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Development of Tool Orientation Strategy with Alternative Orientation and Non-machinable Area Identification in 5-Axis Peripheral Milling of a Sculptured Surface based on a Faceted Models

Eko Arif Syaefudin[1], Gandjar Kiswanto[1*], Ario Sunar Baskoro[1]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*

Abstract. The peripheral milling strategy of using a cylinder cutter is an effective strategy commonly used on planar or ruled surfaces because of its high material removal rate (MRR). However, using a peripheral milling strategy on a sculptured surface presents many difficulties in adjusting the tool orientation during the machining process. Due to the complexity of a sculptured surface, with its various normal vector directions, there is an increase in possible interference, reducing the effectiveness of peripheral milling if the tool orientation is not properly adjusted. In order to understand the peripheral milling process on a sculptured surface, which is difficult to do on a CAD surface (mathematical surface), this research developed a peripheral milling method for sculptured surfaces based on faceted models. To further enhance the effectiveness of the peripheral milling process, machining areas where it is difficult or impossible to apply peripheral milling are identified. In addition, an alternative tool orientation is determined with a reverse tool orientation if the initial tool orientation causes interference. Overall, in this research, the development of peripheral machining strategies goes from the generation of a tool path to an initial tool orientation, an alternative tool orientation, gouging detection, and the identification of non-machinable areas. Then, the strategy results of the process are simulated in 3D and the percentage of the applicable machining area is determined. The simulation indicates that the strategy of choosing an initial and alternative orientation of tools and then identifying non-machinable areas has been successfully developed for the five-axis peripheral milling of sculptured surfaces based on faceted models. This developed method successfully identified areas capable of being milled and maximized machining areas up to 80%. Thus, this strategy is highly applicable to the development of further peripheral milling strategies.

Keywords: 5-axis peripheral milling; Faceted models; Tool orientation

1. Introduction

The 5-axis machining method is very useful in various aspects of manufactured products, including industrial equipment components, automotive components, and aircraft industrial components. These products require high levels of precision. Even special operational strategies on CNC or another 5-axis machining can provide energy savings (Peng and Xu, 2014). The process of using a peripheral milling strategy is more effective than end milling for planar surfaces. However, it will encounter many obstacles

*Corresponding author's email: gandjar_kiswanto@eng.ui.ac.id, Tel.: +62 817-815658
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on the sculptured surface. Many manufactured products contain sculptured surfaces with high curvature, which are generally produced using an end milling machining process. The end milling process requires a longer tool path than the peripherals for general surface milling processes. This process applies to both the initial machining process and the final machining process.

Consequently, the total duration of the machining process is also long. One solution to increase efficiency is to replace the end milling method with peripheral milling. This method is advantageous in terms of material removal rate and can reach areas that end milling cannot access, for example, turbine blades (Senatore et al., 2012). On the other hand, the complexity and cost of machining are important variables that affect the final cost of the product (Budiono et al., 2014), and capability in production or operations significantly influences all aspects of the manufacturing strategy (Nurcahyo et al., 2019). The complexity and the machining strategy greatly impact the production cost and manufacturing strategy, so the effectiveness of the capacity of a 5-axis milling strategy needs to be improved.

In general, peripheral milling machining methods have been developed in various 5-axis milling studies. Most of the solutions are performed using the analytical method with the ruled surface approach, and mostly for completing peripheral milling on the local area of the entire surface, or to analyze a limited area, and rarely apply to the entire surface. Research developed by Gong et al. (2005) exemplifies this. The solution uses an object modeling form with a 3-point square object B-Spline that approaches the ruled surface model of the surface being analyzed. The work is carried out on the ruled surface geometry using analytical solutions, and the envelope surface approach is then interpolated into the tool orientation, tool position, and adjustment of the feed direction rate (Chu et al., 2008). Some researchers also use an approach with tangent surface modeling based on two points as a reference curve to solve the maximum error discretization of the cutter for accuracy in linear modeling; the modeling approach used refers to the surface being analyzed (Senatore et al., 2012). A further example in research developed by Wang and Elber (2014), uses boundary curves, which solves the problem on the Ruled Surface Fitting (RFS) by limiting the area of analysis coverage and forming an isoperimetric boundary sample curve along the normal surface curve, then evaluated along the normal surface between the two curves using multi-dimensional programming. Several research studies have also been developed by Xie et al. (2015), who proposed modifying CNC parameters using a surface approach with a defined model to improve the effectiveness of the work surface work surface in the local area. And to be uniform, the entire surface points require accuracy and further development of the model approach. Chu and Kuo (2016) also developed a strategy of forming a peripheral tool trajectory pattern using a trajectory template, then compared the formed surface template to the surface on the workpiece using the meta-heuristic algorithm method. Previously, a more detailed observation regarding the prediction of peripheral milling development summarized by Harik et al. (2013) concluded that most peripheral milling is still based on ruled surfaces, and peripheral milling machining has not been largely developed for complex surfaces. Based on the summary above, the peripheral milling machining, when used on a surface with high complexity (sculptured surface), will find a lot of interferences. These become typical problems that need to be resolved, and most of the work is done in the local area. Therefore, the method in this study has been developed by analyzing peripheral milling for the entire surface.

