Chapter 9. Five Axis Tool Path Generation Methods

Optimized NC-toolpath generation for 5-axis machining of complex surfaces

Prof. Dr. Ir. J.-P. Kruth (Jean-Pierre.Kruth@mech.kuleuven.ac.be)
Katholieke Universiteit Leuven, Celestijnenlaan 300 B, 3001 Heverlee, Belgium

Prof. Dr. Ir. B. Lauwers, Ir P. Dejonghe and Ir. J. Dotremont
Katholieke Universiteit Leuven, Celestijnenlaan 300 B, 3001 Heverlee, Belgium

Key words: CAD/CAM, 5-axis milling

Abstract: The toolpath generation method described in this paper is enhancing the sculptured surface machining methods, which can be found in commercial CAM-software packages. Tool axis inclination optimization is done based on the properties of the underlying surface and is a guarantee for gouge-free NC-toolpaths. The tool inclination varies along the toolpath in such a way that tool inclination is optimized for each individual tool position. The proposed method uses projected drive patterns and is able to take care of multiple and even trimmed part surfaces.

1. INTRODUCTION

Five axis machining of free form surfaces has many advantages if cylindrical or torical cutters are used instead of ball nose cutters. Compared to traditional three axis machining, the material removal rate increases and the machining time reduces. Commercial CAM-systems with multi-axis capability are forcing the operator to give the tool a certain constant lead and/or tilt angle (1) with respect to the surface normal. Further a set of multiple and trimmed surfaces can be machined within one operation through the use of drive surfaces. The drive surface is used to generate trajectories in a contact driven way, which are then projected onto the part surfaces. The tool orientation is calculated based either on the drive surface or the part surface.

Small lead angles are favourable to the material removal rate, surface roughness and surface accuracy [2]. But, applying a small constant lead angle along the milling path can cause different problems like gouging and variations in the scallop height. As a solution for this, several researchers have investigated the dynamic optimization and adaptation of the tool inclination along the tool trajectory [1][2]. The main drawback of most of these methods is that they are contact driven. This means that the tool is guided along the isoparametric lines of the part surface. As a result, only single surfaces without trimmings can be machined.

The toolpath generation method described in this paper optimizes the tool inclination in each point of the part surface. These developments fit in the frame of the OPTIMACH project. The goals of this EU-funded project are :

- Create reliable collision- and error-free NC-programs through an on-line closed loop simulation system.
- Enhance milling strategies in order to improve the achieved surface quality through optimizing the tool angle w.r.t. the workpiece and the step-over.

The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35392-0_40

G. J. Olling et al. (eds.), *Machining Impossible Shapes*

Depending on the prerequisites posed by the used CAD/CAM system, two main approaches have been followed during the development. The first approach is based on the prototype software, which has been developed in the past at the division PMA of the K.U.Leuven [2]. The second approach is a more practical solution, taking away the disadvantages from the first one. In both cases, the inclination adjustment is done during the tool path generation step (grey coloured block on *Figure 1*) and not during NC-simulation, NC-verification or on the machine.

