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Paper:

Development of Tool Collision Avoidance Method Adapted to Uncut Workpiece Shape

Kento Watanabe*,†, Jun'ichi Kaneko, and Kenichiro Horio****

*Division of Mechanical Engineering, Graduate School of Science and Engineering, Saitama University
255 Shimo-Ohkubo, Sakura-Ku, Saitama City, Saitama 338-8570, Japan
†Corresponding author, E-mail: s16mh136@mail.saitama-u.ac.jp
**Saitama University, Saitama, Japan
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This study developed an automatic planning method for tool collision avoidance, with posture adapted to the uncut shape of a workpiece to avoid collisions between the tool and workpiece in five-axis machining. This method sequentially judges the likelihood of collision between the holder and shank parts of the tool and the workpiece while machining, which is updated with tool motion. Then it automatically determines tool postures in which no collisions occur. The process of setting the search range for collision avoidance postures of the tool when collisions occur is made more efficient; it is possible to prevent rapid changes in tool posture at the time of avoidance, while reducing the time for geometric operations necessary when searching for compatible orientations.

Keywords: collision avoidance, tool posture, voxel representation method, five-axis machining, CAM

1. Introduction

Five-axis machining controls the position and orientation of a tool with respect to the workpiece using motion along five axes, comprising three perpendicular axes in the X, Y, and Z directions and two rotating axes for the tool and the workpiece. Five-axis machining can be performed by a five-axis machine, which has the following advantages: enabling arbitrary shaping in arbitrary directions; reducing process changeover steps; enabling long-term unattended operation; and reducing the proportion of labor costs in operational costs. Owing to these advantages, the use of five-axis machines is increasing in the fields of component machining and die machining, which are benefiting from the permitted high geometric complexity required for high value-added products.

CAM (computer aided manufacturing) software is mainly used for tool routing in machining complex shapes and generating tool posture information. An NC (numerical control) machine executes the cutting instructions by reading the NC data generated using CAM software based on the tool shape and various cutting conditions. Various methods of tool collision avoidance have been proposed by many studies [1–8], and commercially available CAM software is designed to address it. However, five-axis machining, which has a high degree of freedom in tool posture with respect to the workpiece, may involve collisions between uncut parts of the workpiece and the holder and shank parts of the tool during machining. When such collisions occur, the modification of tool posture, based on trial and error, by the operator is necessary. This increases both machining cost and operation time.

The machining of a workpiece with a complicated shape may cause rapid reduction in the actual feed rate of the tool because of rapid posture changes and the degradation of surface quality [9] caused by erroneous synchronization between the swivel shaft and the straight shaft. Therefore, planning for slow posture changes is necessary in addition to collision avoidance.

Focusing on five-axis machining using a ball-end mill, this study proposes an algorithm that does not generate rapid posture changes and automatically modifies the tool posture while considering the uncut shape of the workpiece.

2. Determination of Tool Posture in Cooperation with Evaluation of Workpiece Shape

This study proposes an automatic modification method for tool posture. The outline of the method is presented in **Fig. 1**. The method evaluates shape change in a workpiece for each small step of tool movement when the tool moves according to the route of the tool cutting edge predetermined by CAM software. Then, it judges the likelihood of a collision occurring between the evaluated workpiece shape and the tool shank and holder. When a collision occurs, a tool posture that does not entail a collision is derived. By repeating this process for each small step of the tool movement, tool postures that generate collisions are automatically modified for each tool position.

Realizing the proposed method requires a method for geometric shape description that evaluates the change in workpiece shape according to tool movement, and then refers to this change in shape when determining the tool posture. This study uses a voxel shape representation to

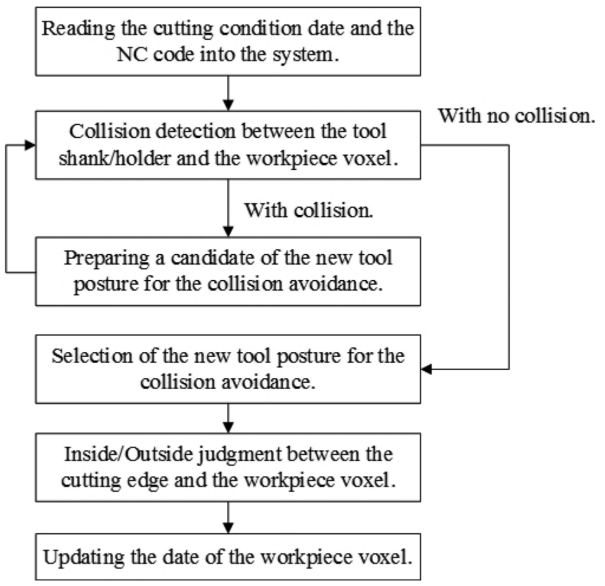

Fig. 1. Summary of the proposed method.

