Title:
Graphical Assistance for Determining Cutter Axis Directions in 3+2-Axis Machining

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Introduction:
Recently, the use of 3+2-axis machining, in which machining is performed by tilting the direction of the cutter spindle axis, has increased in the machining of parts with complex shape. In the 3+2-axis machining, the tool length can be shortened by setting the spindle direction properly. Accordingly, it is feasible to achieve stable machining with comparatively less tool deformation than that of the conventional 3-axis machining (Fig. 1). This type of machining enables the minimization of the number of mounting changes in the workpiece; hence, via this method, machining accuracy can be improved and machining cost minimized. Unlike simultaneous 5-axis machining, it is unnecessary to control the cutter posture during the machining process, so that the introduction cost of the 3+2-axis milling machine is less than that of the simultaneous 5-axis machine.

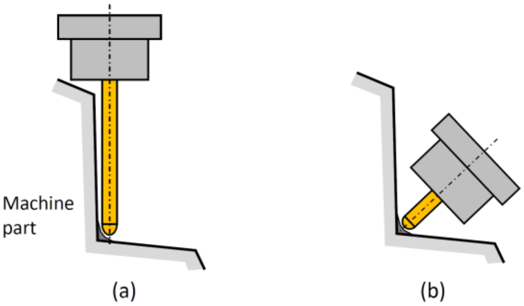

Fig. 1: Conventional 3-axis machining (a) and 3+2-axis machining using a shorter tool (b).

The computation of the numerical control (NC) data for the 3+2-axis machining is usually performed in two steps.
Step 1 Determine the cutter position: A ball-end cutter is generally employed in the 3+2-axis machining. The center point of the ball-end cutter is on the surface offset from the part surface by the cutter radius. At this point, the cutter posture is yet to be determined.
Step 2 Determine the cutter posture: The posture of the cutting tool in the milling process is then determined for each cutter position, such that a certain clearance is ensured between the tool and workpiece surface, to prevent collision between them.
When machining a part with complicated shapes, the cutter's posture must be changed several times to complete the 3+2-axis machining operation. Owing to inevitable positional errors of the milling

machine, the minute level difference is known to be generated in the part where the surfaces machined by the tool of different postures connect. Therefore, to realize an optimal good surface finish, it is desirable to minimize the cutter posture changes. The determination of the proper combination of cutter postures for the 3+2-axis machining is a huge burden for machining engineers.

In this study, we propose a novel software technique for assisting the interactive determination of cutter postures for the 3+2-axis machining. To properly select the cutter posture, the recognition and visualization of the surface region in the part that can be machined using the cutter in the designated posture are important. To minimize the cutter posture changes, it is generally desirable to select the cutter posture, such that the tool can machine the surface area exhaustively. In our software, a tool path representing the locus of the center point of a cutter is provided as input data. Instead of classifying the surface area of the part by the cutter posture, our software classifies points constituting the tool path. For each point in the path, a range of cutter postures without interferences with the machine part is computed. The information on the possible cutter postures for all machining points is "superimposed" in a Gauss map, and the number of machinable points can be examined for each cutter posture. The obtained results are color-coded in the display. By referring to the display, the cutter posture in which several points can be machined is easily identified. When a user selects a cutter posture based on the display, points machinable by the cutter in that posture are automatically selected from the path data. New tool path data are obtained by reconnecting the selected points. Simultaneously, the color display is updated based on the cutter posture information of the remaining points. By repeating the selection of the cutter posture based on the color display, the operator can efficiently generate the NC data required for the 3+2-axis machining.

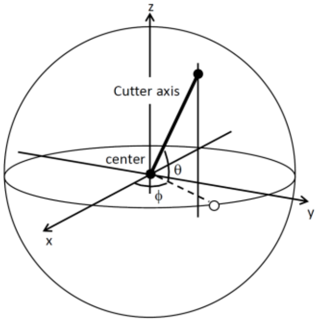

Fig. 2: Cutter posture definition using ϕ and θ.