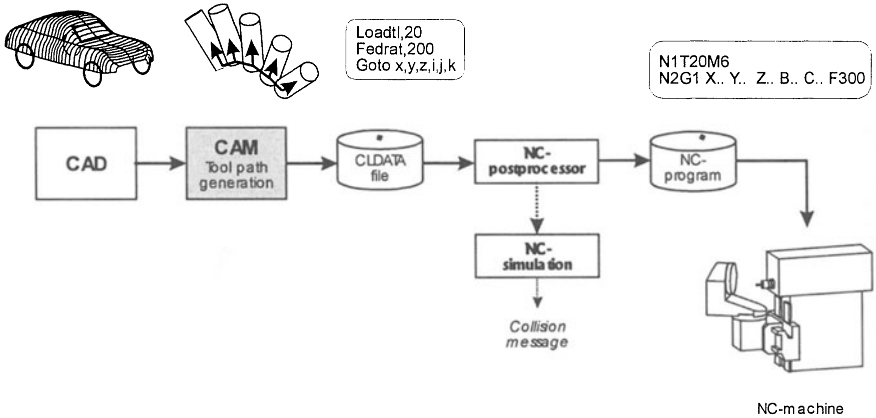


Figure 1. Overview of the toolpath generation process for a 5-axis NC-program

2. FIRST APPROACH : NUMERICAL OPTIMIZATION BASED ON THE ANALYTIC REPRESENTATION OF THE WORKPIECE GEOMETRY.

For this first approach, the standard CAD/CAM-routines are used to calculate each toolposture. A toolposture is the combination of tool position (xyz) and tool orientation (ijk). The tool inclination as calculated by the CAD/CAM-system is then used as the starting value for the optimization algorithms.

The routines of the standard CAD/CAM-system are generating the toolpostures in the following manner (*Figure 2*) :

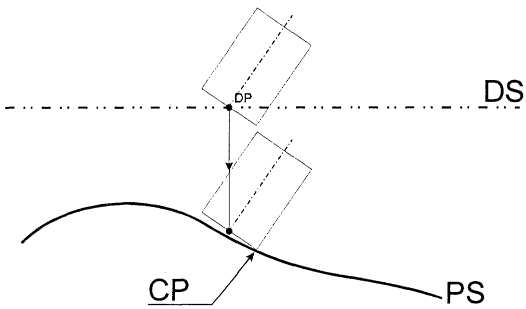


Figure 2. Method for generating toolpostures

A certain inclination angle is applied to the tool w.r.t. the surface normal of the corresponding tool tip point in the part surface.

The tool is then projected onto the part surface, where a contact point (CP) is found. If the inclination angle applied to the tool is large enough, the contact point will lie in front of the cutter.

The optimization algorithm, explained here for a cylindrical cutter, calculates the maximal angle $\Delta\theta$ over which the cutter may be rotated around the contact point (CP) to fit as close as possible to the part surface. To do this, the algorithm constructs a function $\theta = f(u,v)$ representing the relationship between the underlying surface of the tool and the angle over which the cutter is allowed to rotate. This function is then minimized to obtain the angle $\Delta\theta$. The minimization procedure is based on a two-dimensional Newton-Raphson method starting from a given point on the part surface. The result of this minimization method is the nearest local optimum in the surrounding of the given point.

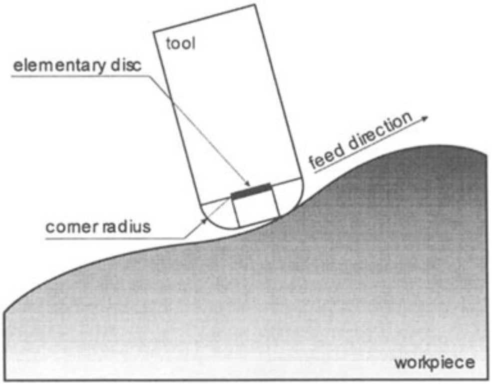


Figure 3. Elementary disc inside the cutter

The size of the underlying surface for which the function $\theta = f(u,v)$ is defined, is directly related to the tool diameter. The chance for having more local minima increases with the size of the cutter. As a consequence, the angle $\Delta\theta$ has to be calculated for more than one point, to be sure to find the smallest one. This is done by choosing a number of points on the bottom of the cylindrical cutter. For each point, the following is executed :

1) Compute the shortest distance to the underlying part surface. Consequently, the nearest point (P1) on the part surface is found.
2) The minimization is of $\theta = f(u,v)$ is done starting from the point P1.
3) Repeat step 2 until the requested accuracy is achieved.