Although the tool periphery's use provides a maximum removal rate, avoiding gouging requires a special strategy. In this study, a peripheral milling method was developed on sculptured surfaces based on the faceted models. This is because the faceted model has many advantages compared to the parametric model, including: (1) it is simpler to represent the model; (2) it is easier to detect and avoid gouging/interference; (3) the topology of the milling process can be adjusted for complex surfaces; and (4) collision checking between tool and surface can be done easily (Kiswanto et al., 2006). The development of the peripheral milling method in this study begins with determining the tool trajectory's cc-point and direction (Syaefudin et al., 2017). According to Kiswanto et al. (2006), each cc-point in the faceted plane will always have normal vector information so that it can be used to determine the feed direction and the initial tool orientation. If the tool's initial orientation at a cc-point causes interference, then a special strategy is required that will be described in this paper. To increase the machining process's effectiveness, sculptured surfaces that can be worked with peripheral milling are divided into groups of machinable areas, while sculptured surfaces that cannot be worked are grouped into non-machinable areas.

2. Development of the Peripheral Milling Method

In this research, the development of peripheral milling machining strategies and the detection of non-machinable peripheral milling areas was carried out in the following steps:

1. Determine cc-points on the surface, determining the nominal vector at each cc-point, the feed direction, and the initial tool orientation at each cc-point.
2. Specify the initial peripheral tool orientation and tool path.
3. Detect interference at each tool path based on the initial orientation of the tool and the alternative orientation. Then, avoidance of interference is carried out with an inclination (α) to a maximum limit of 10^{o}.
4. Group the feed direction based on the orientation of the tool and classify the machinable and non-machinable peripheral milling areas.

To test the method's simulation, three test models with different complexity (different combinations of convex, concave, and saddle) that represent the sculptured surfaces are developed. Facet data in 3 dimensions from the test models were created using CAD software. Each of these models is shown in Figures 1a, 1b, 1c below.

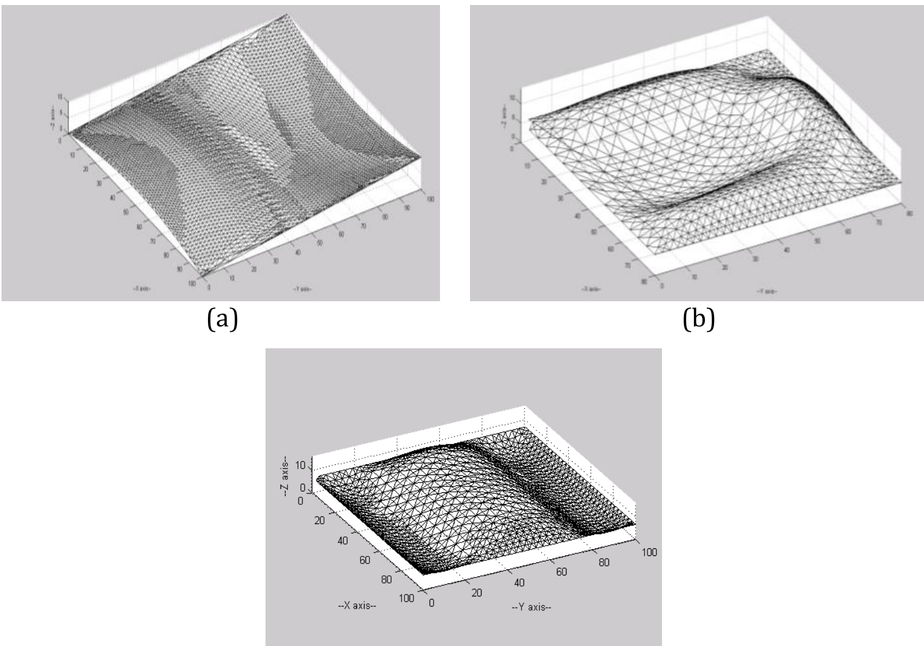


Figure 1 (a) Surface test models; (b) Surface test models 2; and (c) Surface test models 3

The overall flow of the method developed is shown in the diagram below in Figure 2.

