Direct NC Toolpath Generation from 3D Point Cloud Datasets

Muslimin[1]*, Katerina Mukti[1], Hasvienda M. Ridlwan[1], M. Sholeh[1], Ade Sumpena[1], Jiang Zhu[2],
Hayato Yoshioka[2], Tomohisa Tanaka[3]
[1]*Department of Mechanical Engineering, Politeknik Negeri Jakarta, Jl. Prof. Siwabewssy Kampus UI, Depok, Indonesia*
[2]*Department of Mechanical Engineering, School of Engineering, Tokyo Institute of Technology*
I1-35, 2-12-1, O-okayama, Meguro, Tokyo 152-8552, Japan
[3]*Laboratory for Future Interdisciplinary Research of Science and Technology (FIRST), Institute of Innovative Research (IIR), Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8550, Japan*

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Abstract: In reverse engineering, the measurement of the object's surface is carried out by 3D scanning producing 3D point cloud data. Scanning performed from various positions will have different data, which will then be registered to form a product topography. The next process is to reconstruct 3D CAD, which is then converted into working drawings, used for manufacturing processes such as CNC machining by generating G-Code. The crucial stage was the 3D CAD reconstruction of the point cloud dataset, which required a complicated triangulation process and long computation time. In this research, 3D point cloud data is used directly to generate tool paths for CNC machining without 3D CAD reconstruction. The goal is to shorten the reverse engineering time with a quality that can still meet the requirements. The stage is to model the tool path of the tools used in CNC machining relative to feature point cloud sets. This toolpath will be used as the basis for creating G-code. The toolpath makes it possible to degenerate directly from the verified 3D point cloud registration data based on the modeling results.

1 INTRODUCTION

In reverse engineering, the measurement of an object's surface is carried out using a 3D laser scan, which produces 3D point cloud data sets. Scanning from various positions will have different data, which will then be registered to form a product topography. The next stage is the CAD reconstruction of the data points (Muslimin et al., 2015). CAD surfaces created are usually in the form of a parametric computer representation, such as B-helical, Bezier, non-uniform rational surfaces, and so on. However, 3D CAD reconstruction is complicated, time-consuming, and requires operator expertise since accuracy is the primary reverse engineering goal. Today's laser scanners are equipped with 3D CAD reconstruction software, but they are not compatible enough to handle data noise, edge sharpness, holes, and so on (Sun et al., 2002)(Muslimin et al., 2015). On the other hand, the manufacturing process directly from the point cloud data set without prior CAD reconstruction is possibly implemented (Chui et al., 2002)(Makki et al., 2011)(Liu et al., 2013).

Many manufacturing processes can apply to realize product duplication directly from the point cloud data set. The method includes additives using a 3D printer, CNC machines to duplicate molds and moldings for molded products, forging products, and permanent mold casting products, and so on. In the additive manufacturing process using a 3D printer, the point cloud dataset at x, y, z coordinates are converted into STL format and can then be directly processed by a 3D printer. In the CNC machining

An application by developing numerical control (NC) pathways directly from a point cloud dataset is proposed in this work. The tool path is restricted by part material, cutter tools, cutting speeds, and work features. The NC-tool way directly from the point cloud data has been developed since the popular 3D scanner used in the reverse technique (Chui et al., 2002)(Yau & Hsu, 2009)(D. Zhang, 2009). However, its effectiveness still needs further development. This method includes NC tool line generators for 3-axis milling (Zhang et al., 2010) and 5-axis milling (Marie et al., 2004).

The tool path planning issues were how to make more accurate machining and smoother, efficient NC-

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tool paths to speed up the process and complete the complex reconstruction process. This research's main contribution is to propose an innovative method for NC (numerical control) tool path generation directly from a registered point cloud data set. The final goal is to make a point cloud data conversion system into G-code CNC machines in the reverse engineering process.

2 LITERATUR REVIEW

Two critical objectives of the NC-tool path are machining effectivity and accuracy. Machining effectiveness deals with tool motions, consisting of two methods: forward and sidestep. The forward step is for the line portion connecting adjacent CC (cutter contact) circumstances, and the highest permissible chordal variation is called machining tolerance. The machining accuracy deals with the geometry and tolerance of the machining process's final result compared to the specified target. Also, it deals with surface finishing.

