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# Description formats of tool trajectory suited to High-speed machining

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**Abstract.** Numerous works have shown that the linear format of tool path is not well adapted to HSM for it does not allow an optimal follow-up of the tool trajectory by the NC unit, nor a good part surface quality. This paper deals with formats of tool trajectory relying on polynomial models. The tool path can be described as polynomial curves as well as polynomial surfaces. Geometrical and dynamical advantages of using such formats are exposed.

## Introduction

From now on, High-Speed Machining (HSM) is largely used for the machining of sculptured surfaces within the fields of aeronautics, automotive, and moulds and dies, for it ensures a high level of geometrical surface quality and a competitive machining time [1]. From a CAD model of the surface, the tool trajectory is calculated using a CAM system. The trajectories, and the corresponding feedrates, are transmitted to the numerical control unit of the machine tool that allows the control of the tool axes. Therefore, the optimization of HSM is strongly linked to the performance of the CAM system/Numerical control unit couple.

Usually, algorithms for tool trajectory calculation only rely on geometrical criteria and do not consider dynamic capacities of both the numerical control unit and the machine tool. Recent work pointed out that constraints and limits linked to HSM must be integrated when calculating tool trajectory [2]. Other work highlighted that the linear format is not well adapted to HSM, for geometrical as well as dynamical considerations. The machined surface is an approximation of the CAD surface, and the feedrate is largely decreased when traversing discontinuities.

To answer both constraints, a good geometrical description of the surface and a better follow-up by the numerical control unit, this paper deals with polynomial formats for tool trajectory well adapted to HSM. Henceforth, CAM systems can calculate tool trajectories expressed as polynomial curves directly from the CAD model. In the same time, Numerical Control (NC) units have evolved to interpret and control these curves. As the continuity is guaranteed, the dynamical follow-up by the numerical control unit is thus improved [3]. An extension of the previous model is obtained by considering that both curves belong to surfaces. Therefore the tool trajectory is defined as a bi-parametric space, the machining surface [4]. Such a model allows uncoupling geometrical and dynamical effects.

## Tool trajectory and HSM specificity

Within the context of high speed machining of free form surfaces, two main objectives must be reached. The first one is machining time reduction for cost reasons: the high speeds must be maintained all trajectory long preserving the most continuous movements possible. The second one deals with improving the quality of the machined surface or with ensuring the part to satisfy the expected quality.

Tool trajectory is essential in this context for it makes the link between the CAD model of the free form to be machined and the NC unit. The NC unit controls machine tool axes so that the tool moves along the calculated trajectory with the programmed feedrate. Therefore, the nature and the

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description of the tool trajectory are of major influence on the machine-tool behavior and the part quality. Basically, the tool trajectory is calculated from the CAD model using a CAM system. The trajectory consists of a discrete set of tool positions calculated according to the machining tolerance (in the machining direction) and the maximum scallop height allowed (in the perpendicular direction). The continuity of the trajectory is obtained from the tool movement during machining. When using the linear interpolation format, the tool is supposed to be moving in straight line between two successive positions. Therefore, the use of the linear interpolation introduces tangency discontinuities all trajectory long. Due to the limits of the NC unit, significant decreases in feedrates compared with specified ones are observed, leading to an increase in machining time as well as an alteration of the geometrical quality of the machined surface [3]. Physical limits of the NC have to be considered when calculating the tool trajectory from the CAD model.

As each axis is moved using a linear motor, the system cannot physically traverse  $C^0$ ,  $C^1$  or  $C^2$  discontinuities: the tension should be infinite. To overcome this problem when using linear interpolation format (only  $C^0$  continuous), the NC unit's own trajectory generator recalculates a  $C^2$  continuous trajectory near the discontinuity point. One solution is to add an arc of circle between the two successive lines. The most popular solution is the real-time polynomial interpolation, which approximates the initial calculated trajectory by a polynomial trajectory. To preserve continuity of the tool path while maintaining the programmed feedrate, authors suggest different parameterization techniques to generate real-time trajectories with smooth velocity [5-6]. Nevertheless, the whole tool path is approximated.

Therefore, to be efficient at high speeds, the follow-up of the tool path imposes that the calculated tool path must be at least  $C^2$  continuous. Our work has concentrated on this issue by proposing a native polynomial format for tool trajectory. Whatever the nature of the machining, the tool path is calculated from the CAD model using polynomial curves. These curves are transmitted to the NC unit, which is now possible considering recent evolutions of the NC unit.