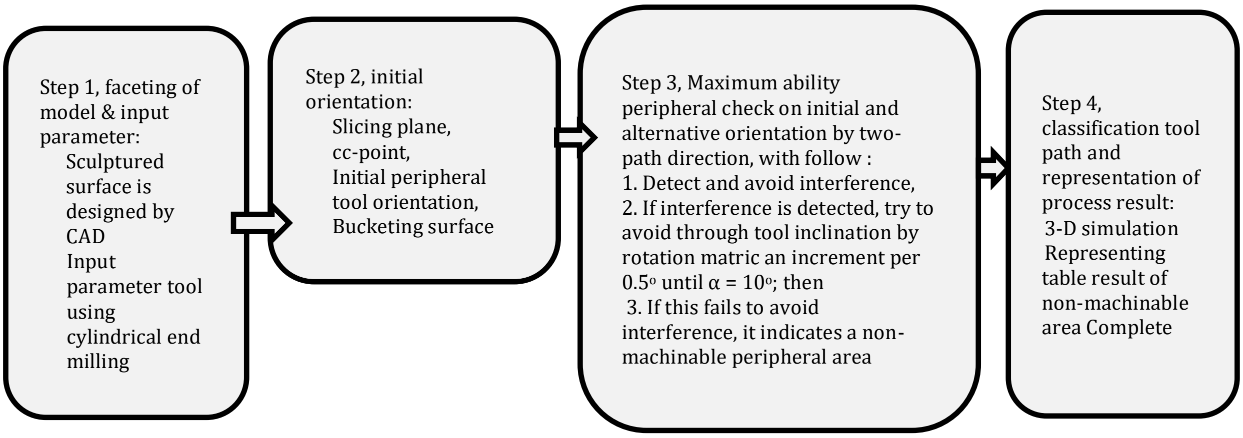


Figure 2 The method of developing peripheral milling

Each test surface model used contains the following data: (1) the coordinates of the triangle vertices; (2) the group of vertex coordinates in 3D space, i.e. the coordinates of the Cartesian system; (3) the normal vector of each triangle (Kiswanto et al., 2006; Lee et al., 2002). Furthermore, the development of peripheral milling machining strategies using 2-way tool orientations and surface identification of machinable and non-machinable area by peripheral milling is described in more detail as follows:

2.1. Determine the cc-point on the Surface, Normal Vector cc-point, and the Tool Path.

To get cc-points on the surface, use the slicing plane method on the surface. The slicing plane is an imaginary auxiliary plane that cuts the facet surface model, then produces the slicing line. The intersection between the facet and the slicing line produces a point and its normal vector, and then it will be reference for cc-point and a normal vector of the cc-point. (Kiswanto et al., 2010; Kiswanto et al., 2006), as shown in Figure 3. The distance between the slicing planes is determined based on the effective tool length of the peripheral milling.

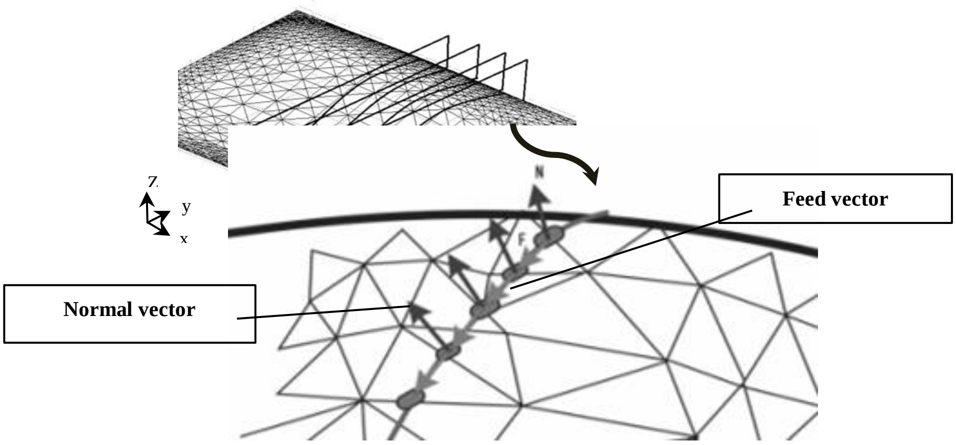


Figure 3 Determining the normal vector and the feed direction vector (Kiswanto et al., 2006)

To simplify the analysis process, the data is indexed using the bucketization method as shown in Figure 4 and termed as bucket index. Furthermore, the slicing line is used as a reference for the feed direction of the tool.