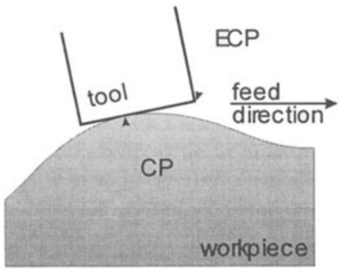


Figure 4. The expected contact point (ECP) is lying in front of the cutter, while the actual contact point (CP) is somewhere in the middle of the tool.

If a torical cutter is used, it can be mathematically reduced to a cylindrical cutter by subtracting the corner radius (*Figure 3*). All the equations can be written with respect to the elementary disc inside the cutter. Having a cylindrical cutter, this elementary disc equals to the bottom surface of the cutter.

Although this described method is working, it is not hold back for several reasons :
The algorithm is not robust enough. The contactpoint that is used in the method, is the contactpoint that is calculated by the used CAD/CAM-systems' tool position algorithm. Each tool posture that is not gouging is assumed by the CAD/CAM-system to be valid. This assumption results in the fact that the contactpoint is not necessary lying in front of the cutter (*Figure 4*)
The algorithm and especially the Newton-Raphson minimization method, is consuming too much CPU. Each toolposture is also calculated twice : first by the standard tool position algorithm of the CAD/CAM-system, second by the optimization algorithm.

3. SECOND APPROACH : ITERATIVE FULL PROJECTION METHOD

To cope with the disadvantages of the first approach a new method has to be found which is robust and faster.

Within the second approach, the first estimation of the tool axis inclination is not done by the standard CAD/CAM system, but is based on the properties of the part surface. This can be realized by constructing a local surface approximation at the contact point as explained below.

Consider a contact point (CP) on the part surface. First and second order derivatives can be calculated and from there, principal curvatures k_1 and k_2 are derived [6]. The surface near the contact point can be approximated by its quadratic approximation :

$$z = \frac{1}{2}(k_1 x^2 + k_2 y^2) \qquad (1)$$

If a cylindrical or torical cutter is positioned onto the part surface, it will be located on a sphere given by the equation (cr = corner radius of the cutter) (*Figure 5*) :

$$R_{sphere} = \frac{R_{cutter} - cr}{\sin(\theta_{inclination})} + cr \qquad (2)$$

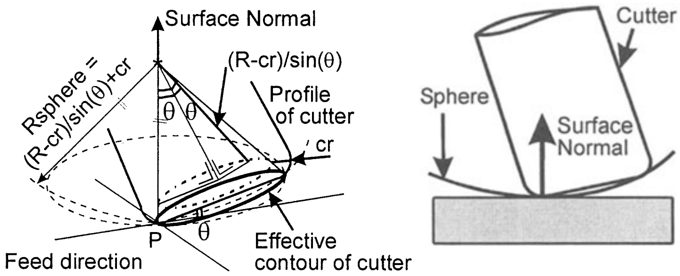
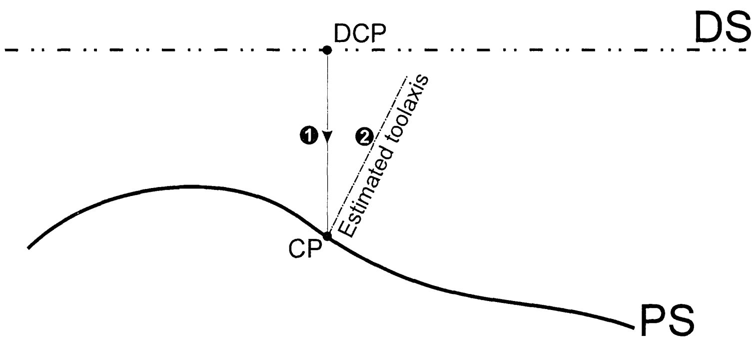


Figure 5. Contour of a cylindrical tool with corner radius located inside a fictive sphere

