameters on foam surface quality. Machining time was manually recorded and compared with SprutCAM simulation times to analyse the accuracy of simulated cutting time. The experimental setup, shown in Fig. 7, featured a vacuum-secured foam workpiece on a flat, stable table to minimise vibration during machining. Mundim et al. [39] highlighted that shorter tools reduce vibration by limiting cutting length and preventing machining, particularly crucial for soft material where lower stiffness necessitates reduced force for improved stability. Similarly, Niu et al. [40] confirmed that shorter tools enhance stability by reducing cutting force and vibration. This setup underscores the advanced control offered by robotic manufacturing, ensuring consistent and reliable experiments under precise cutting conditions.

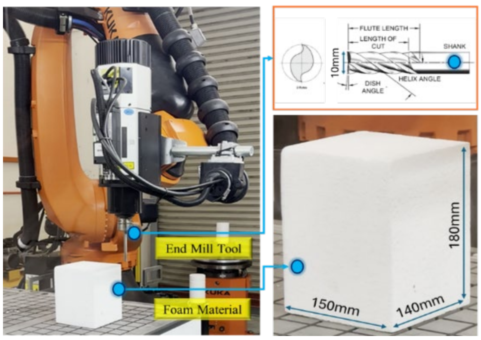


Fig. 7. Experimental setup

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

3. RESULT AND DISCUSSION

This study compared simulation and physical machining times to assess the efficiency of parallel and equidistant toolpaths, as shown in Fig. 8. SprutCAM predicted 54 s for the parallel path and 62 s for the equidistant path, whereas actual machining required 73 s and 86 s, respectively. The percentage errors were 26.0% (parallel) and 26.7% (equidistant), indicating that the software underestimated the machining times. This discrepancy arises because the simulation does not fully capture fundamental machining factors such as tool deflection, vibration, and robot joint compliance. While SprutCAM provides reliable trajectory planning and collision avoidance, its time estimation remains optimistic compared to practice. Therefore, calibration against experimental data is necessary to improve the predictive accuracy of simulated machining time.

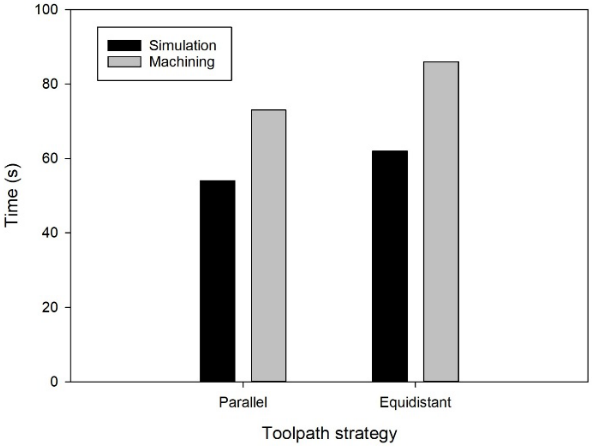


Fig. 8. Comparison of simulation and machining times for different toolpaths

The difference between simulated and experimental machining times indicates a modelling error. The percentage error was calculated using the following expression (Eq. (6)):

$$\text{Error (\%)} = \frac{T_{actual} - T_{simulated}}{T_{actual}} \times 100 \qquad (6)$$

For the parallel strategy:

$$\text{Error (\%)} = \frac{73 - 54}{73} \times 100 = 26.0\%$$

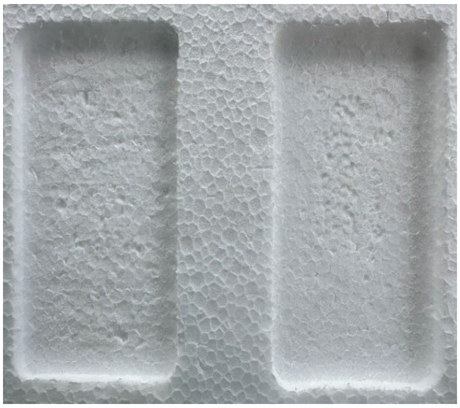
For the equidistant strategy:

