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Development of a System to Generate Tool Orientation Information for Positional 5-Axis Machining of Die and Mold

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ABSTRACT

Die & mold industry is characterized as one of a kind production, and must simultaneously cooperate with product design, die & mold design, tool-path generation and machining. High-speed machining and 5-axis machining have been dramatically developing in die & mold industry. Due to the lack of skilled technicians, however, an intelligent system that can suggest feasible and optimal machining condition is strongly required mainly for non-skilled technicians. Moreover the kinematic structure of each machine type in 5-axis NC machining is different, which makes it difficult to select optimal machining condition. Especially the positional 5-axis machining in which tool orientation is fixed during material removal process has been widely used in mold & die manufacturing. In that case, it is important for a CAM programmer to decide an optimal tool orientation as well as the tool-length such that there will be no collision, gouging, and machine stroke-over. In this paper a system that generates feasible tool orientation information is presented, which enable the CAM programmer to decide optimal and feasible orientation.

Keywords: positional 5-axis machining, tool orientation, CAPP.
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1. INTRODUCTION

In general 5-axis machining is known to have a few strengths compared with 3-axis machining, such as set-up & tooling time reduction, machinability and machining quality [1,2]. Conventional 5-axis machining has been applied to mass production of specialized parts by use of specialized machine [3,4]. It becomes popular, however, to utilize 5-axis NC machine in die & mold machining because of high efficiency and value added manufacturing.

It is important to consider various factors such as the machine's kinematic structure, control characteristics, and machining features of design surface for proper 5-axis machining, but also it is strongly required to make optimal machining process plan based on the machining environment. However, it seems that the 5-axis machining technology has not been matured enough for die & mold manufacturing industry, compared to 3-axis machining. Instead, positional 5-axis machining is widely used on a 5-axis NC machine in mold & die manufacturing industry. It is clear that simultaneous 5-axis NC machining possibly results in best machining quality and efficiency, but the positional 5-axis machining has been widely used in die & mold machining. Also it should be noted that curvature matched machining produces better surface finish with fewer tool passes, but is difficult to plan and implement.

In Positional 5-axis machining, it is required for a CAM programmer to decide optimal tool orientation as well as tool-length such that there will be no collision, gouging, and machine stroke-over. In this paper a system that generates feasible tool orientation information is presented, which enables the CAM programmer to decide optimal and feasible orientation for each machining stage from rough-cut to clean-up cutting, thereby facilitating efficient process planning and machine operation.

2. POSITIONAL 5-AXIS MACHINING

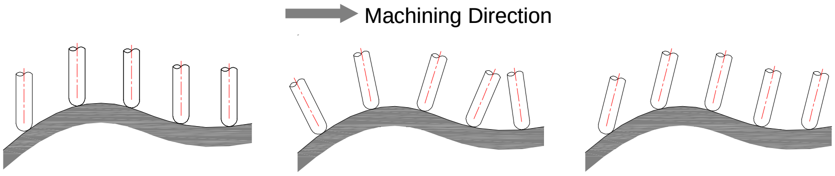
2.1 Type of Mold and Die Machining

Being categorized by the tool-orientation availability in material removal, the NC machining can be summarized as follows:

(1) Fixed-axis case: e.g., 3-axis, attachment, positional 5-axis machining,
(2) Variable-axis case: e.g., continuous (simultaneous) 5-axis machining.

Fig.1 depicts conceptual diagrams of NC machining, which are mostly used in mold & die machining. The ordinary 5-axis machine has three translating axes and two rotational axes, though with some exceptions. The positional 5-axis machine on a 5-axis NC machine, what so called 3+2 axis machining, is operated with two rotational axes fixed during the material removal process.

Overall die & mold machining for a product consists of several machining stages–rough-cut, finish-cut, clean-up cut, and form EDM, each of which is composed of UMO(unit machining operations)[9]. Each UMO for mold & die machining utilizes one of the three machining type: 3-axis, positional 5-axis, and continuous 5-axis machining. It is a CAM programmer's responsibility to make an optimal or near-optimal process plan, based on local form features of part surface, tooling, material removal, etc.