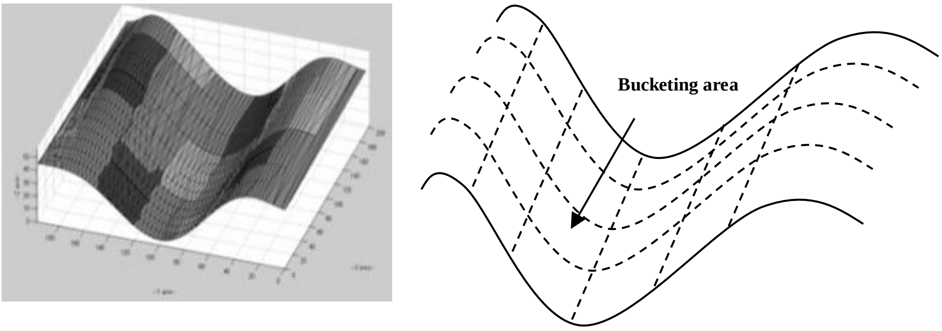


Figure 4 The process of data bucketing for triangle vertex

Data grouping so that it can be read at any time and easy analysis is needed to increase facet data processing effectiveness. The need for data processing effectiveness by grouping data to support the database management process and to increase the effectiveness of manufacturing activities was also carried out by several researchers, for example, in management data production including manufacturing process and material parameter of Tote Box (Baskoro et al., 2015). And here, the way facet data management of surface is carried out in this study by grouping in the form of a bucket index where including coordinate value and the normal vector of facet triangle. View of the method is adopted from previous research to collect facet data on the surface using the bucketing method (Kiswanto et al., 2010). The bucket method increases efficiency, and homogeneous data analysis becomes more efficient so that the characteristics of significant data properties in large data sets can be carried out faster. After the data is collected in a bucket it is then mapped, so that if there is a significant difference in structure the data can be immediately classified and can be used for further processing.

2.2. Specifies the Initial Peripheral Tool Orientation and the Tool Path.

The local coordinate system and initial tool orientation are obtained using the right-hand rule where the Tool vector (T) is a cross product between the feed direction vector (F) and the normal vector (N) of a cc-point. Each cc-point has a Tool vector (T) used as the tool's initial orientation. For further analysis in the peripheral milling machining strategy, the tool vector is always oriented perpendicular to the feed direction vector, as shown in Figure 5 below.

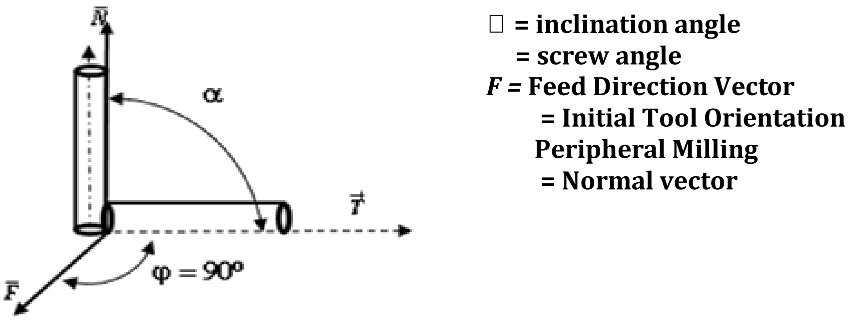


Figure 5 Determining the tool orientation for the Peripheral milling (Syaefudin et al., 2017)

Then, construct the tool path based on the indexed data and the feed direction that has been made between the points, as shown in Figure 6.

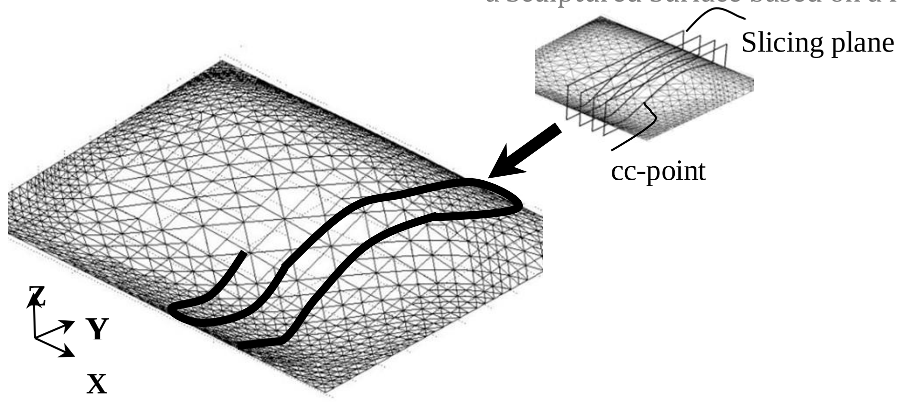
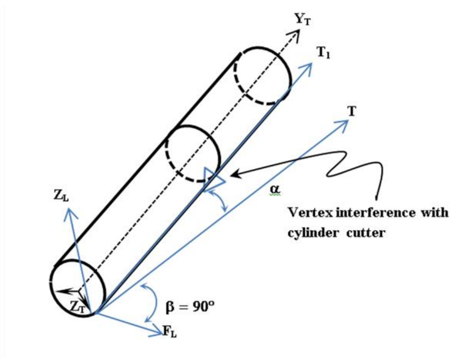


Figure 6 Creating a tool path on the surface (Kiswanto et al., 2006)

2.3. Detect Interference on Each Tool Path and Find an Alternative Tool Orientation on the cc-point when the Interference Occurs