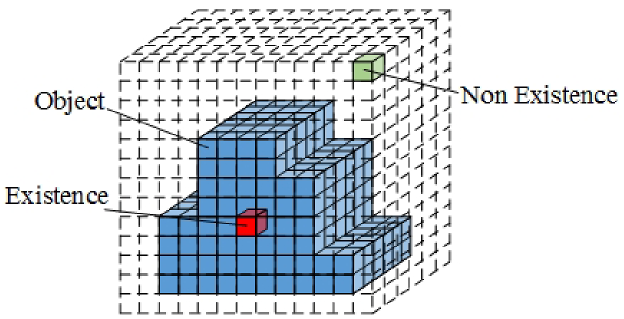

Fig. 2. Voxel representation method.

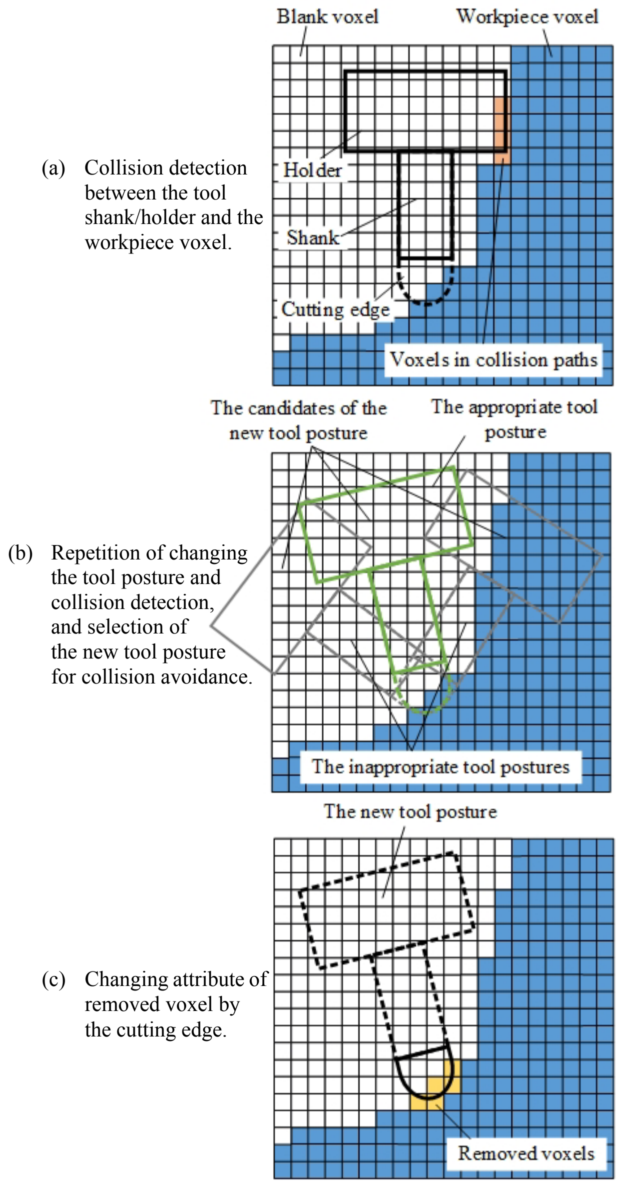

Fig. 3. Summary of the proposed method.

describe the workpiece during machining [10–14]. As presented in **Fig. 2**, the voxel shape representation describes the shape of the workpiece as a set of discrete spaces divided at regular intervals. When updating the shape, the multi-axis control cutting simulator [14] (cutting simulator) used in the method changes the attribution of each voxel; this is accomplished by an inside/outside judgment between the passage coordinate of the tool's cutting edge, as defined by CAM software, and the passage trajectory of the tool's cutting edges based on the tool posture, which is determined by the posture determination method depicted in **Fig. 1**. The procedure by the proposed method for each small step of tool movement is as follows (**Fig. 3**): (a) First, judges the likelihood of a collision between the tool shank and holder and each voxel of the workpiece; (b) when a collision is detected, repeat the collision detection shown in **Fig. 3(a)** using a posture candidate for the tool and thereby determine one posture that avoids collision; and (c), finally, judges the possibility of collision between the cutting edge of the new posture and each voxel of the workpiece to identify removed voxels and change attributions accurately.