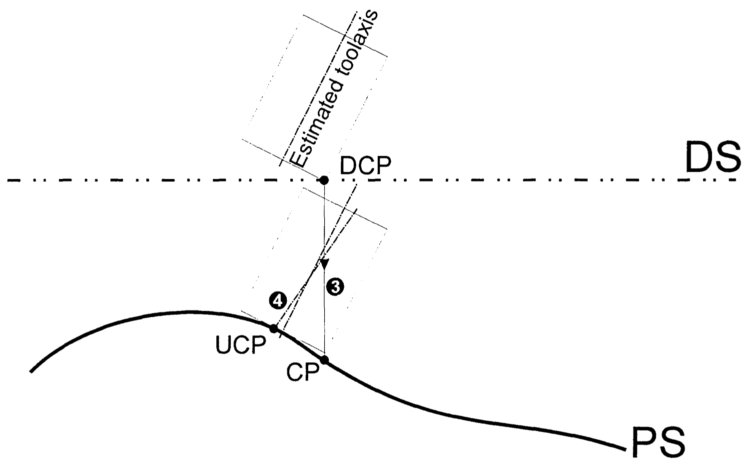
Combining equation 1 and 2 in an appropriate co-ordinate system, they are solved for the lead angle. The fact that this method is purely analytical counts as its' main advantage. However, if the surface is highly detailed and is milled with a large cutter (e.g. five-axis semifinishing), gouging can occur. Therefor, the estimated inclination need to be further optimized for avoiding gouging.

The principle of the second approach is fully described below :



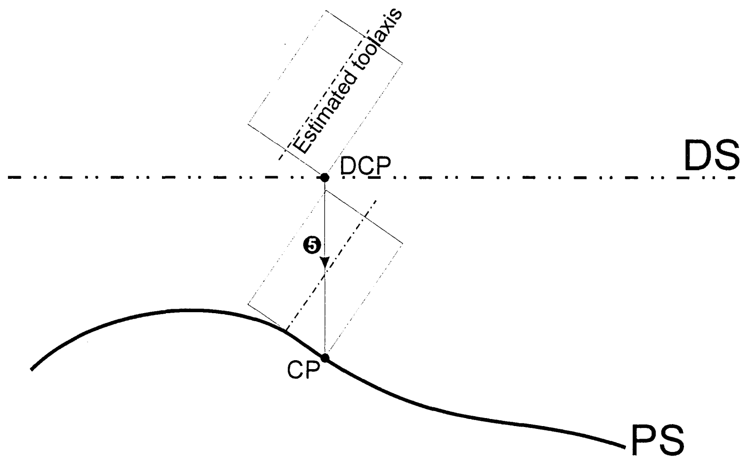
A given drive point is projected on the part surface (PS) and will be the contact point of the tool (CP). Therefor, the drive point is called the DCP, because it reflects to the contact point. This differs from commercial CAM systems, where a drive point normally corresponds to the tool tip.

In this contact point (CP), the local surface approximation is calculated (eq. 1). Out of this, an approximation of the toolaxis inclination can be calculated (eq. 2). The approximation is always made in such a way that gouging is very likely to occur when this estimated tool axis inclination would be used.



The full tool with the estimated toolaxis is projected down on the surface. This is done by using the standard CAD/CAM systems' functionality for tool projection. The tool projection returns a contact point (UCP), which might actually being located everywhere on the bottom of the cutter.

The toolaxis is then adjusted (a certain value is added for θ), based on the relationship between the contact point (CP) and the contact point returned by the tool projection method (UCP). The goal is to get CP as close as possible to UCP.



The tool is projected again with the newly found toolaxis. Doing the tool projection every time, gouging is avoided.

Steps ❸, ❹ and ❺ are repeated until a certain criterion is fulfilled. Possible criterions are : UCP close enough to CP, $\Delta\theta$ not positive anymore, ...