(a) 3-axis machining (b) Continuous 5-axis machining (c) Positional 5-axis machining

Fig. 1: NC machining types.

2.2 Related Data for Positional 5-axis Machining

It is required to obtain feasible tool-orientation data to machine given region on a part surface in positional 5-axis machining, which further can be one of the following cases:

(1) Feasible tool-orientation data for given region,
(2) Feasible region for a given tool-orientation on the part surface,
(3) Feasibility of a given tool-orientation at a cutter contact point.

The developed system handles the above cases, which provides necessary tool-orientation data to the CAM programmer. Then he/she can select a feasible tool-orientation for a local area, or the whole part surface. Otherwise he/she defines a region that can be machined by the selected tool-operation.

To be more specific, a local coordinate system is defined in the part coordinate system in order to define the tool-orientation by the CAM programmer, as shown in Fig.2. The developed system provides with necessary data to define such local coordinate frame.

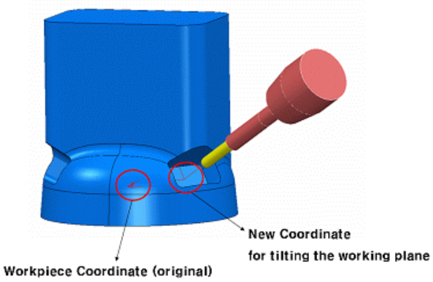


Fig. 2: Local coordinate system to define tool-orientation.

2.3 Feasibility Check

As previously mentioned feasibility check is required to find interferences between various components, that is to say, we should check any collision, gouging, and machine stroke-over at a CC(cutter contact)point for a given tool-orientation. It is a simple job to check strok-over, since we olny have to know the machine kinematics as explained in section 3.

2.3.1 Collision Check

Collision or crash is checked between following components : part surface, tool shank, tool holder, machine components. Each component is constructed by the following geometric elements :

- Part surface : *hybrid model of z-map and triangular facet*,
- Tool shank, tool holder, machine components : *triangular facet*.

Z-map[4,9] has been widely adopted in cutting simulation and tool-path generation, due to various strengths of simple structure, computational robustness, efficient surface modification such as offsetting and blending. It has, however, a few difficulties in overhang shape modeling and huge memory requirement to cope with high accuracy on vertical walls or sharp edges.

Extended z-map[8] and dexel[7] structures have been suggested to overcome such obstacles, but there still exists difficulties. In addition, it should be noted that triangular facet itself is a very accurate and robust model in shape representation as well as interference checking, but somewhat large computation time compared with the z-map or hybrid model cannot be neglected for practical use.

A hybrid of z-map and triangular facet is suggested in this paper, whose schematic diagram is shown in Fig.3. Given a set of whole part surface, the whole region is modeled via z-map with proper grid-interval of 0.5~1mm. Each face of the whole part surfaces is tessellated into a triangular facet model only if it is near vertical or the maximum gap to the z-map is larger than a specified tolerance. Then the hybrid model has local triangular facets only on regions where z-map represents discrepancy.

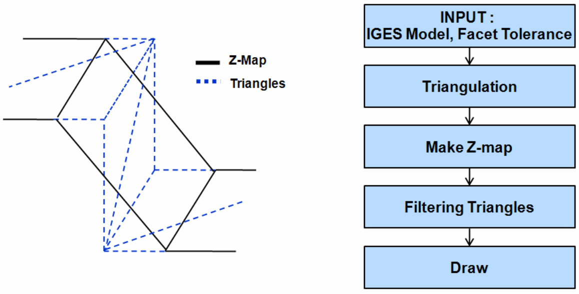


Fig. 3: Hybrid model structure.

Having a hybrid model in hand, the authors can selectively consider appropriate geometric elements (i.e., z-map grid point or triangle), thereby reduce computation time in collision check between workpiece and other machining components. It should be noted that the triangles take precedence over the z-map grid points in a local region where both elements are coexistent. Fig.4 represents an example of hybrid model construction.