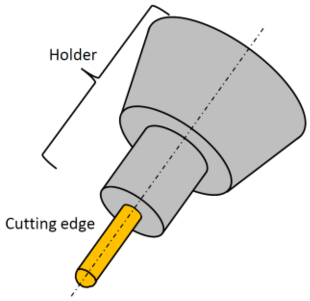

Fig. 3: Definition of cutter shape.

Main Idea:

In the following discussion, milling operation with a ball-end cutter of radius r is assumed. Position of the ball end cutter is represented by the center point of the spherical blade of the cutter. The cutter posture is given by the spindle axis direction of the cutter, which is specified by two rotational angles around two mutually perpendicular axes of the milling machine. In this research, azimuth angle ϕ and elevation angle θ in the world coordinate frame is used to define the cutter posture (Fig. 2). As input data to the software, a polyhedral model of a machine part, shape data of a ball-end cutter, and a cutter path data representing the position change of the cutter are given. A ball-end cutter is composed with a cutting-edge part and cutter holder (Fig. 3). A holder shape can be regarded as a series of cylindrical shapes and/or truncated cones with a common center axis.

Detection of Cutter Postures without Interference

Our software first calculates the range of cutter postures that do not cause tool interference for each machining point. In this paper, the cutter posture is treated as a discrete combination of azimuth and elevation angles. 720 azimuthal angles were considered in 0.5-degree steps in the range from 0 to 360 degrees, and 361 elevation angles were considered in 0.5 degree steps in the range from 90 degrees to - 90 degrees. Therefore, $720 \times 361 = 259{,}920$ tool postures are considered for each machining point, and the existence of the intersection of the cutter shape and machine part shape is checked and recorded for each posture of the machining point. We prepare a bit sequence of 259,920 length for recording the cutter interference detection results for each machining point. 0 is recorded to a bit corresponding to the posture in which cutter interference occurs, and 1 is recorded for the posture bit without interference.

We divide the problem of the cutter interference detection into two sub-problems: detection of the interference of the cutting edge and detection of the interference of the holder part of the cutter. An offset shape $\boldsymbol{M}$ is obtained by expanding the part shape by the cutter radius r. We developed a fast-offsetting algorithm of a polyhedral object using parallel processing function of GPU [1]. By using this algorithm, polyhedral model of the offset shape can be obtained. The interference detection of the cutting edge whose reference point is at point $\boldsymbol{p}$ is geometrically equivalent to the intersection detection of a line segment whose endpoint is at $\boldsymbol{p}$ and a polyhedron $\boldsymbol{M}$ (Fig. 4). A holder shape can be regarded as a swept surface obtained by rotating a series of line segments around the center axis of the cutter, therefore we can represent the holder shape as a set of line segments (Fig. 5). The interference between a holder and a part shape thus can be judged by checking the intersection between line segments in the holder surface and polygons representing the part shape. Intersections between line segments and polygons can be computed at high speed by using a RT core hardware of GPU [2].

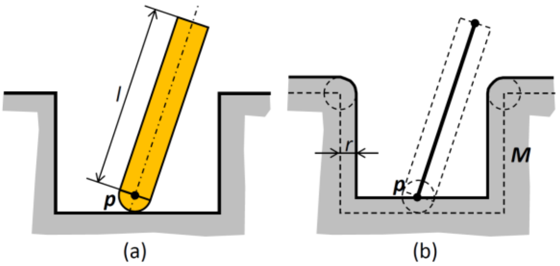

Fig. 4: Interference detection using offset shape.

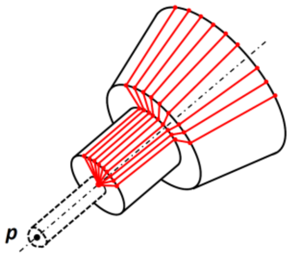

Fig. 5: Holder representation.

Graphical Interface for Assisting Cutter Posture Selection

After recording the interference-free cutter postures for all machining points, obtained bit sequences are superimposed. For each of the 259,920 tool postures, the number of machining points where 1 (= no interference) is recorded in the bit corresponding to the posture is counted (Fig. 6). Obtained count results are then visualized using Gauss map. For each cutter posture, its corresponding point on the map is painted using a unique color according to the number of machinable points for the posture. This time, the point corresponding to the cutter posture with the most machinable point is painted in blue, and the cutter posture point with the least machinable point is painted in red. The color changes from blue, to green, yellow, and red, in that order, as the number of the machinable points decrease.