In general, after 2 or 3 iterations the optimized tool posture is found. Great care is taken to not rush the tool axis variations. Fast decreases of the tool inclination angle θ can cause the cutter to cut with his back. This is not favourable for tools that do not cut with the centre (e.g. torical cutters). Quickly increasing the tool inclination on the other hand can help the cutter to avoid gouging. As a result, the disturbance of the tool inclination angle θ per distance unit is limited to different values for decreasing and increasing tool axis inclination values.

4. \MACHINING RESULTS

For the experimental verification of the applied method, a workpiece (dimensions 100 x 100 mm) with a concave and convex region (*Figure 6*) was milled out of ureol and aluminium using a five-axis MAHO 600C milling machine. During the experiments, a torical cutter with a diameter of 20 mm and a corner radius of 4 mm was used. The number of tracks always equals to 20.

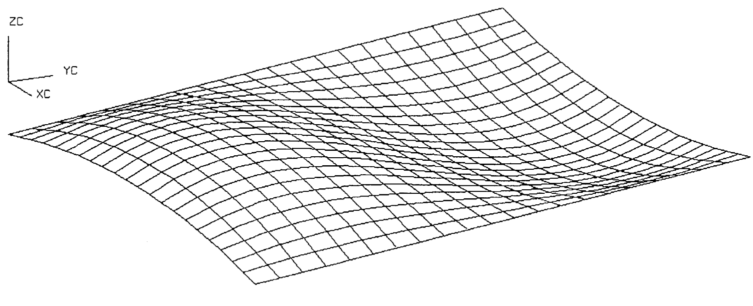


Figure 6. Surface with convex and concave region

One workpiece was milled with the standard routines of the CAD/CAM-system. For this test, a minimal inclination angle of 9 degrees has been applied. Another workpiece was milled using the optimized tool axis inclination routines.

The scallop height of the two workpieces was investigated using a 3D coordinate measuring machine COORD3 equipped with a Wolf&Beck laser-scanning probe. *Figure 7* shows the raw scanning data.

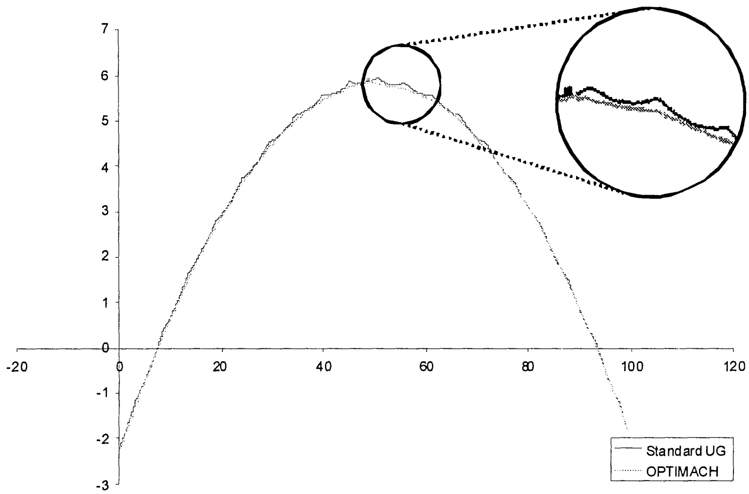


Figure 7. Measured profile of the workpiece in the convex region.

For this specific case, the largest benefit of the optimized method compared with the standard method was found in the convex region. In the concave region the cutter will always be forced to a larger tool inclination in order to prevent gouging.

5. CONCLUSION & CONTINUATION OF WORK

The proposed algorithms have been implemented inside a commercial CAD/CAM system. Experiments prove the algorithms from the second approach to be robust and general applicable. Since the optimization of the tool posture results in a larger material removal rate and a smaller scallop, the need for an accurate step-over calculation algorithm is originating.

ACKNOWLEDGEMENTS

The OPTIMACH project is being carried out in the frame of the Industrial and Materials Technologies research and technological development programme of the European Community with a financial EC contribution up to 1.923 kECU.