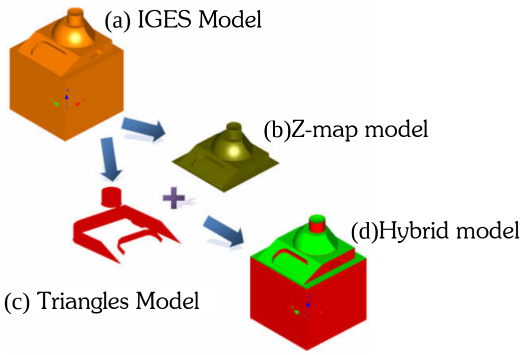


Fig. 4: Hybrid model structure example.

2.3.2 Gouge Check

Gouging is defined to be interference between cutting edge and the part surface. It is meaningful to avoid gouged CC-points on given region in this research, as is the case of tool-path generation. The developed system considers gouging of ball-end milling cutter, and the case can be handled with ease by checking interference between a CC-point and ball offset z-map[9]. Then the gouged CC-points are removed from the given region in order to avoid and further computation.

3. TOOL ORIENTATION DATA GENERATION

3.1 Kinematics Modeling

Computation of CL (cutter-location) data as well as machine axis values in 5-axis machining needs machine kinematics modeling: forward and inverse kinematics. Fig.5 shows link coordinate frames on the applied NC machine – DINO by FPT Co., which has two rotational axes of B and C axes. The link coordinate frames are defined by Denavit-Hatenberg representation, and link parameters are shown in Table 1.

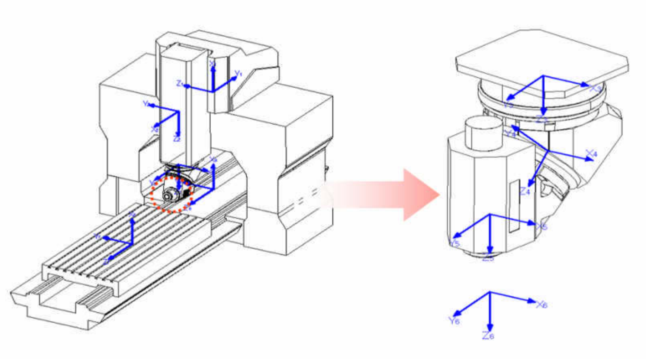
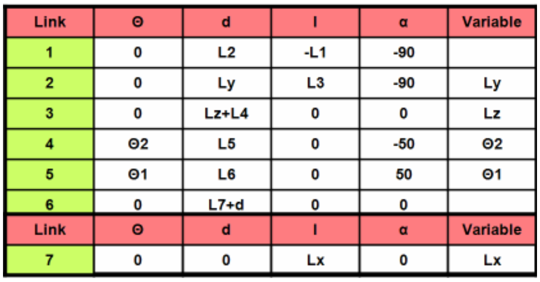


Fig. 5: Link coordinate frames on the NC machine.



Link	Θ	d	l	α	Variable
1	0	L2	-L1	-90	
2	0	Ly	L3	-90	Ly
3	0	Lz+L4	0	0	Lz
4	Θ2	L5	0	-50	Θ2
5	Θ1	L6	0	50	Θ1
6	0	L7+d	0	0	
Link	**Θ**	**d**	**l**	**α**	**Variable**
7	0	0	Lx	0	Lx

Tab. 1: Link parameters for DINO machine.

The relation of the tool coordinate and link coordinate frame is defined by Eqn. (1) as follows. Also the forward and inverse kinematics solutions are found by solving the equation.

$$[n \quad o \quad u \quad p] = ({}^0T_7)^{-1}({}^0T_1{}^1T_2{}^2T_3{}^3T_4{}^4T_5{}^5T_6) \tag{1}$$