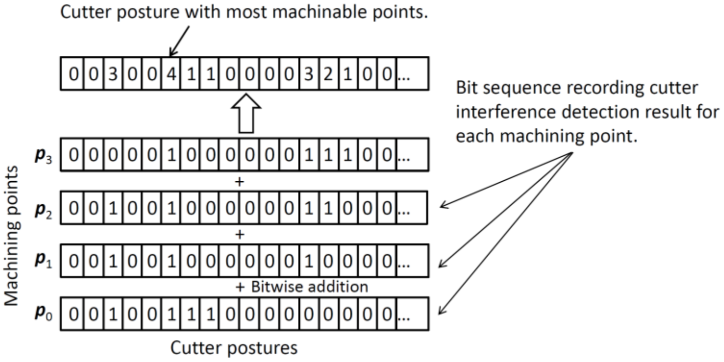

Fig. 6: Determination of number of machinable points for each cutter posture.

When a user clicks a point on the Gauss map using a mouse, its corresponding cutter posture is selected. The software then collects points machinable using the cutter in the selected posture, and the interference-free NC data for machining the part with the cutter are generated by appropriately connecting the collected points. The software recalculates the number of machinable points for each cutter posture using the remaining points, and updates the color-coded display using the result. After that, selection of the tool posture by using mouse, generation of the NC data using points machinable with a cutter in the selected posture, and update of the color-coded display are repeated. When all machining points become machinable, NC data for 3+2-axis machining is completed. In order to minimize the cutter posture changes in the machining process, it is generally a good strategy to repeat the selection of the cutter posture with many machinable points, that is, select the cutter posture with bluest color in the Gauss map.

Computational Experiments:

We implemented a software for assisting the tool posture determination using the mentioned algorithm. In the implementation, VisualStudio 2017, CUDA 10.2, and OptiX 7.2 were used. A 64-bit PC with an Intel Core i7 Processor, 32 GB memory, and an nVIDIA GeForce RTX-2080 SUPER GPU was used in the experiments. At present, we are developing a 5-axis machining CAM software for dental technicians, and this time, tooth model was used as the machining object. A polyhedral model of the tooth shape (Fig. 7(a)), the tool shape data (ball-end cutter of 0.3mm radius), and the cutter path for contouring the tooth (Fig.7 (b)) are given as inputs to the software. The number of polygons of the tooth model is 15,000. Input cutter path data consist of contour curves of 510 slices (0.02mm intervals) and the total number of machining points in the path is 161,199. This path data was computed by using CAM software for conventional 3-axis machining.

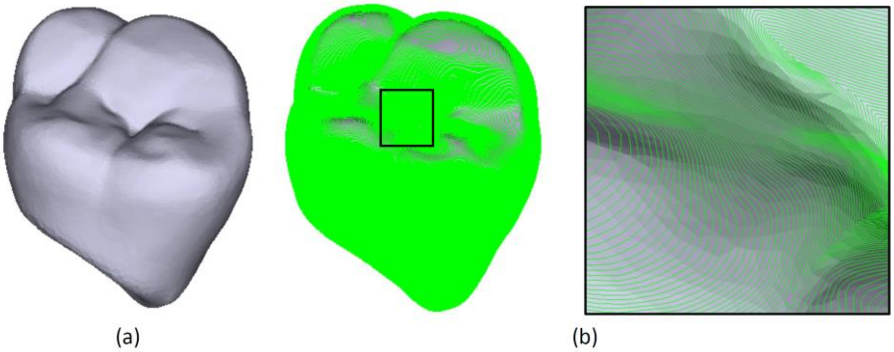

Fig. 7: Tooth model (a) and initial contour-type cutter path data for the tooth model (b).