There are two approaches to converting the point cloud dataset into NC toolpath, the direct and indirect methods. The differences between the direct method and indirect method in tool path creation from 3D point cloud data set are as the following (Zhang, 2009):

1) Indirect tool path generation: In this method, surface CAD model reconstruction is generated from the point cloud dataset. Some CAD software such as CATIA, SolidWorks, and IMAGEWARE support surface remodeling from 3D point cloud data sets; however, it still needs interaction from the users to get more precise surface regeneration with advanced experience in facade modeling.
2) Direct tool path generation: This method is used directly from the point cloud dataset without CAD image regeneration. Due to the inadequacy of an underlying surface representation, there are two problems:
    a) It is challenging to obtain adaptive advancing steps and track intervals, driving to lower machining performance because without a continuous surface.
    b) It is laborious to restrain the machining exactitude when the input is complex geometry and noisy.

3 DIRECT NC TOOL PATH GENERATION

In industry, 3-axis CNC machines are employed for both the coarse and finish machining process. Regularly, 3-axis machining techniques for complex surfaces use a ball end mill cutter. The ball end mills is a zero cutting speed at the bottom of the ball. This issue can be overcome by using other cutter geometries such as flat end mills or multi-axis tool paths such as four axes or five axes CNC machines.

In this research, NC-milling is used because the object is the prismatic shape. A three-axis tool path is adopted for computation. The main steps of the generation of an efficient NC tool path directly from point cloud datasets registration proposed in this research are as follows:

1) Orient the point cloud data with a machined surface into the z-axis and consider the cutting tool's direction. It is crucial to start the planning of the tool path from (0,0,0).
2) Classify all main machined surfaces into complex features and non-complex features. Complex surfaces include free-form surfaces, curves, and ruled surfaces.
3) Select the machining method, tool type, and tool diameter and shape.
4) Establish a cutting step. Assume all process consists of three stages of machining processes: rough machining, semi-finishing, and finishing.
    a) Rough machining: using 10 mm diameter of a flat end mill cutting tool.
    b) Semi-finishing: employing 5 mm diameter of a ball end mill.
    c) Finishing: Using 3 mm diameter of a ball end mill.

    Rough machining (flat-end mill)
    a) Establish cutting range and the distance between the cutting process using flat-end mill parameters.
    b) Establish space (allowance) for cutting.
    c) Consider the forward steps and backward steps of tools regarding point cloud conditions. The grid method is applied to evaluate the forward and backward steps of tools so that there is no over-cut.

    Semi-finishing cutting and Finish Cutting using a ball-end mill.
    a) Select the diameter of the cutter.
    b) Establish cutting range and the distance between the cutting process by using ball-end mill parameters.
    c) Establish space (allowance) for cutting.

d) Consider the forward steps and backward steps of tools regarding point cloud conditions. The grid method is used to evaluate the forward and backward steps of tools to no over-cutting.
e) Consider interpolation.

3.1 Method of Machining Type and Tools Selection

In the selecting machining method, it can be recognized easily by looking at the object's shape. If the object shape is prismatic, the NC milling process is chosen. On the other hand, if the object shape is cylinder NC turning process is applied. The next step is selecting the tools and parameters of the cutting process. Single-step machining or multi-steps machining can be considered depending on the complexity of an object to be cut.

The selection of a milling cutter, according to the six steps:

1) Define the operation type
2) Define the material of the workpiece.
3) Select the cutter concept
4) Select the milling cutter
5) Select the insert
6) Define the start values

Considering the feature type in the tools selection is very important to ensure the machining process (Lin & Koren, 1996).

3.2 Toolpath Planning Selection

The current tool path generation used has mainly two steps. The first is to specify the cutter contact point, often called cutter cutting (CC), on the part surface, and then the second is to offset that point to yield the cutter location (CL). The cutter cutting is the location where the tool touches the part surface. There exist some tool path generation methods that are popular in the industry. Some of them are discussed in the next sections.