Interference detection is carried out using the method developed in previous studies to see whether each tool orientation interferes with the surface (Kiswanto, 2005). To avoid interference that does occur, the tool inclination angle is adjusted to the maximum limit of 10° until interference-free conditions are obtained. Then an initial identification of the surface is made to determine whether it is planar or sculptured by looking at the number and density of the triangle facet formed in each bucket index, and analysis of the cc-point's normal vector along the tool path. When the tool path passes through an index bucket and there are more than 2 triangular facets in it with different normal vector directions, this indicates a non-planar (sculptured) surface. Furthermore, interference detection between the tool and the triangle facet occurs when the facet's vertex is inside the tool, as illustrated in Figure 7.



where:
FL : Feed Direction Vector LCS
α : Inclination angle
TL : Tool Vector LCS
NL : Normal Vector LCS
YT : Center of Tool
T : Vector Tool

Figure 7 The vertex inside the tool and the tool inclination system orientation (Kiswanto et al., 2006)

To easily check the interference between the tool and a vertex of a facet, the tool coordinate system (*TCS;* X_T, Y_T, Z_T) is formed. The Z_T-axis is initially defined from the tool center to the cc-point, and the Y_T-axis is the tool axis. Then, the X_T-axis is the result of multiplication between Y_T and Z_T, where the vector product ($X_T = Y_T \times Z_T$) is based on the right-hand rule. By assuming a vertex on the Local Coordinate System, LCS is represented by $V_{L,i} = (F_{L,i}, T_{L,i}, n_{L,i})$. The transformation of LCS coordinates to TCS ($V_{T,i} = (X_{T,i}, Y_{T,i}, Z_{T,i})$) can be done as follows:

$$\left[x_{T,i}\, y_{T,i}\, z_{T,i}\right] = Trans\left[-f_{L,i}cos\beta - t_{L,i}sin\beta\, -f_{L,i}cos\alpha.sin\beta + t_{L,i}\,cos\alpha.cos\beta + n_{L,i}sin\alpha\, - f_{L,i}sin\alpha.sin\beta + t_{L,i}sin\alpha.cos\beta - n_{L,i}cos\beta + R\right] \quad (1)$$

The interference mode is identified when each vertex value within the boundary satisfies the condition $y_{T,i} \geq 0$ and $\left(x_{T,i}^2 + y_{T,i}^2\right) \leq R^2$. Then, interference occurs, as shown in Figure 7. If the interference condition is met, then it is marked and entered into the database.

To avoid interference, a numerical method with fixed angle interpolation is used. Regarding the cc-point, rotation with an angle of change of (α) has the basic function of: *x1 = x cos α – y sin α* and *y1= x sin α + y cos α*. Therefore, for the rotation matrix, the following formula is used:

$$[x1\; y1\; 1\,]=[cos\; cos\,\alpha \quad -sin\,\alpha \quad 0\;\; sin\,\alpha \qquad cos\,\alpha \quad 0\;0 \qquad 0 \qquad 1\,][x\; y\; 1\,] \quad (2)$$

Starting from the initial position of the tool orientation, with the cc-point as the direction rotation axis (i, j, k) = α^{0}, while for (i^1, j^1, k^1) = (I, j, k) + increment α and by increment α every step of 0.5 degree is carried out until the angle increment has a maximum α of 100 and free interference. To speed up the scanning process, the analysis is limited to the area of possible interference by taking all vertices in the area of 2R along T as the extent of the tool projection on the surface, and the value is stored in the database of projection tools to be calculated by the LCS transformation (Kiswanto et al., 2006). This method is illustrated in Figure 8.

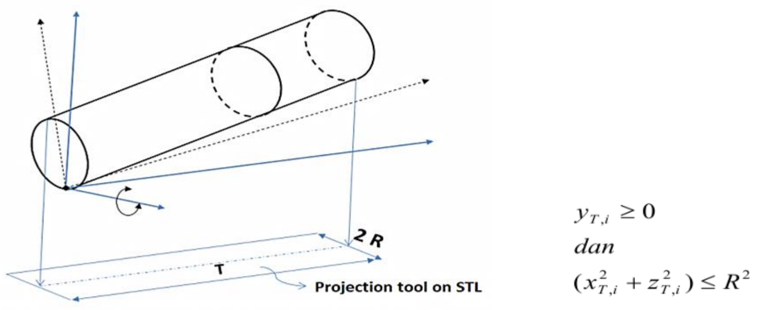


Figure 8 Projection tool

To examine the possibility of doing peripheral milling strategy around the cc-point, an interference analysis is carried out in the reverse direction or reverse tool orientation as an alternative tool orientation, as shown in Figures 9a and 9b. The effectiveness of tool peripheral orientation is shown in Figure 9c.