Normally, long calculation times are necessary for the inside/outside judgment of the cutting edge and the voxel. However, this study uses a GPU (graphics processing unit) to perform the calculation in a simultaneous and parallel manner, which produces high-speed updates related to the workpiece shape in accordance with the tool motion.

3. Outline of Collision Avoidance Algorithm

3.1. Interpolation of Tool Position Information

NC data describes the tool route. In NC data, when the tool is instructed to move, the destination is discretely identified using a coordinate value or a movement distance in each axis direction. This discrete information must be close to the sequence represented by the cutting simulator to allow greater accuracy in evaluating the

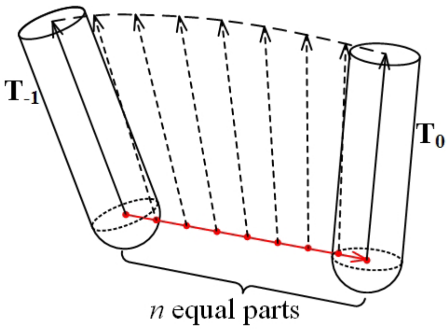

Fig. 4. Interpolation of tool position.

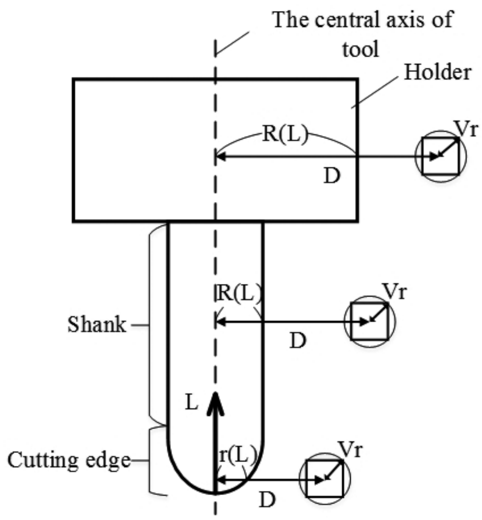

Fig. 5. Interpolation of tool position.

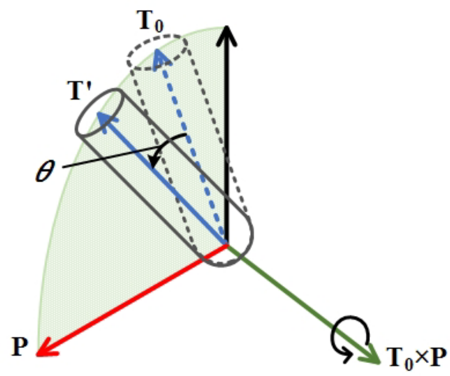

Fig. 6. Rotation by θ in step (3).

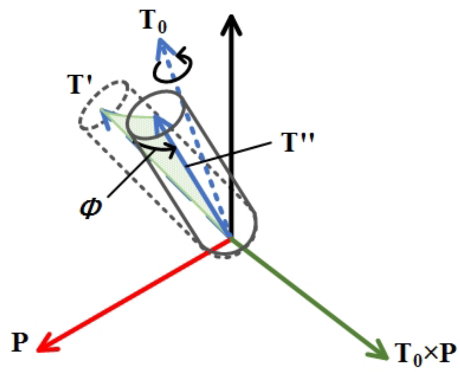

Fig. 7. Rotation by φ in step (4).

shape of the workpiece during machining. This study assumes that, at first, the tool linearly moves between two consecutive tool positions in the NC data, and the tool posture changes in proportion to the movement distance of the tool. This allows the division of the gap between two consecutive tool positions into n equal steps; as a result, $(n-1)$ tool positions are interpolated by this division in accordance with the tool diameter, as illustrated **Fig. 4**. As for the tool posture, the angle α between the tool axis vectors at the back and front tool positions is equally divided into n parts, and the tool axis vector rotated by α/n is designated as the tool axis vector for each interpolation point. The number of divisions n is set so that the distance between the added interpolation points is 1/4 of the radius of the tool being used to consider the representational accuracy of the shape being machined and the drawing speed of the simulator.