$$\text{Error (\%)} = \frac{86 - 63}{86} \times 100 = 26.7\%$$

The analysis of machined surfaces using the equidistant and parallel strategies reveals significant differences in surface quality, as shown in Fig. 9. The parallel strategy, with its linear tool passes, produced a visibly smoother finish with fewer irregularities. In contrast, the equidistant strategy resulted in a rougher surface with more noticeable machining marks. These observations indicate that parallel toolpaths facilitate more uniform cutting passes, whereas equidistant toolpaths increase tool–workpiece interactions that can

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

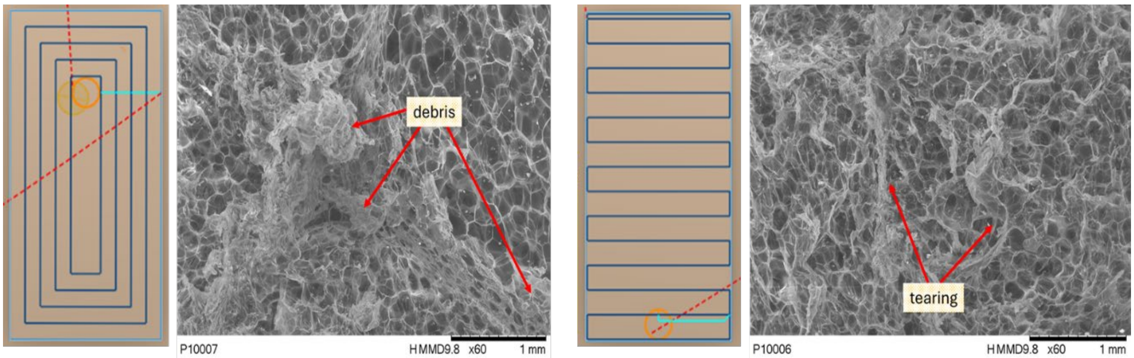
degrade the final surface quality. Although the evaluation is qualitative, the visual evidence provides a clear distinction between the two strategies and supports the effectiveness of SprutCAM toolpath simulation in predicting machining outcomes.



(a) (b)

Fig. 9. Machined workpiece using different toolpaths (a) equidistant: (b) parallel

SEM imaging provides further insights into the microstructural surface morphology of the machined samples, as shown in Fig. 10. The parallel strategy produced a more uniform texture, whereas the equidistant strategy resulted in a rougher surface with noticeable material buildup. Detailed inspection revealed debris accumulation along the cell walls in the equidistant path, indicating incomplete chip evacuation, while the parallel path showed evidence of tearing, where cell walls were mechanically ruptured and elongated grooves appeared across the surface. Although the evaluation is qualitative, these observations are consistent and confirm that toolpath selection plays a critical role in preserving the integrity of the foam's cellular structure, which directly influences its surface quality and potential application.



(a) (b)

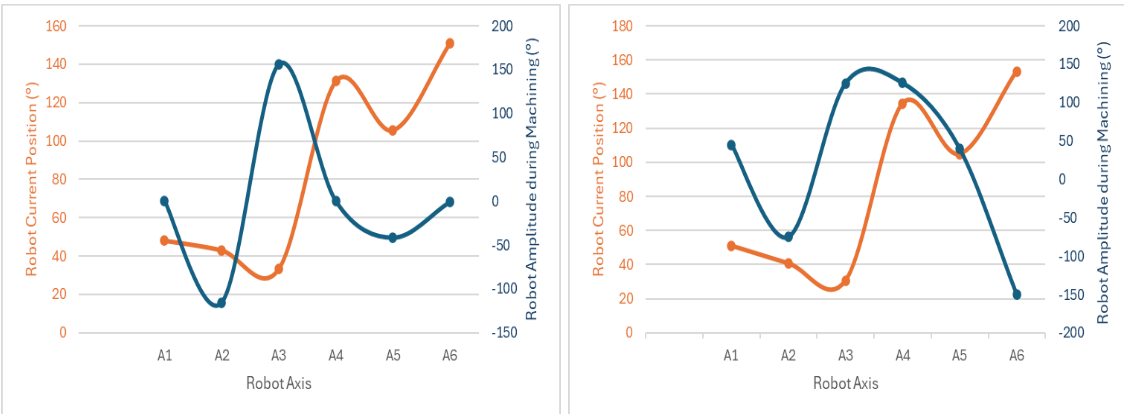
Fig. 10. SEM image with different toolpaths (a) equidistant: (b) parallel