More information about this project can be found on the OPTIMACH-webpages : http://www.mech.kuleuven.ac.be/~optimach

APPENDIX

Different angular systems are in use to define the tool axis inclination. The most popular system, which also is found in most commercial CAM-systems is the lead-tilt system

(*Figure 8*). However, the inclination-screw system has advantages in the way the calculations are done, but is less obvious for the user of the CAM-system.

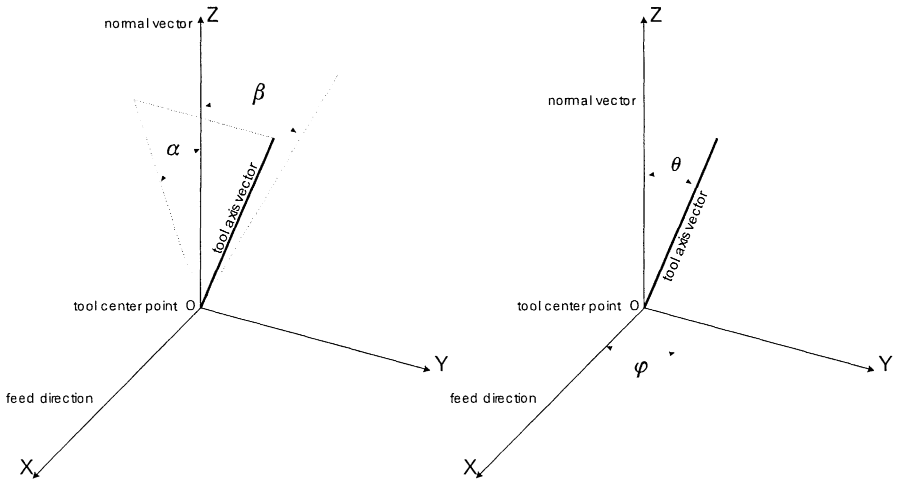


Figure 8. The lead-tilt system (lead = α and tilt=β) versus the inclination-screw system (inclination = θ and screw = φ).

The ability exists to switch from one angular system to another using these formulas :

Table 1. Transistion formulas between both angular systems

$x_{inclination-screw} = \cos\varphi.\sin\theta$	$x_{lead-tilt} = \sin\alpha$
$y_{inclination-screw} = \sin\varphi.\sin\theta$	$y_{lead-tilt} = -\cos\alpha.\sin\beta$
$z_{inclination-screw} = \cos\theta$	$z_{lead-tilt} = \cos\alpha.\cos\beta$

REFERENCES

[1] Choi B.K., Park J.W., Jun C.S., Cutter-location data optimization in 5-axis surface machining, Computer Aided Design, vol. 25, no. 6, 1993.

[2] Kruth J.-P., Klewais P., Optimization and Dynamic Adaptation of the Cutter Inclination during Five-Axis Milling of Sculptured Surfaces, Annals of the CIRP, vol. 43/1, p. 443-448, 1994

[3] Lee Y.S., Decision Support Environment for Advanced Multi-axis CNC Machining, 4th Industrial Engineering Research Conference Proceedings, p. 260-268, 1995.

[4] Lee Y.S., Ji H., Surface interrogation and machining strip evaluation for 5-axis CNC die and mold machining, International Journal of Production Research, vol. 35, no. 1, p. 22-252, 1995

[5] Li S.X., Jerard R.B., 5-axis machining of sculptured surfaces with a flat-end cutter, Computer Aided Design, vol. 26, no. 3, 1994.

[6] Marciniak K., Geometric Modelling for Numerically Controlled Machining, Oxford University Press, 1991.

[7] Marciniak K., Influence of surface shape on admissible tool positions in 5-axis face milling, Computer Aided Design, vol. 19, no. 5, 1987.

[8] Saar A., Lauwers B., Dejonghe P., Optimised tool path generation methods for economic and collision free multi-axis machining, Proceeding of the 31st ISATA conference, 1998.