The CL data, or tool orientation **U** = (Ux, Uy, Uz) and position data **P** = (Px, Py, Pz) for given machine axis values are obtained by the forward kinematics solution as Eqn.(2)

$$\begin{aligned}
u_x &= S\theta_1 C\theta_2 S\theta_\alpha + (C\theta_1 - 1)S\theta_2 C\theta_\alpha S\theta_\alpha \\
u_y &= -S\theta_1 S\theta_2 S\theta_\alpha + (C\theta_1 - 1)C\theta_2 C\theta_\alpha S\theta_\alpha \\
u_z &= -S\theta_\alpha{}^2 C\theta_1 - C\theta_\alpha{}^2 \\
p_x &= (S\theta_1 C\theta_2 S\theta_\alpha + S\theta_2 C\theta_\alpha S\theta_\alpha (C\theta_1 - 1))(L_7 + d) - S\theta_2 S\theta_\alpha L_6 + L_3 - L_1 - L_x \\
p_y &= (-S\theta_1 S\theta_2 S\theta_\alpha + C\theta_2 C\theta_\alpha S\theta_\alpha (C\theta_1 - 1))(L_7 + d) - C\theta_2 S\theta_\alpha L_6 + L_y \\
p_z &= (-C\theta_1 S\theta_\alpha{}^2 - C\theta_\alpha{}^2)(L_7 + d) - C\theta_\alpha L_6 - L_5 - L_4 + L_2 - L_z
\end{aligned} \tag{2}$$

In addition, the inverse kinematics solution of the machine – Lx, Ly, Lz, θ_1, θ_2 is obtained via Eqn.(3), which represent axis values of X, Y, Z, B, and C machine axes, respectively.

$$C\theta_1 = \frac{C\theta_\alpha^{\,2} - u_z}{S\theta_\alpha^{\,2}}, \quad S\theta_1 = \pm\sqrt{\frac{u_x^{\,2} + u_y^{\,2} - (C\theta_1 - 1)^2 C\theta_\alpha^{\,2} S\theta_\alpha^{\,2}}{S\theta_\alpha^{\,2}}} \qquad \therefore \theta_1 = a\tan 2\left(\frac{S\theta_1}{C\theta_1}\right)$$

$$\begin{pmatrix} u_x \\ u_y \end{pmatrix} = \begin{pmatrix} A & B \\ B & -A \end{pmatrix}\begin{pmatrix} C\theta_2 \\ S\theta_2 \end{pmatrix}, \quad A = S\theta_\alpha S\theta_1, B = (C\theta_1 - 1)C\theta_\alpha S\theta_\alpha, \quad W = -(A^2 + B^2)$$

$$C\theta_2 = \frac{1}{W}\begin{vmatrix} u_x & B \\ u_y & -A \end{vmatrix}, \quad S\theta_2 = \frac{1}{W}\begin{vmatrix} A & u_x \\ B & u_y \end{vmatrix} \qquad \therefore \theta_2 = a\tan 2\left(\frac{S\theta_2}{C\theta_2}\right)$$

$$\begin{aligned} L_x &= (S\theta_1 C\theta_2 S\theta_\alpha + S\theta_2 C\theta_\alpha S\theta_\alpha (C\theta_1 - 1))(L_7 + d) - S\theta_2 S\theta_\alpha L_6 + L_3 - L_1 - p_x \\ L_y &= (S\theta_1 S\theta_2 S\theta_\alpha - C\theta_2 C\theta_\alpha S\theta_\alpha (C\theta_1 - 1))(L_7 + d) + C\theta_2 S\theta_\alpha L_6 + p_y \\ L_z &= (-C\theta_1 S\theta_\alpha^{\,2} - C\theta_\alpha^{\,2})(L_7 + d) - C\theta_\alpha L_6 - L_5 - L_4 + L_2 - p_z \end{aligned} \tag{3}$$

3.2. Feasible Region for Given Tool Orientation

It may cause unexpected problem to empirically select the tool orientation angle even for an experienced CAM programmer. The developed system searches feasible region for a given tool orientation, which enables the programmer to recognize where can be machined by which tool orientation. The computing flow is depicted in Fig.6, where the part surface model is given via IGES format.

CC points on the part surface are sampled so that three-dimensional distance(interval)between points is consistent. The gouged CC points at concave area are filtered out as explained in section 2.3.2 so as to reduce computing time. Additionally each CC point is classified as infeasible(i.e., interfered point) if the tool orientation vector lies under the tangent plan defined by CC Point's normal and position Fig.7 shows an example result.