This microscopic structure offers critical insight into the effects of machining strategies on the material's integrity. Notably, robot machining using a parallel toolpath strategy has been observed to produce a more pronounced spongy surface texture. This may indicate either practical preservation of the

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

foam's cellular structure or, in some cases, the result of excessive mechanical stress, depending on the selected cutting parameters. These SEM findings are beneficial particularly useful for guiding the optimisation of machining parameters, such as spindle speed, feed rate, tool selection, and depth of cut, to minimise surface degradation and enhance final product quality. The porous foam texture benefits biomedical uses like tissue scaffolds and orthotics [42] and energy-absorbing applications. In contrast, equidistant machining causes cell wall tearing and debris, making it less suitable for such applications without post-processing to smooth and restore surface integrity.

Evaluating the robot's position alongside amplitude measurements during machining operations is essential for enhancing precision, optimising machining parameters, and ensuring high product quality The location and orientation of each robot axis are illustrated in Fig. 3(a), which provides a useful reference to interpret the motion trajectories presented here. In Fig. 11, the y-axis represents displacement in degrees. The robot's current position indicates the actual trajectory values captured by the controller, while robot amplitude refers to the deviation of the tool from its nominal reference path. Although both are plotted together for comparison, their interpretation differs: the current position reflects commanded motion control, whereas amplitude indicates dynamic error or oscillation from the reference point. Elevated amplitude readings at specific positions may signal mechanical issues, necessitating adjustments to machining parameters such as feed rates and spindle speeds. This evaluation helps identify areas where excessive mechanical stress could damage cutting tools and degrade surface quality. By implementing optimal dynamic control, manufacturers can achieve faster machining speeds, maintain tool integrity, ensure protection, and enhance robotic productivity, especially when working with soft material. Fig. 11 presents robotic machining techniques, emphasising the operational distinctions between parallel and equidistant strategies, especially in terms of motion patterns and amplitude control during delicate material processing. To date, there is limited literature directly comparing the parallel and equidistant robotic machining strategies with respect to their motion patterns and amplitude control in delicate material processing. Consequently, this study addresses a gap by providing novel experimental insights into the operational distinctions between these techniques. The results enhance the current understanding of robotic machining approaches and offer valuable information for future research and industrial applications in precision manufacturing.



(a) (b)

Fig. 11. Robot current position and amplitude during machining for (a) equidistant and (b) parallel toolpath strategies. The left Y-axis represents the robot's current position (°), while the right Y-axis indicates the amplitude during machining (°).

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

The robot's current position patterns show that the parallel strategy produces smoother toolpath movements. By consistently implementing parallel passes, this approach improves efficiency in terms of machining time and motion stability, as fewer corrective adjustments are required during operation. This contributes to more predictable tool behaviour and reduces unnecessary dynamic load on the system. In contrast, the equidistant strategy exhibits less uniform trajectory patterns, with oscillatory variations observed along its movement path. These irregularities require more frequent control corrections, which may increase the likelihood of vibrations and reduce overall motion stability [43].