Tool path patterns are commonly applied in NC-path generating: parallel, iso-parametric method, iso-planar method, isophote, constant scallop method, and spiral.

The isoparametric method (Zou & Zhao, 2013) is one of the simplest methods used to create a tool path. In this method, the cutter contact positions are specified along with the isoparametric lines on the part surface. Isoparametric lines are curves of constant parameter value on the parametric body. Linear segments usually approximate the isoparametric track. However, if the linear features are extensive, it may result in undercuts on the model's surfaces, which are already machined in the previous operation.

The other methods commonly used are the Cartesian method, offset surface method, and sidestep method. The offset surface process (Chen & Ravani, 1987) generates the tool path by compensating the part features by the cutter's radius. The center of the cutter tool traces along the offset surface to machine the piece, and the tool path is then calculated by identifying tool passes on the offset surface. However, self-intersections of tool path can occur that leads to over cut or cavities of undercut must be detected or corrected while performing offset surface algorithm.

3.3 Selection and Definition of NC Tools Path Parameters

A mill with a large radius will be efficient in removing a more significant amount of material volume in common. However, if the mill's radius is greater than the concave curvature radius, the tool will interfere and over-cut. Therefore, choosing the proper parameter of the device is very important to make the process more efficient.

The most important thing to select tool diameter is the minimum curvature in workpieces to be processed. The minimum curvature of the product to be cut has to be known. The minimum curvature requirement is more significant than the radius of tools to execute the cutting process. If the minimum curvature is lower than the tool's part's radius, it cannot be cut.

3.3.1 Flat-end Mill Parameters

The flat-end mill is used to remove the maximum material to be cut and result in a shorter path. This cutter is useful in face and shoulder cutting operations. Notations used in defining flat end mill parameters are CL=cutter location in $O(x_0, y_0, z_0)$, vertex point $p(x_p, y_p, z_p)$, and cutter radius R cutting allowance = δ.

The material will be cut if the location of material is within the radius of the cutter (point p is inside CC-region) formulated as bellow:

In this case, it always starts from point $p(0,0,0)$. Parameters are selected as below:

a) Cutting direction, related to the x-direction.
   - For the forward step: $x_A = x_0 + R$ for free boundary and $x_A = x_0 + R + \delta_,$ for the net-shape boundary, where $\delta$is cutting allowance.

- For the backward step: $x_A = x_0 - R$ for free boundary and at the end, $x_A = x_0 - R - \delta$ for net shape boundary.

b) Depth of cut, related to the z-direction
  - For free boundary: $z_A = z_0$.
  - For net shape boundary: $z_A = z_0 - \delta$.
  - Interval z (subdivision surface) is *d* (*d*=depth of cut, depending on the material).

c) Cutting interval related to the y-direction
  - Maximum interval is 2R
  - For free boundary: $y_A = y_0$.
  - For net shape boundary: $y_A = y_0 - \delta$ for a right step and $y_A = y_0 + \delta$ for a left step.

The steps of NC tool path planning are as follows:

1) Define the grid method (see [1][3]) with grid size equal to the size of cutter diameter minus half of the allowance (2R – 0.5* δ). See Fig. 1.

2) Start from CL in x minimum of material $(x_{min} - 0.5 * \delta)$, and y minimum of material $(y_{min} + 0.5 * \delta)$, and z maximum - the depth of cut $(z_{max} - the\ depth\ of\ cut)$(see Fig. 2).

3) Move forward to the next grid and check the condition::

   ✓ If the grid is empty, the point is cutter location

   ✓ If the grid consists of points, check the requirement to move to the other direction, such as move-in z-direction or y-direction (see Fig. 3). Figure 3 shows the CL when the CC is over cut. Therefore, moving the CL so that there is no overcut. Figure 4 depicts the tool path for one completed step. There are some grids with the point cloud so that CL is moving in the up direction. Figure 5 illustrates the tool path for one completed step in x- and y-direction.

4) After finishing one cycle, forward-moving to x+. If x is the maximum tool, it is then moved into y+ and then moved backward to x-. If the tool reaches y foremost tool moves into z-. The process is iterative until rough cutting is finished.