3.2. Detection of Collision with Workpiece

The cutting simulator calculates the distance D of each voxel from the tool's central axis and the distance L from the tip of the tool's cutting edge whenever the tool moves. The radius of each part of the cutting tool is equal to $r(L)$; V_r is the radius of the smallest sphere that includes each voxel. When $D < r(L) - V_r$, it implies that the voxel was removed. In this study, as presented in **Fig. 5**, this process is extended to the shank and the holder parts of the tool. When a voxel exists for which $D < R(L) + V_r$ is true, using the radius $R(L)$ of the shank and the holder parts, it is determined that a collision has occurred between the tool and workpiece.

3.3. Search for Collision Avoidance Posture

If a collision occurs between the tool and the workpiece, the collision detection is performed sequentially for the following postural candidate of the tool.

(1) Posture by the tool axis vector T_0 of the initial posture.

(2) Posture by the tool axis vector T_{-1} of the tool position immediately before.

(3) Posture by the vector T' (**Fig. 6**), which is the tool axis vector T_0 of the initial posture rotated by θ ($0° < \theta \leq 180°$) around the cross product $T_0 \times P$.

(4) Posture by the vector T'' (**Fig. 7**), which is the vector T' of step (3) rotated by φ ($0° < \varphi \leq 180°$) around the tool axis vector T_0 of the initial posture.

(5) Posture by the vector T''', which is the vector T' of step (3) rotated by $-\varphi$ ($0° < \varphi \leq 180°$) around the tool axis vector T_0 of the initial posture.

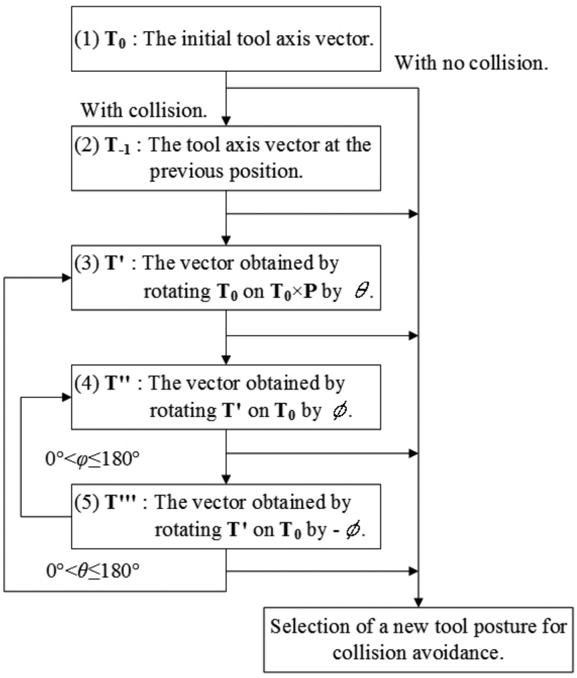

Fig. 8. Tool axes for candidates of the new tool posture.

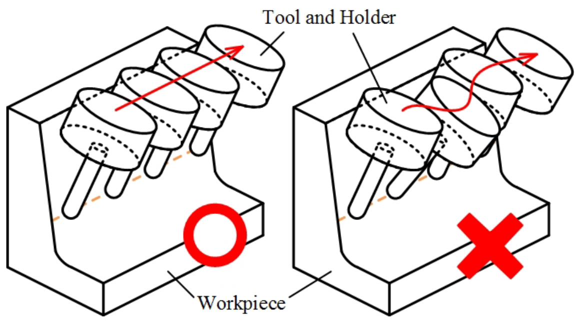

Fig. 9. Preventing vibrational changes in tool posture.