The amplitude comparison further highlights the differences between the two strategies. The parallel strategy maintains a more stable amplitude trend throughout its operation, ensuring consistent performance within a predictable operating range. This stability helps to reduce the risks of unpredictable vibrations, which could lead to imbalanced cutting forces and enhance process reliability. In contrast, the equidistant strategy generates amplitude signals that follow a linear progression between axis points but exhibit unstable measurement values at certain positions, which may be attributed to machine irregularities and vibrations.

4. CONCLUSION

This study compared parallel and equidistant toolpath strategies in robotic milling of foam material using SprutCAM simulation and experimental validation. The results demonstrated that the parallel strategy consistently achieved shorter machining times in both simulation (54 s vs. 62 s) and physical machining (73 s vs. 86 s), showing time savings of approximately 26% compared with equidistant paths. Although SprutCAM tended to underestimate machining times, the error margin between simulated and actual machining was comparable for both strategies, confirming the software's reliability for trajectory planning. Surface quality assessment through visual inspection and SEM imaging revealed that the parallel toolpath generated smoother surfaces with fewer machining marks, while the equidistant strategy produced rougher finishes with evidence of debris and tear at the cellular structure. Analysis of robot kinematics further indicated that the parallel strategy maintained more stable trajectory patterns and lower amplitude variations, reducing the risk of instability during machining. Overall, the findings confirm that toolpath selection has a significant influence on machining performance in robotic milling of foam materials. The parallel strategy offers better machining efficiency in terms of time, surface quality, and motion stability, whereas the equidistant strategy results in longer machining times, less uniform surfaces, and less stable robot motion. These insights provide useful references for optimising toolpath planning in robotic machining of soft materials, particularly foams, and highlight the need for calibration of simulation models against experimental data for improved accuracy.

5. ACKNOWLEDGEMENT

The authors would like to acknowledge and thank the Mechanical Engineering, Faculty of Engineering Universiti Teknologi Mara and Mechatronic Robotics Technology Center, Politeknik Tuanku Sultanah Bahiyah, Malaysia.

6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits or commercial or financial conflicts and declare the absence of conflicting interests with the funders.

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

7. AUTHORS' CONTRIBUTIONS

Wan Nor Shela Ezwane Wan Jusoh: Conceptualisation, methodology, formal analysis, investigation and writing-original draft; **Shukri Zakaria, Mahamad Hisyam Mahamad Basri**: Conceptualisation, methodology, and formal analysis; M**ohamad Irwan Yahaya**: Conceptualisation, formal analysis, and validation; **Md Razak Daud, Noor Iswadi Ismail**: Conceptualization, writing- review and editing, and validation.

8. REFERENCES

[1] Y. Xu *et al.*, "Synthesis and properties of CO2-based plastics: Environmentally-friendly, energy-saving and biomedical polymeric materials," *Elsevier Ltd*. May 01, 2018. Available: https://doi.org/10.1016/j.progpolymsci.2018.01.006

[2] R. Hafner, F. Pušavec, L. Čerče, and J. Kopač, "Influence of milling process on machined surface of porous polyurethane (PU) foam," *Tehnicki Vjesnik*, vol. 23, no. 4, pp. 1089–1093, Aug. 2016. Available: https://doi.org/10.17559/TV-20150729135016

[3] Hanxing Zhu, "The Elastic Properties and Yield Strengths of Low-Density Honeycombs and Open-Cell Foams," Dec. 2023. Available: https://doi.org/10.5772/intechopen.1003167

[4] A. Baroutaji, A. Arjunan, A. Niknejad, T. Tran, and A.-G. Olabi, "Application of Cellular Material in Crashworthiness Applications: An Overview," in *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2019. Available: https://doi.org/10.1016/b978-0-12-803581-8.09268-7

[5] X. Chengyi, "Application Analysis on Modern Machinery Manufacturing Technology and Precision Machining Technology," 2018.