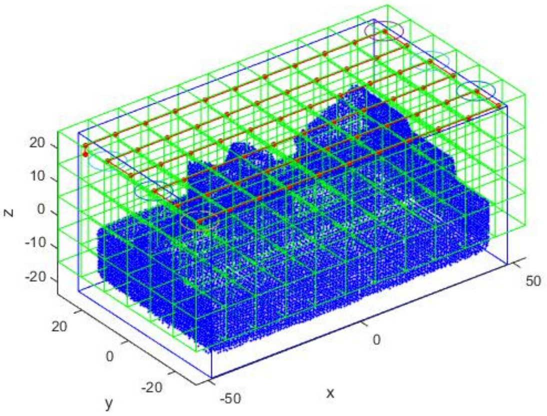


Figure 1 Grid System for Rough Cutting by Using Flat-End Mill

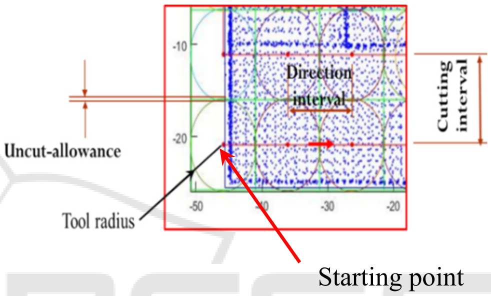
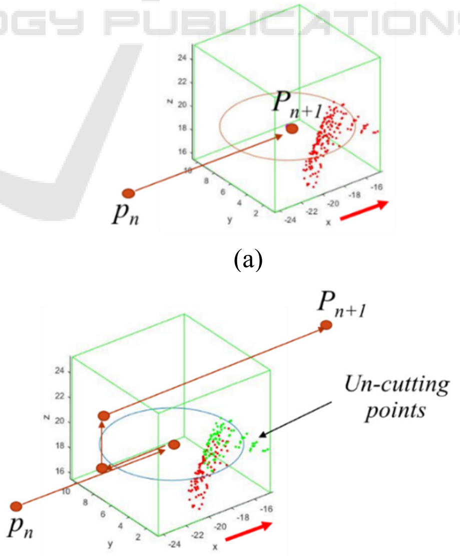


Figure 2 Parameters of Cutting and Starting Point of Cutting



(a)

(b)

Figure 3 Evaluation of Next Step of Tools (a) CC Cut Point Cloud (Over-Cut) and (b) the Solution by Moving CC of the Tools