In addition, collision detection is performed repeatedly using the postures of steps (4) and (5) with gradual increases in φ until $\varphi = 180°$, and the postures in steps (3) and those in the later steps are repeated by gradually increasing θ until $\theta = 180°$. A candidate confirmed not to cause collision is designated as a new posture. The above outline is presented in **Fig. 8** as a flow chart.

For the initial posture of the tool, the proposed method uses the tool posture in three-axis machining or the one determined using the CAM software. If the tool posture is modified by collision avoidance in the immediately preceding tool position, the posture in the penultimate tool position is used to approach the initial posture, which is within the allowance value of the posture change rate for use as an initial posture in step (1). Using this technique, maintaining a posture as close to the initial posture as possible may create a machining surface with surface quality close to that assumed at the time of tool posture planning.

In addition, if collision avoidance with respect to a linear workpiece shape occurs successively, as presented in **Fig. 9**, the use of a posture in the tool position immediately before that in step (2) may prevent vibrational changes in the tool posture, thereby reducing the number of collision detections.

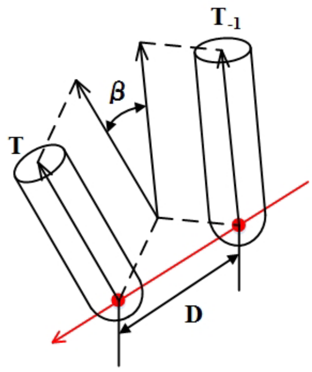

Fig. 10. Tool posture change and distance between two cutting points.

In a collision detection using the posture candidate mentioned above, a posture with which a collision is successfully avoided is designated as a new posture. The shape after cutting by the cutting edge of the tool in that posture is then calculated and represented. After this calculation, the simulation moves on to the next tool position.

3.4. Narrowing of Search Range

When the cutting simulator performs a collision detection, the forwarding of attribution information for each voxel between the CPU and GPU is necessary. The time required for the forwarding is an overhead, and the larger the number of forwards becomes, the less significant the use of the GPU becomes. To reduce the number of necessary collision detections, the posture candidates for which collisions are determined, as presented in Section 3.3, are narrowed according to the angle between the tool posture and the moving direction and the posture change rate as follows:

- Around the tip of the ball-end mill, sufficient circumferential speed cannot be obtained; machining here can cause tearing. Posture candidates for which the angle of the moving direction vector P of the tool is 85° or less are preferentially used for collision detection.

- Using the angle β between the tool axis vector T_{-1} in the tool position immediately before the tool axis vector T of the posture candidate in the current tool position and the distance D (**Fig. 10**) between the tool positions immediately before the current tool position, the posture change rate is defined as β/D. The allowed maximum of this posture change rate is set; only posture candidates with allowed posture change rates are used for collision detection.

Figure 11 presents an example of the distribution and the produced order of posture candidates for which a col-

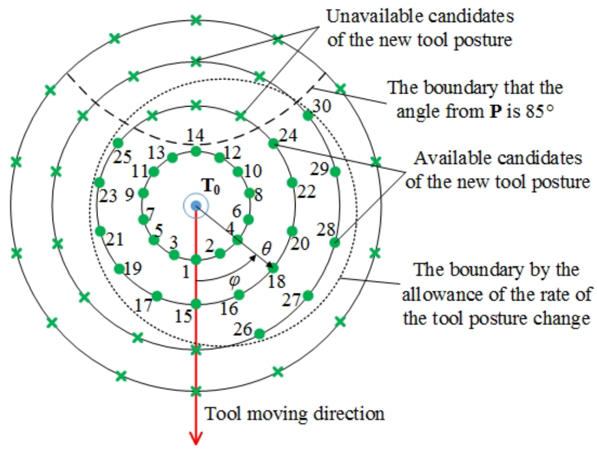

Fig. 11. Examples of candidates for new tool posture.

Table 1. Cutting condition.

	Roughing (Square end mill)	Finishing (Ball-end mill)
Tool diameter	10.0 mm	5.0 mm
Tool holder diameter	40.0 mm	30.0 mm
Tool projecting length	70.0 mm	25.0 mm
Axial cutting depth	3.0 mm	2.0 mm

lision is determined when the above narrowing is applied. The line connecting the center of the concentric circle to each numbered point (presented as •) represents the projection of the tool axis vector of each effective posture candidate. The line connecting the center of the concentric circle to each cross mark (×) represents the projection of the tool axis vector of each posture candidate excluded by the narrowing process.