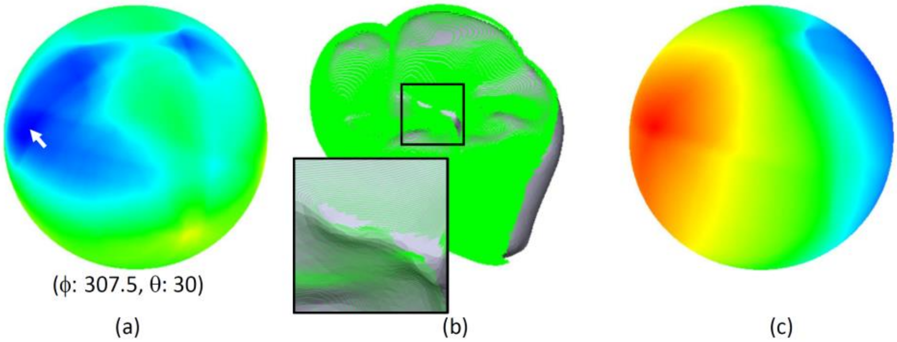

Fig. 8: Selection of the cutter posture using Gauss map (a), generated cutter path for a cutter in the selected posture (b), and updated color of the Gauss map.

For all machining points, cutter interferences for 259,920 cutter postures were investigated and recorded. This time, the cutting-edge part of the cutter was only considered in the interference detection. This process took a total of 233.6 seconds (84.7 s for offsetting and 148.9 s for intersection computation). Based on the results, we obtained color-coded Gauss map as shown in Fig. 8(a). The blue color region represents the cutter postures with many machinable points. When the bluest point in the sphere was selected by the mouse (white arrow in Fig. 8(a)), a contour-type cutter path using a cutter in the selected cutter posture (ϕ = 307.5 degree, θ =30 degree) was generated by properly connecting the machinable points (Fig. 8(b)). At the same time, the software recalculates the number of the machinable points for each cutter posture using the remaining points, and the color-coding result of the Gauss map was updated as shown in Fig. 8(c). In this example, all required cutter postures for 3+2-axis machining of the tooth model could be selected by repeating the operation four times. Fig. 9 illustrates the selection process of the cutter postures. Selection processing of cutter posture and update processing of color coding were very fast, and sufficiently interactive work was possible.

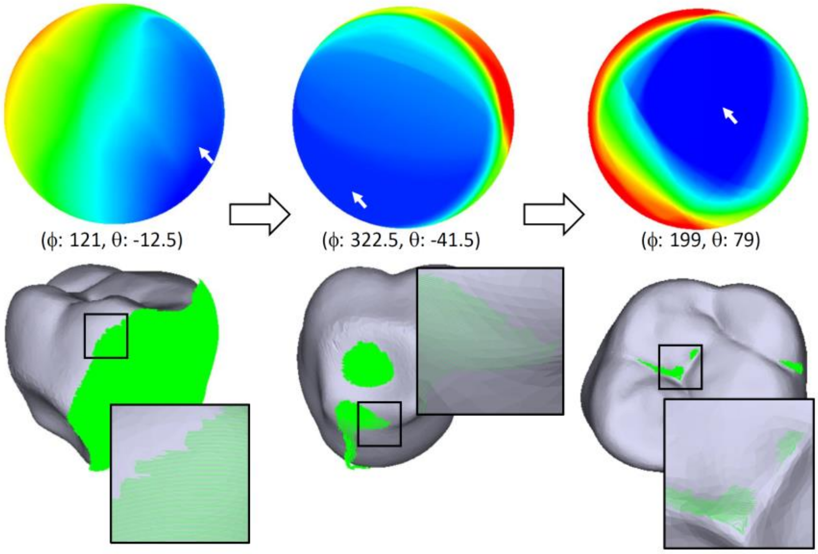

Fig. 9: Cutter posture selection process and cutter paths for a cutter in a specific posture.

Conclusions:
This paper describes novel interactive software technique for assisting 3+2-axis machining. This software needs a path data of the tool center, polyhedral model of a part shape, and tool shape data. It computes a range of the tool postures without interferences with the machine part for each point in the path. The information of the possible tool postures for all points are examined, and the number of the machinable points is counted for each tool posture. The obtained results are color-coded in the Gauss map. By referring to the color information of the Gauss map, tool postures necessary for machining can be efficiently selected. By repeating the selection of the cutter posture based on the color display, the operator can efficiently make the NC data for the 3+2-axis machining.

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