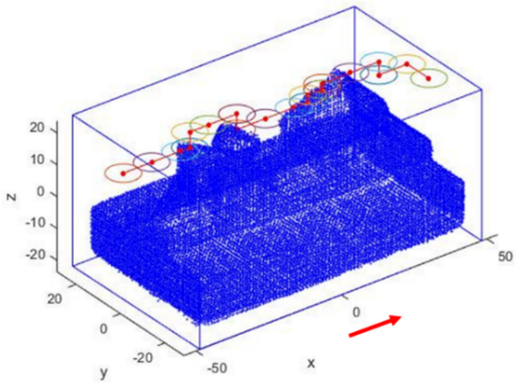


Figure 4 Tool Path for One Cycle. There is some tool cl moving

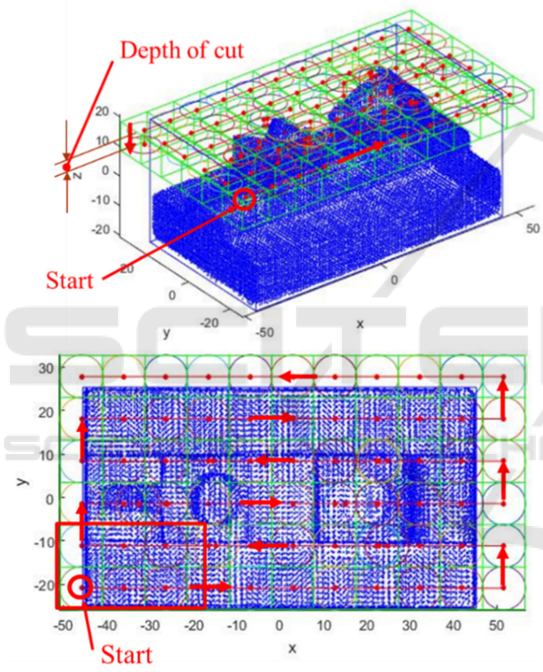


Figure 5 Tool Path for One Cycle x and y Direction

3.3.2 Ball-end Mill Parameters

The objective of using the ball-end mill, in this case, is to pursue the accuracy with certain tolerance and surface smoothness with certain surface quality (Ingeniería et al., 2016)(Yin, 2004).

The condition should be considered in the ball-end parameter selection as the following:

- Assume the vertex point is *p* (x_p, y_p, z_p) and the cutter's radius R. The center point of the cutter's bottom is $r_C=(x_C, y_C, z_C)$, and cutting allowance = δ.
- Verify the point *p* is within the CC region or not by using the following formula (see Fig. 6.11):

$$(x_p - x_c)^2 - (y_p - y_c)^2 \le R^2$$

- Cutting direction, related to x-direction
  - ✓ In flat surface:
    - ➢ Interval= 2R
  - ✓ For concave and convex surface
    - ➢ Using interpolation
- Depth of cut, related to z-axis
  - ✓ In net shape: t (t = tolerance)
  - ✓ Calculate maximum z_c of based on the point in CC region using the following formula:

$$z_c = z_p + (R^2 - (x_c - x_c)^2 - (y_c - y_c)^2)^{\frac{1}{2}} + t$$

Where t is tolerance.

- Cutting interval related to y-axis direction is using the following formula (see Fig. 2):

$$d = 2\sqrt{(2R - h)h}$$

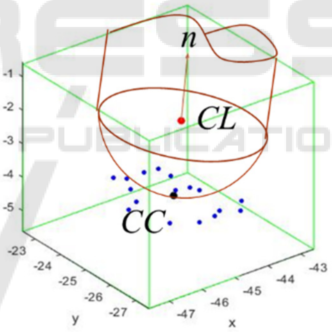
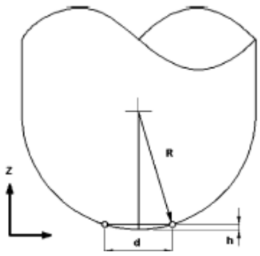
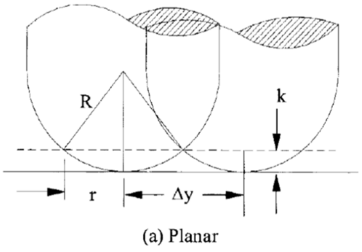


Figure 6 Ball-End Mill Position



(a) Ball and mill parameters



(a) Ball in interval

Figure 7 Ball-End Mill Cutting Interval (Yau & Hsu, 2009)

To define cutter location, it firstly generates a grid in z-value maximum (for z-direction cutting) (Park, 2003). The second step is to check the tool location (CC and CL) in each consecutive grid (forward and backward moving). The principal of semi-finished and finished process are equal. However, ball diameter and interval of cutting are different as shown in Fig. 8.

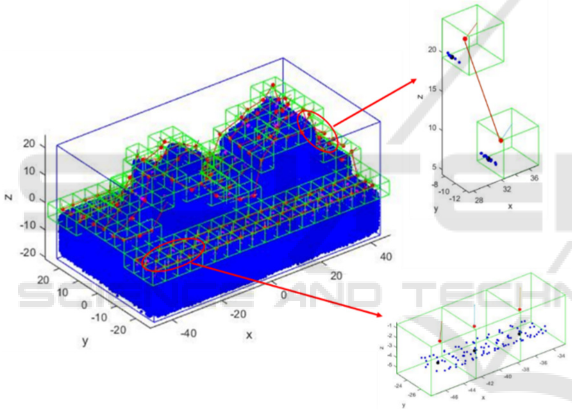


Figure 8 Ball-End Mill Path Checking

The condition of each grid in which CC and CL are located is checked. There are two cases of grid CC and CL condition.