4. Example of Implementation of Collision Avoidance Plan Using the Developed Method

Using the method proposed in this study, a plan for avoiding collision between the tool shank and holder and the workpiece was executed under the conditions presented in **Table 1**. The workpiece has a post-roughing shape as shown in **Fig. 12**, which is similar to a 100 mm^3 cube with a gouge. This piece is finished by the ball-end mill using the contour route shown in **Fig. 13**.

NC data were generated using the Autodesk Fusion 360 software. The tool axis vectors corresponding to the initial postures of the tool are all in the positive direction along the Z-axis, similar to those for three-axis machining. The posture candidate mentioned in Section 3.3 was created with a θ step size of 1° and φ step size of 2°. **Fig. 14** presents the cutting simulator that performs collision avoidance. (1) When the posture change rate is not provided with a maximum value, and when the posture change rate has a maximum value of (2) 11°/mm, (3) 9°/mm, and (4) 7°/mm, the posture change rate in each line of the NC data and the number of collision detections using the created posture candidate are presented in **Figs. 15** and **16**, respectively. The lines of the NC data presented in **Figs. 15** and **16** are from line 26261 on which the collision avoidance plan was executed. The

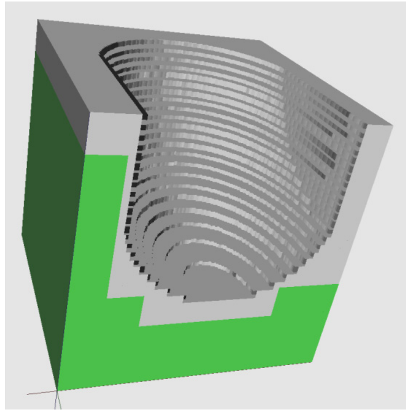

Fig. 12. Workpiece after roughing.

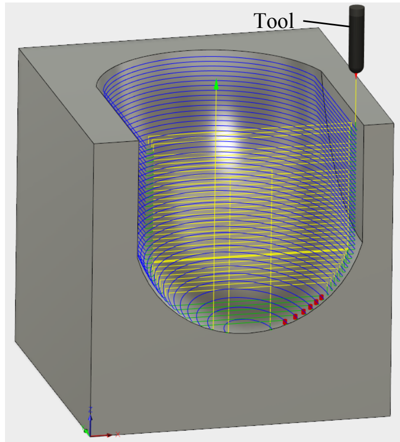

Fig. 13. Completed shape of the workpiece and tool path.

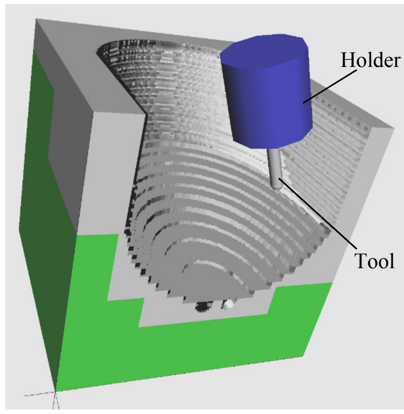

Fig. 14. Machining simulation.

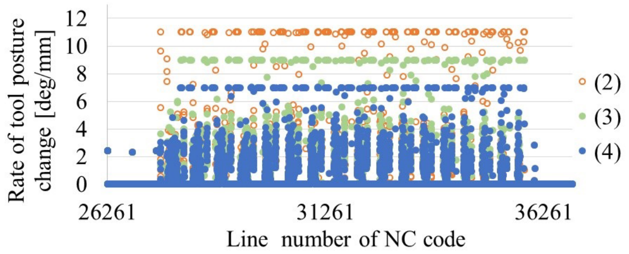

Fig. 15. The rate of the tool posture change.

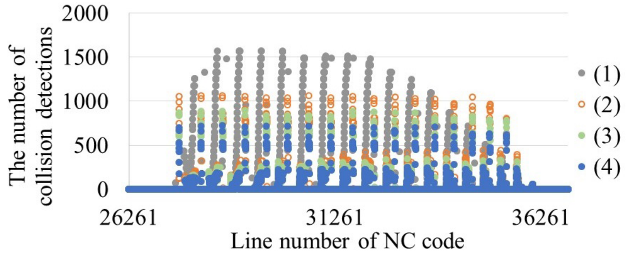

Fig. 16. The number of the collision detections.