[6] R. Hafner, D. Grguraš, and D. Kramar, "Milling process optimization for the best surface coat adhesion of the rigid polyurethane foam," *Journal of Polymer Engineering*, vol. 38, no. 10, pp. 995–1005, Nov. 2018. Available: https://doi.org/ 10.1515/polyeng-2018-0035

[7] A. K. C. Utomo, Ubaidillah, W. W. Raharjo, and W. Harwijayanti, "Analysis of Polyurethane Foam Machining Parameter Influence: Current Status and Perspective," in *E3S Web of Conferences*, EDP Sciences, Apr. 2024. Available: https://doi.org/ 10.1051/e3sconf/202451712008

[8] M. Wabner, H. Rentzsch, S. Ihlenfeldt, and A. Otto, "Technological robot—Machine tool collaboration for agile production," *Front Robot AI*, vol. 9, Oct. 2022. Available: https://doi.org/ 10.3389/frobt.2022.1027173

[9] D. K. Dubey, A. Dixit, and V. Kumar, "Robotic Milling: A New Era of Machining," 2023. [Online]. Available: www.ijfmr.com

[10] R. Munasypov, S. Fetsak, and P. Vasiliev, "A Robotic Milling Center for Orthoses and Prostheses Forms Production," in *Proceedings - 2024 International Ural Conference on Electrical Power Engineering, UralCon 2024*, Institute of Electrical and Electronics Engineers Inc., 2024, pp. 294–298. Available: https://doi.org/10.1109/UralCon62137.2024.10718712

[11] D. Klempner, K. C. Frisch, and J. H. Saunders, "Handbook of Polymeric Foams and Foam Technology edited by," 2004

[12] S. S. P. Santosa and I. Mashudi, "The Effect of Depth of Cut and Spindle Speed on Cutting Parallelism Results on Aluminum 6061 CNC TU-3A Retrofit Machine," *TRANSMISI*, vol. 20, no. 2, pp. 60–65, Aug. 2024. Available: https://doi.org/10.26905/jtmt.v20i2.13726

[13] P. Xu, Y. Gao, X. Yao, Y. H. Ng, K. Liu, and G. Bi, "Influence of process parameters and robot postures on surface quality in robotic machining Influence of process parameters and robot postures on surface 1 quality in robotic machining," 2022. Available: https://doi.org/10.21203/rs.3.rs-1712459/v1

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

[14] B. R. N. Murthy, S. R. Harisha, G. D. Deepak, and P. Hiremath, "Experimental Design and Optimization of Machining-Induced Cutting Force and Its Effect on Surface Roughness during Milling of Fiber-Reinforced Polymer Composites," *Journal of Composites Science*, vol. 8, no. 9, p. 346, Sep. 2024. Available: https://doi.org/10.3390/jcs8090346

[15] U. M. Dilberoglu, U. Yaman, and M. Dolen, "A comprehensive guide to milling techniques for smoothing the surfaces of 3D-printed thermoplastic parts," *Rapid Prototyp J*, vol. 30, no. 8, pp. 1648–1662, Aug. 2024. Available: https://doi.org/ 10.1108/RPJ-08-2023-0277

[16] A. Wahjudi, A. R. Yusoff, S. Sabil, B. O. P Soepangkat, S. Suhardjono, and P. Al-Sultan Abdullah, "A study of end milling process parameter's effect on thin wall aluminum-7075 surface roughness under minimum quantity lubrication," *Jurnal Tribologi*, vol. 43, pp. 185-196, 2024

[17] M. Abdul Hadi, "Machinability and tribological investigation of nano-hybrid cryogenic-MQL during milling Ti-6Al-4V alloy," *Jurnal Tribologi*, vol. 44, pp. 67-82, 2025

[18] J. Cheng, S. Bi, and C. Yuan, "Dynamic Parameters Identification Method of 6-DOF Industrial Robot Based on Quaternion," *Mathematics*, vol. 10, no. 9, May 2022. Available: https://doi.org/10.3390/math10091513