- Case 1: the same z-value for the next grid, so only check the cutter contact (CC).
- Case 2: different z-value, besides checking the cutter contact (CC), the interpolation is applied and paths between grids are checked..

3.3.3 Interpolation

The interpolation method (Yau & Hsu, 2009) is used to solve the convex and concave curvature condition in the tool's moving, as displayed in Fig. 9. Figure 10 presents the condition of overcutting in tool moving. The solving is by generating buffer points (points from interpolation process) to avoid over-cut. A binary tree can be used to define the next buffer point that created.

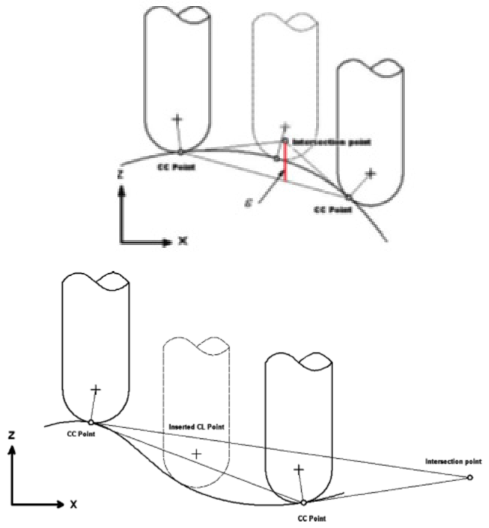


Figure 9 Overcut Condition in Concave and Convex Surface (Yau & Hsu, 2009).

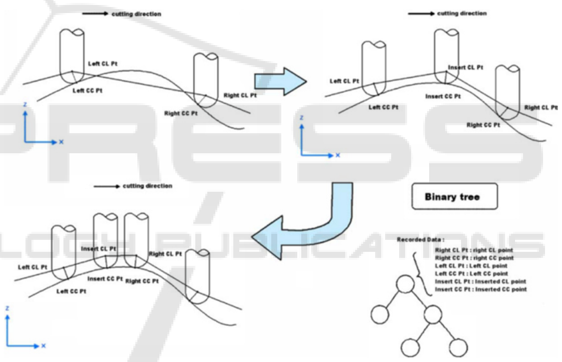


Figure 10 Ball-End Mill Overcut Condition and the Solving by Using Buffer Point (Yau & Hsu, 2009).

Buffer points are generated by using interpolation method. Figure 11 shows the interpolation method. The principal of interpolation is using the intersection line. Buffer point that calculated by interpolation method are using the following equation:

$$P_d.z = P_1.z - (P_1.x - P_i.x)\left(\frac{P_1.z-P_2.z}{P_1.x-P_2.x}\right)$$

where P_d is the projection of the intersection point to the CC line.

$$\begin{aligned}\varepsilon = P_i.z - P_d.z = P_i.z - P_1.z \\ - (P_1.x - P_i.x)\left(\frac{P_1.z - P_2.z}{P_1.x - P_2.x}\right)\end{aligned}$$

where ε is step error. If ε is greater than the machining tolerance, a different CL (buffer point) should be interpolated at the intersection point.

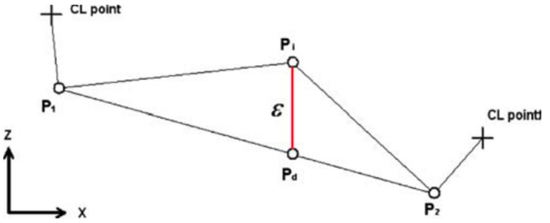


Figure 11 the Interpolation Method (Yau & Hsu, 2009).

4 RESULT AND DISCUSSION

The computation CL for rough cutting and semi-finished cutting is shown in Fig. 12 and Fig. 13, respectively.