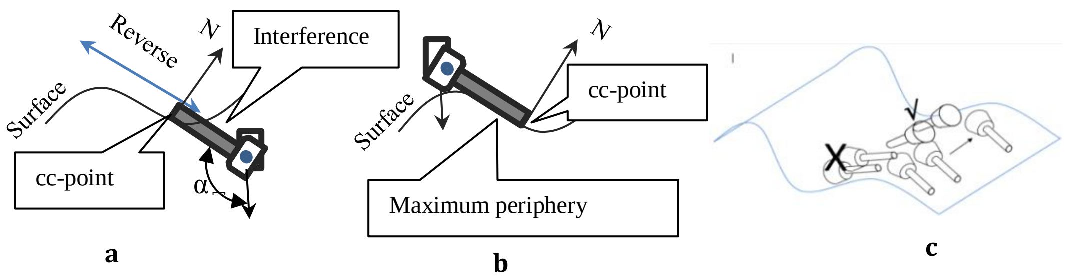


Figure 9 (a) Orient the initial tool with a large inclination angle; (b) Avoid interference with reverse orientation; (c) Illustration of maximum peripheral tool orientation in 3 dimensions

Reverse orientation is done based on the reference value of k on the ijk tool vector from each cc-point, whether negative or positive. Suppose the *k* value of the unit vector *ijk* on the tool vector (T (i, j, k)) is positive. In that case, the initial tool orientation will be used, and the necessary inclination angle adjustment will be carried out. This simulation is illustrated in Figure 10. When the value of *k* is negative, then the reverse tool orientation will be carried out on that cc-point, as shown in Figure 11.

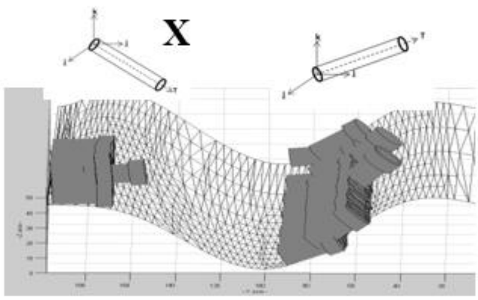


Figure 10 The orientation tool vector used is based on ($T_{(i,j,k)}$) as a tool orientation on the surface

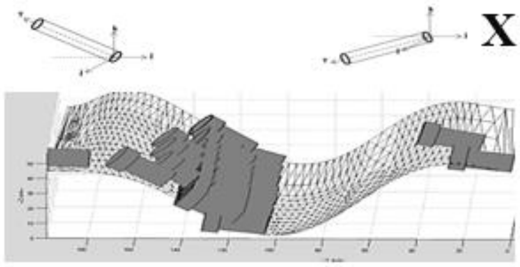


Figure 11 The reverse tool orientation vector used is based on ($T_{(i,j,k)}$) as a tool orientation on the surface

2.4. Grouping the Feed Direction based on Tool Orientation and Classifying the Machinable and Non-machinable Peripheral Milling Areas

During the analysis process of the entire surface, the resulting tool orientation varies to cause large orientation dynamics during the milling process. To avoid this, the tool orientation and feed direction are grouped as shown in Figure 12.

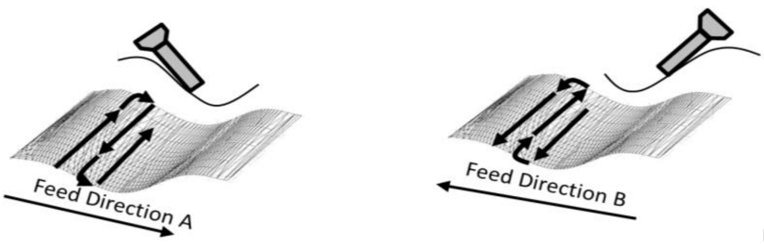


Figure 12 Grouping the feed direction based on the tool orientation

The final process of the strategy developed in this study results in peripheral milling as a whole on the sculptured surface. The methods described (interference detection, bucketization, maximal peripherals milling area) can be classified according to machinable and non-machinable peripheral milling areas. An example of areas that prohibit peripheral milling can be seen in Figure 13.

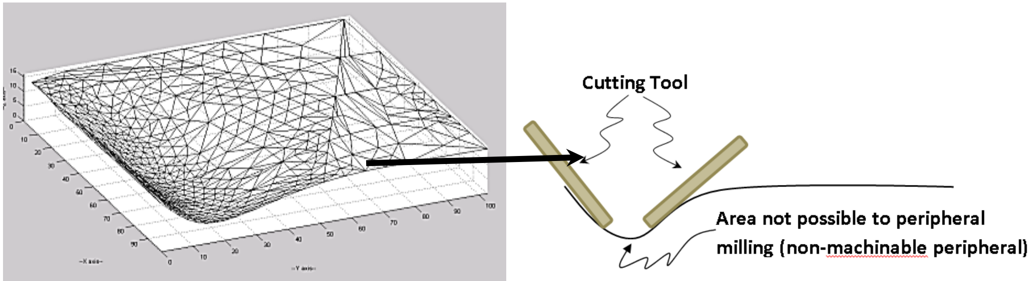


Figure 13 The area that cannot be peripherally milled (non-machinable)