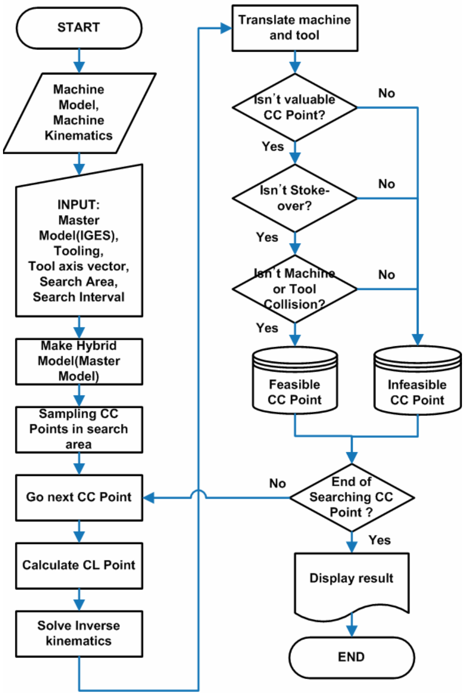


Fig. 6: Overall flow to obtain feasible region for given tool orientation.

It is noted that each CC point is colored to recognize specific interference as shown in Fig. 7: for example, red for CC point gouging, black for tangent plane interfering case, and green for feasible point.

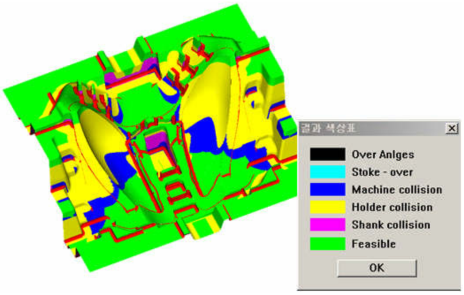


Fig. 7: Example of feasible region for given tool orientation.

3.3 Feasible Tool Orientation for given Region

It has been based on an experienced CAM programmer to find a feasible tool orientation in positional 5-axis machining, which may cause some interference problem in real machining if the part surface shape is complicated. Therefore the system computes feasible range of tool orientation for given part surface area, whose flow is depicted in Fig.8.

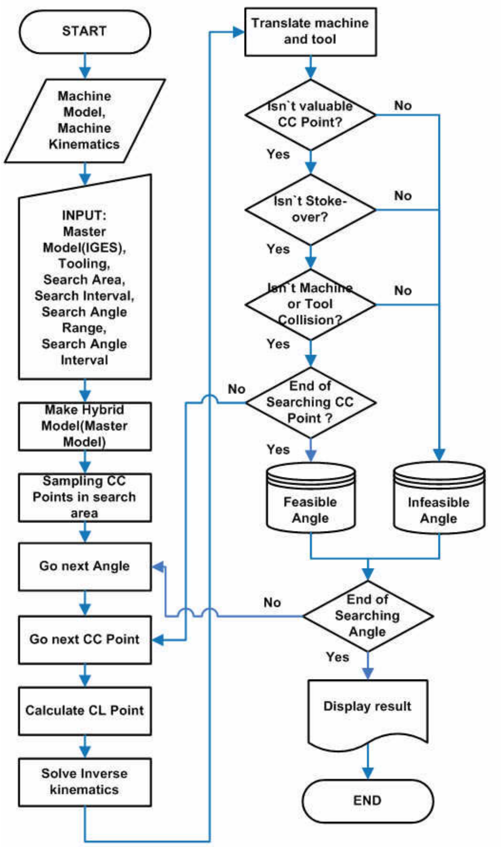
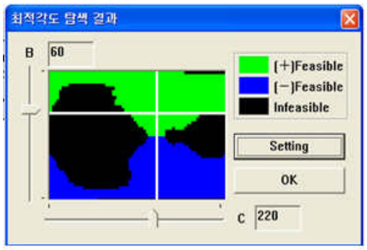


Fig. 8: Flow to compute feasible range of tool orientation.