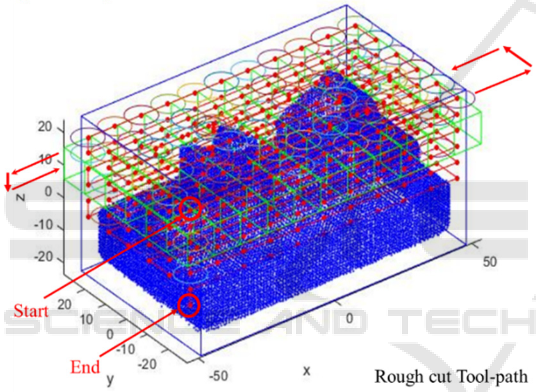


Figure 12 Rough Cutting CL Computation Result

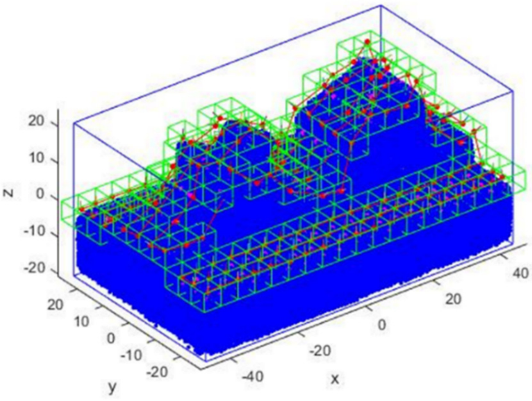


Figure 13 Semi-finished Cutting CL Computation Result

In this research, the method to generate a tool path from validated point cloud datasets registration is described. The broader implementation can be useful in mechanical design, die and mold, and even art and medical. The machining tools step consists of several stages: rough cutting, semi-finishing cutting, and finishing cutting.

As seen in Fig. 12 and Fig. 13, the tool orientation vectors are correctly oriented towards each point's normal vector. This section proposes an algorithm for generating a tool path of a 3-axis or 5-axis directly from a point cloud dataset. However, some shortcomings must be considered. As The grid is created, the grid's size must be set, as shown in Fig. 1. The grid size would influence the machine accuracy in the actual contour. The point number filtered out within the grid affects the path precision. If a rough grid is employed, i.e., in mm order, numerous points can be filtered out. Consequently, the tool path is not proper, and the feature surface to be cut is rough.

The developed method can be applied to generate tool paths from the subsurface relative to the corresponding grid point cloud. Based on the point cloud's isolation in the formed grid, the tool center point relative to the point cloud data is determined. The tool path between the tool center points of two neighboring grids is obtained from the two-nodal trajectory projection in a 2D triangular lattice. This path is verified whether it is tangent to another point or not. If there is a tangent point to the tool path in the triangle's projection, it is necessary to filter it; if it does not attain, it will go directly to the next point. 3D distance between cutter center points in adjacent grids is not taken into account.

If another feature form (in the form of data cloud points) exists between two cutter center points in the adjacent grid, that feature must be considered in determining the tool path. The accuracy of the cutter cuts in the two adjacent grids will also be affected. In addition, special features such as sharp edges, sharp elbows, sharp edges in the projection profile cannot be recognized in the proposed algorithm. Thus, for these cases, some algorithm modifications have to be made.

5 CONCLUSIONS

This research discusses generating the NC-tool path directly from point cloud data. Firstly, the machining process and cutter used are defined. Secondly, selecting the type of path will be used in this system. Some parameters can be assigned to control machining processes such as the dimension of an object, its position and orientation, surface roughness, workpiece material, and machining tolerance, and so on. The other machining parameters to be considered in the process are cutting speed, spindle speed, feed per minute, maximum chip thickness, feed per tooth, and some tooth of the cutter, feed per revolution, and depth of cut, remove rate, machining time, power, pitch and so on. Those parameters will influence the efficiency machining and surface quality of machining.

Thirdly, the tool path type is defined. In this case, the iso-parametric method is selected. Fourthly, the parameters of the tool are defined. The flat-end cutter for coarse cutting and ball-end cutter for the semi-finished and finished surface is confirmed in this case. Fifthly, a tool path with selected tools parameters is generated. In this case, the grid method is applied to evaluate the next tool moving direction. The tool path for rough cutting and semi-finishing cutting is generated. By implementation into a real case, it can be concluded that the proposed method is beneficial to create point NC-tool path directly from point cloud data.

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