3. Results and Discussion

Regarding implementation, the peripheral milling development strategy that has been made is applied to a programming algorithm and simulated in 3D. Figure 14 shows the implementation of step 1 of method strategy development, namely determining cc-points, normal vectors and tool trajectory by utilizing the slicing plane on the surface. The purpose of step 2, which is to specify the initial peripheral milling tool orientation and form a 3D simulation of the tool motion on the entire surface (for example, using model 1), is shown in Figure 15. In step 3, interface detection is simulated (see Figures 16 and 17), and step 4 classifies the initial and alternative tool orientations (see Figures 18 and 19). After identifying interference and avoidance, feed directions are grouped according to the peripheral tool orientation, as illustrated in Figure 20. The simulation of the final machining result in the test model is shown in Figure 21, illustrating the non-machinable and machinable areas for peripheral milling.

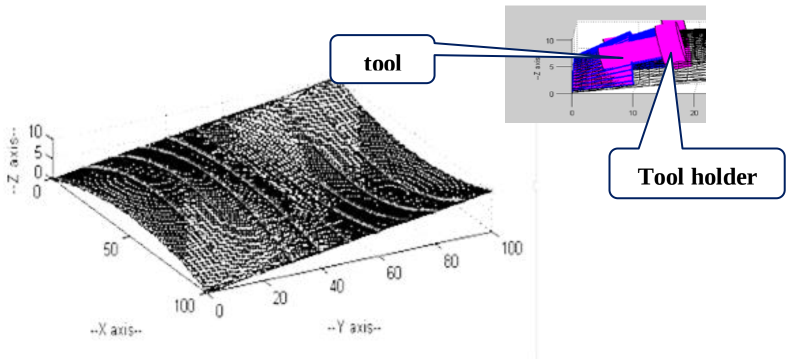


Figure 14 Initial cc-point using the slicing plane

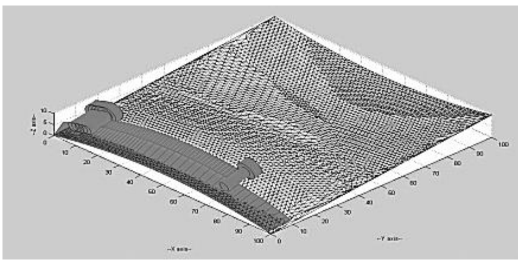


Figure 15 Process simulation on the surface of model-1

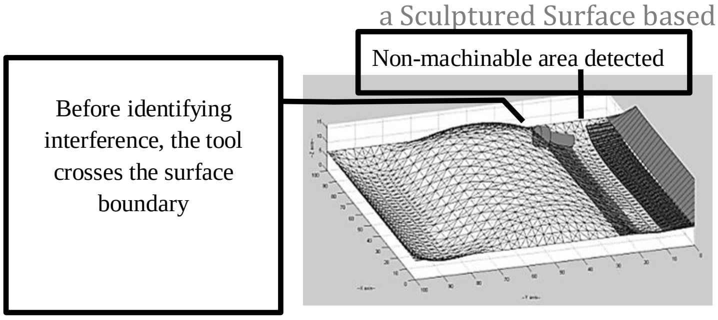


Figure 16 Milling the whole surface with identification and avoiding collision on model-3 as sample

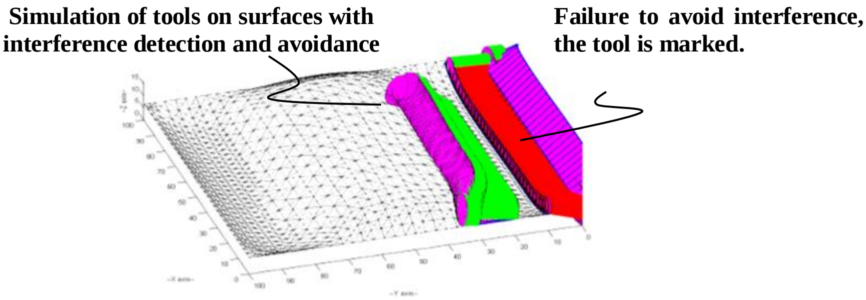


Figure 17 Orientation after interference detection and avoidance

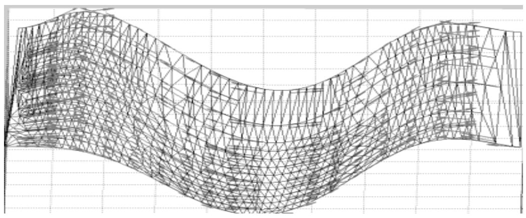


Figure 18 Implementation of initial orientation vectors and alternative peripherals to the convex surface