[19] T. Zhang, K. Lin, and A. Zhang, "Research on flexible dynamics of a 6-DOF industrial robot and residual vibration control with a pre-adaptive input shaper," *Journal of Mechanical Science and Technology*, vol. 33, no. 4, pp. 1875–1889, Apr. 2019. Available: https://doi.org/10.1007/s12206-019-0340-z

[20] Kuka AG, "Datasheet Robot Kuka KR120 R2700," 2024, Accessed: Dec. 29, 2024. [Online]. Available: https://www.kuka.com/en-us/products/robotics-systems/industrial-robots/kr-quantec

[21] J. Musiał, T. Kałaczyński, R. Polasik, M. Szczutkowski, and M. Łukasiewicz, "Milling Efficiency Aspects During Machining Of 7075 Aluminium Alloy with Reference To The Surface Geometrical Structure," in *Engineering Mechanics 2018*, Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, May 2018, pp. 569–572. Available: https://doi.org/ 10.21495/91-8-569

[22] K. Gao, X. Zhou, R. Wang, M. Fan, and H. Han, "Robotic milling stability optimization based on robot functional redundancy," *Industrial Robot*, vol. 50, no. 6, pp. 1036–1047, Nov. 2023. Available: https://doi.org/ 10.1108/IR-06-2023-0130

[23] W. N. S. E. Wan Jusoh, M. I. Yahaya, S. Zakaria, M. H. Mahamd Basri, M. R. Daud, and N. I. Ismail, "New approach to minimise surface roughness in Polytetrafluoroethylene (PTFE) through robotic spindle speed control," *ESTEEM Academic Journal*, vol. 21, no. March, pp. 106–118, Mar. 2025. Available: https://doi.org/10.24191/esteem.v21iMarch.4359.g3122

[24] Kriswanto, W. Sumbodo, W. Aryadi, and J. Jamari, "Optimization of milling parameters to increase surface quality and machining time of the bohler m303 extra," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Mar. 2021. Available: https://doi.org/10.1088/1755-1315/700/1/012009

[25] N. Villarrazo, Á. Sáinz de la Maza, S. Caneda, L. Bai, O. Pereira, and L. N. López de Lacalle, "Effect of tool orientation on surface roughness and dimensional accuracy in ball end milling of thin-walled blades," *International Journal of Advanced Manufacturing Technology*, Jan. 2024. Available: https://doi.org/10.1007/s00170-024-14523-6

[26] H. R. Morano-Okuno, R. Caltenco-Castillo, and G. Sandoval-Benitez, "Flexible Manufacturing Systems: CAD Programs to Simulate the Movements of Industrial Robots," in *4th International Conference on Electrical, Communication and Computer Engineering, ICECCE 2023*, Institute of Electrical and Electronics Engineers Inc., 2023. Available: https://doi.org/10.1109/ICECCE61019.2023.10442058

[27] P. Shi, X. Tong, H. Qu, and M. Cai, "Rapid generation of contour parallel toolpaths for 2.5D closed cavity based on accurate discrete medial axis transform," *Precis Eng*, vol. 92, pp. 231–252, Mar. 2025. Available: https://doi.org/10.1016/j.precisioneng.2024.11.014

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

[28] A. Jacso, G. Matyasi, and T. Szalay, “The fast constant engagement offsetting method for generating milling tool paths,” *International Journal of Advanced Manufacturing Technology*, vol. 103, no. 9–12, pp. 4293–4305, Aug. 2019. Available: https://doi.org/10.1007/s00170-019-03834-8

[29] MN Talibin, Z Bakar, and S Abdul Halim, “Simulation of Toolpaths Using 3D Method Strategies for Complex Shape in Milling Application,” *International Journal of Advanced Research in Technology and Innovation*, Oct. 2022. Available: https://doi.org/10.55057/ijarti.2022.4.3.5

[30] A. Tzotzis, C. García-Hernández, J. L. Huertas-Talón, and P. Kyratsis, “Cad-based automated design of fea-ready cutting tools,” *Journal of Manufacturing and Materials Processing*, vol. 4, no. 4, Dec. 2020. Available: https://doi.org/10.3390/jmmp4040104