Table 2. Total time and average time per line of NC code required for deciding the new tool postures for collision avoidance.

	Total time	Average time per line
(1)	53.81 min	0.196 sec
(2)	25.10 min	0.0912 sec
(3)	23.44 min	0.0852 sec
(4)	19.49 min	0.0708 sec

total time used to derive the tool collision avoidance posture throughout the finishing route calculated for each allowance value and the average time per line of NC data are presented in **Table 2**. **Fig. 15** indicates that the posture change rates in the planned new postures can be reduced to the set allowance value or less. **Fig. 16** and **Table 2** indicate that setting an allowed maximum for the posture change rate and a lower maximum value can reduce the number of collision detections and the time required to derive the tool collision-avoidance posture.

5. Conclusions

Targeting five-axis machining using a ball-end mill, this study involved developing a method to avoid collisions between the tool and workpiece by modifying the tool posture. The specific findings of the study are as follows.

- We extended the inside/outside judgment of the tool's cutting edge and the workpiece voxel in the cutting simulator. We confirmed that collisions between the tool shank or holder and the workpiece can be detected.
- We confirmed that the number of collision detections and the amount of time required to determine a new posture can both be reduced by narrowing the candidates of new postures for the tool by setting a maximum value for the posture change rate in the collision avoidance plan.

Acknowledgements

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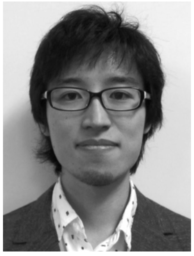
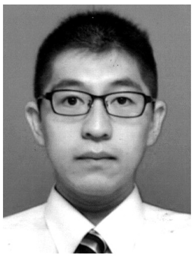


Name:
Kento Watanabe

Affiliation:
Graduate Student, Division of Mechanical Engineering, Graduate School of Science and Engineering, Saitama University

Address:
255 Shimo-Ohkubo, Sakura-Ku, Saitama City, Saitama 338-8570, Japan

Brief Biographical History:
2016 Graduated from Department of Mechanical Engineering, Faculty of Engineering, Saitama University



Name:
Jun'ichi Kaneko

Affiliation:
Associate Professor, Division of Mechanical Engineering, Graduate School of Science and Engineering, Saitama University

Address:
255 Shimo-Ohkubo, Sakura-Ku, Saitama City, Saitama 338-8570, Japan

Brief Biographical History:
2004- Research Associate, Saitama University
2008- Assistant Professor, Saitama University
2013- Associate Professor, Saitama University

Main Works:
- "Tool Posture Planning Method for Continuous Multi Axis Control Machining with Consideration of Shortening Shank Length of End Mill," Int. J. of Automation Technology, Vol.6, No.5, pp. 648-653, 2012.
- "Fast Cutter Workpiece Engagement Estimation Method for Prediction of Instantaneous Cutting Force in Continuous Multi-Axis Controlled Machining," Int. J. of Automation Technology, Vol.7, No.4, pp. 391-400, 2013.

Membership in Academic Societies:
- The Japan Society for Precision Engineering (JSPE)
- The Japan Society of Mechanical Engineers (JSME)

Name:
Kenichiro Horio

Affiliation:
Professor, Division of Mechanical Engineering, Graduate School of Science and Engineering, Saitama University

Address:
255 Shimo-Ohkubo, Sakura-Ku, Saitama City, Saitama 338-8570, Japan

Brief Biographical History:
1981- Joined Production Engineering Research Laboratory, Hitachi Ltd.
1987- Lecturer, Saitama University
1991- Associate Professor, Saitama University
1995- Visiting Researcher, Precision Engineering Center, North Carolina State University
2000- Professor, Saitama University

Main Works:
- "A study on damaged layer remaining in diamond mirror cut surface," Annals of the CIRP, Vol.41, No.1, pp. 137-140, 1992.

Membership in Academic Societies:
- The Japan Society for Precision Engineering (JSPE)
- The Japan Society of Mechanical Engineers (JSME)
- The Japan Society for Abrasive Technology (JSAT)