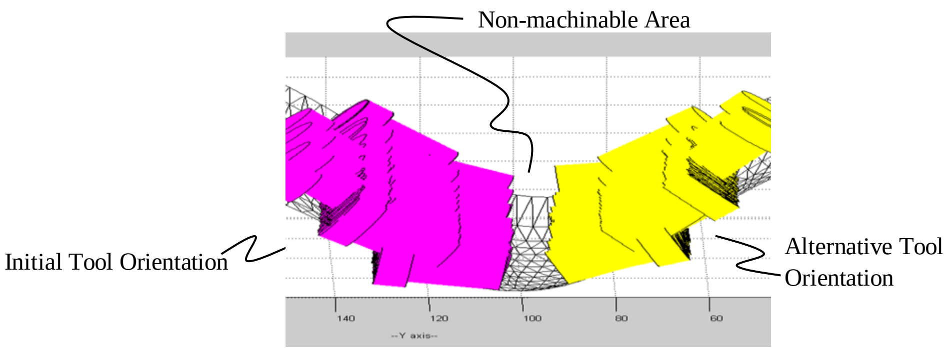


Figure 19 3D simulation of the tool orientation for the peripheral milling process

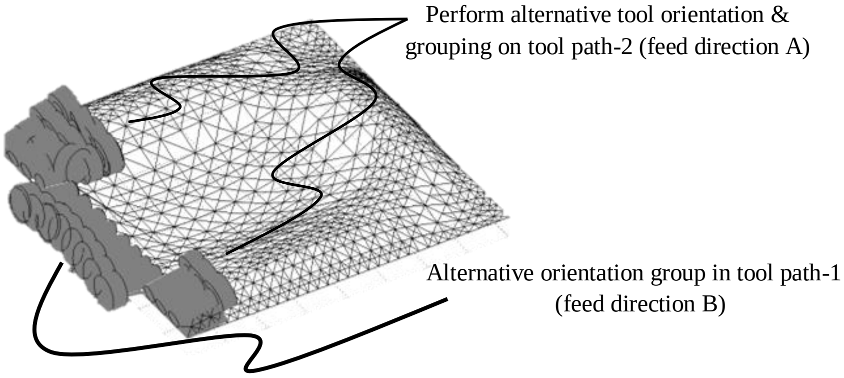


Figure 20 Results of the peripheral simulation algorithm's implementation on model-2 surface

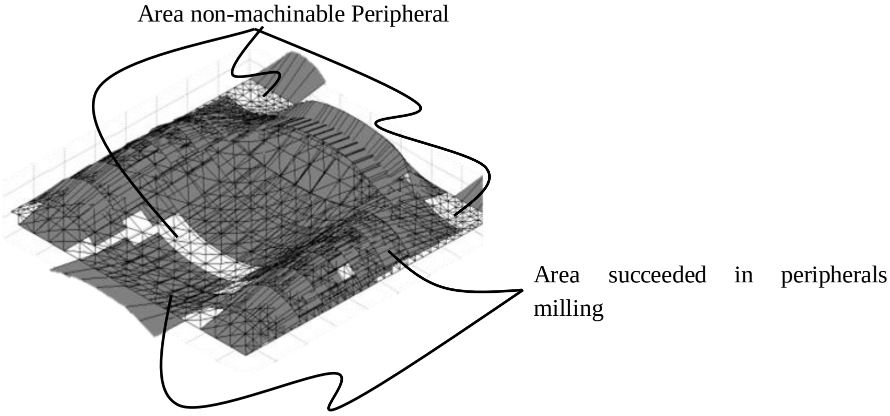


Figure 21 Marking the peripheral milling area in model-2; the white area is a non-machinable peripheral area

After simulating the three test models, the final results of the areas that can and cannot be machined by peripheral milling are included below in Table 1.

Table 1 The results of three simulated models that identify the percentage of machinable and non-machinable areas by peripheral milling

No. Model	Total cc-point on surface	Total cc-point failure	Non-machinable area (%)	Machinable area (%)
1	1567	180	11.49	88.51
2	664	107	16.10	83.90
3	896	124	13.77	86.23

4. Conclusions

This paper has presented the development of a peripheral milling strategy to cover all sculptured surfaces. This method starts from tool orientation, then gouging detection, then a strategy to reverse the orientation tool as an alternative to maximizing peripheral milling oriented tools and finally detecting non-machinable peripheral areas. The machining strategies developed in this research were tested on 3 simulated models using the same machining parameters and were displayed in a 3D simulation. The maximum peripheral milling area that can be worked out of the total surface is indicated by the percentage.

The results of this simulation show that the algorithm is successful and operating well as the first step in developing the peripheral milling strategy for sculptured surfaces. The identification of the non-machinable area can determine the total peripheral milling area.

Based on this study's results, further research in this area could potentially develop a strategy as a solution to milling the area of non-machinable peripheral, for example is by an end milling strategy.

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