A sample result of the flow is shown in Fig. 9 the tool orientation is translated into B & C axis values of the machine. Due to the machine's kinematical structure, two different inverse kinematic solution(see θ1 in Eqn.(3))for a CL data are obtained, which is denoted as two kinds of feasible solutions(+ and -).


최적각도 탐색 결과

B 60

C 220

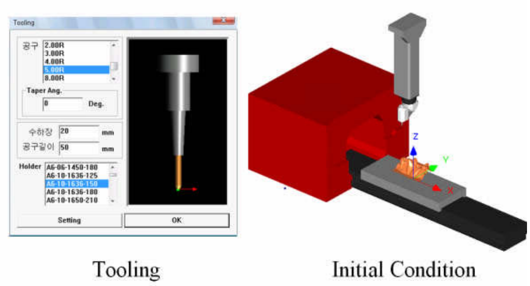
Fig. 9: Example result of feasible tool orientation for given region.

4. IMPLEMENTATION AND ILLUSTRATED EXAMPLE

The developed system has been implemented by Visual C++ on the Windows XP platform. Fig. 10(a) shows the applied NC machine. Also part surface of a molding die for auto headlamp is shown in Fig. 10(b), whose size is 1020x730x480mm. The implemented UI and test results are illustrated in Fig. 11.


(a) (b)

Fig. 10: Applied NC machine and sample molding die model.


Tooling

공구 5.00R

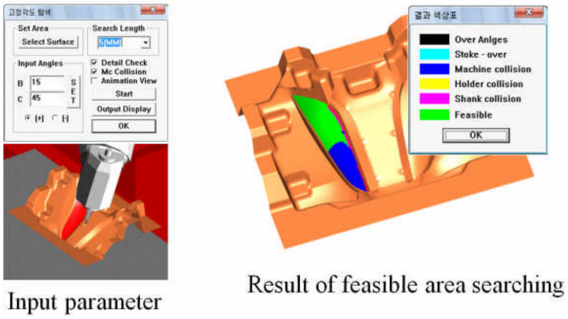
Taper Ang. 0 Deg.

수하장 20 mm

공구길이 50 mm

Holder A6-10-1636-150

(a) Tooling and Initial condition


고정각도 탐색

Search Length 5[MM]

B 15

C 45

● [+] ○ [-]

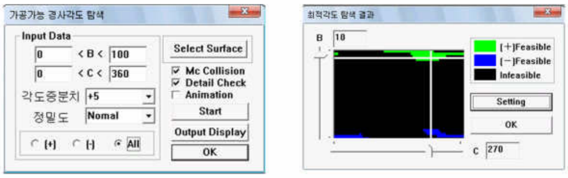
☑ Detail Check

☑ Mc Collision

☐ Animation View

결과 색상표

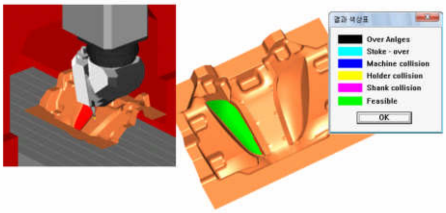
(b)Result of feasible region for given tool orientation



0 < B < 100
0 < C < 360
각도증분치 +5
정밀도 Nomal
○ (+) ○ (-) ● All
☑ Mc Collision
☑ Detail Check
☐ Animation

B 10
C 270

Input parameter   Result of valuable angles



Verification

(c)Result of feasible tool orientation for given region

Fig. 11: Developed system.

5. CONCLUSION AND FUTURE RESEARCH

A system has been developed, which generates feasible tool orientation and machinable region information in positional 5-axis NC machining. It provides the CAM programmer with feasible set-up condition, thereby facilitates avoiding unintentional machining error but also efficient process planning. The two approaches described in Section 3.2 and Section 3.3 (i.e., search of feasible region for a given tool orientation, search of feasible tool orientations for a given region) are selectively used by a CAM programmer depending on what kind information he/she needs.

Further research should be done as follows:

- Accuracy enhancement by adopting cut workpiece model,
- Applying general cutter types such as filleted and flat-ended cutters,
- Finding the optimal tool orientation for each sculptured form feature.

6. ACKNOWLEDGEMENT

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