[31] L. Ye, “Design and manufacturing of mechanical parts based on CAD and CAM technology,” *Engineering Research Express*, vol. 6, no. 4, Dec. 2024. Available: https://doi.org/10.1088/2631-8695/ad8056

[32] J. Li, L. Lu, S. Wang, S. Dai, L. Sun, and Z. Wang, “Axis Path Planning of Five-axis Surface Machining by optimizing Differential Vector of the axis movement considering tool posture limits,” May 30, 2023. Available: https://doi.org/10.21203/rs.3.rs-2955980/v1

[33] Z. J. Qiao, J. Liu, S. Q. Yang, J. J. Zhang, and J. Z. Li, “Robot-assisted Blade Polishing and Process Control Based on SprutCam Offline Programming Software,” in *Proceedings of the 33rd Chinese Control and Decision Conference, CCDC 2021*, Institute of Electrical and Electronics Engineers Inc., 2021, pp. 345–349. Available: https://doi.org/10.1109/CCDC52312.2021.9602088

[34] O. F. Sapmaz and L. T. Tunc, “Tool Axis Optimization for Robotic 5-axis Milling Considering Kinematics,” 2018

[35] I. Iglesias, M. A. Sebastián, and J. E. Ares, “Overview of the State of Robotic Machining: Current Situation and Future Potential,” in *Procedia Engineering*, Elsevier Ltd, pp. 911–917, 2015. Available: https://doi.org/ 10.1016/j.proeng.2015.12.577

[36] J. Brüning, B. Denkena, M. A. Dittrich, and H.-S. Park, “Simulation Based Planning of Machining Processes with Industrial Robots,” *Procedia Manuf*, vol. 6, pp. 17–24, 2016. Available: https://doi.org/ 10.1016/j.promfg.2016.11.003

[37] Y. Gao *et al.*, “Optimizing the performance of serial robots for milling tasks: A review,” Aug. 01, 2025, *Elsevier Ltd*. Available: https://doi.org/10.1016/j.rcim.2025.102977

[38] R. T. Coelho, H. H. T. Rodella, V. F. Martins, and R. Barba, “An Investigation into the Use of Industrial Robots for Machining Soft and Low Density Materials with HSM Technique.” *J. of the Braz. Soc. of Mech. Sci. & Eng*, no. 3, pp. 343-350

[39] R. B. Mundim and A. V. Borille, “An approach for reducing undesired vibrations in milling of low rigidity structures,” *International Journal of Advanced Manufacturing Technology*, vol. 88, no. 1–4, pp. 971–983, Jan. 2017. Available: https://doi.org/10.1007/s00170-016-8804-0

[40] J. Niu, J. Xu, F. Ren, Y. Sun, and D. Guo, “A short review on milling dynamics in low-stiffness cutting conditions: Modeling and analysis,” *Journal of Advanced Manufacturing Science and Technology*, vol. 1, no. 1, 2021. Available: https://doi.org/10.51393/j.jamst.2020004

[41] V. F. C. Sousa *et al.*, “Cutting forces assessment in cnc machining processes: A criticalreview review,” *Sensors (Switzerland)*, vol. 20, no. 16, pp. 1–26, Aug. 2020. Available: https://doi.org/10.3390/s20164536

[42] Hollie Kirwan and Rose Pignataro, “Chapter 2 - The Skin and Wound Healing,” in *Pathology and Intervention in Musculoskeletal Rehabilitation (Second Edition)*, 2016, pp. 25–62

[43] M. Lin and L. Xu, “Scorecard Model-Based Motion Stability Evaluation of Manipulators for Robot Training,” *Applied Sciences (Switzerland)*, vol. 12, no. 14, Jul. 2022. Available: https://doi.org/ 10.3390/app12147100

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961

https://doi.org/10.24191/esteem.v21iSeptember.6483.g4961