### **Tool trajectory as polynomial curves**

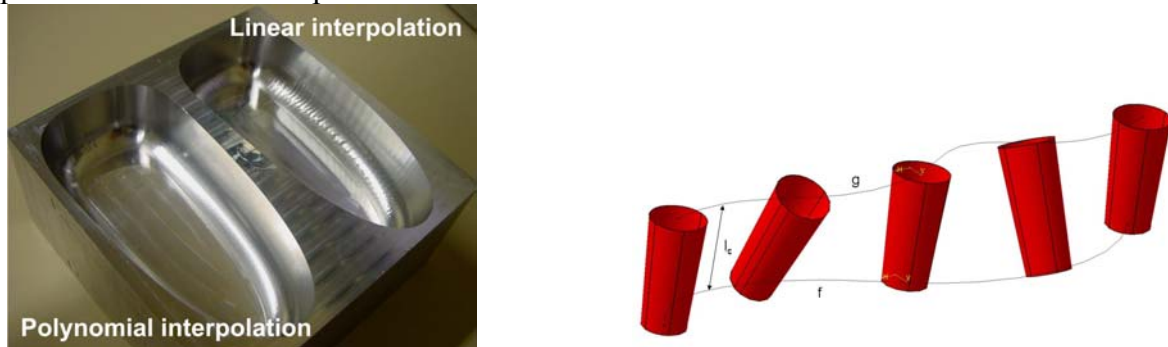
When using the polynomial format, the tool trajectory is calculated as two curves: one curve,  $f$ , corresponding to the trajectory of the tip ( $C_L$  point), and the second curve,  $g$ , is the trajectory of a particular point of the tool axis. The distance between the two curves is a constant value during the whole tool movement (Fig. 1). Each curve is defined in the part coordinate system by its nodal sequence and by a set of control points.

Some advanced industrial NC units interpret this format. In order to dissociate this format from this calculated using real-time curve interpolators [5-6], we define this trajectory format as *native polynomial trajectory*. However, only the NC unit can interpret a few models. For simplicity reasons, and considering that the majority of free-form surfaces are described through B-spline curves, this model is retained. To ensure a  $C^2$  continuity,  $f$  and  $g$  are calculated as cubic B-spline curves. Therefore, the trajectory is simply calculated using usual interpolation algorithms modified to take machining specifications into account.

The first interesting result is that there is no loss of information in the process of data transmission between the CAD/CAM system and the NC unit. The CAD/CAM system ensures the calculation of the tool path according to geometrical specifications as polynomial curves. The NC unit manages the instructions of positions and speeds while respecting the follow-up of the desired tool path within the given tolerance using the same description format.

Previous work has shown benefits of using native polynomial format in HSM in comparison with the linear one [3]. The follow-up of the tool trajectory is better when traversing  $C^1$  discontinuity; in particular decreases in velocity are lower. Tool movements are smoother which leads to a better part surface quality (Fig. 1). Moreover, the mean velocity is increased which involves a decrease in machining time. In 5-axis machining, we take advantage of the native polynomial format to solve

different problems. Indeed, as the trajectory is a  $C^2$  continuous model, it can easily be deformed in order to optimize tool trajectories within the context of HSM, or to answer geometrical criteria. The paper relates various examples we have treated.



**Figure 1.** Tool trajectory as polynomial curves

The first one addresses a method well adapted to correct positioning errors in 5-axis flank milling. In a first stage, positioning errors are evaluated calculating geometrical deviations between the envelope surface of the tool movement and the surface to be machined [7]. The next step is the deformation of the two curves  $f$  and  $g$  that are representative of the tool trajectory (or of portions of the tool trajectory) so that geometrical deviations are optimized. Note that,  $f$  and  $g$  define a ruled surface. The correction thus consists in optimizing the position of the ruled surface so that the envelope surface generated by the tool movement better fits the surface to be machined according to the least-square criterion. With such a correction method, the continuity of the tool path is preserved: the corrected tool path is derived from a surface model. Indeed, a new ruled surface corresponding to the tool trajectory can be built from the deformed B-spline curves, the position of which is optimized with regard to the surface to be machined.

Our second example concerns the detection and the avoidance of the singular cone [8]. Due to the inverse kinematics transformation allowing to express *articular* variables in function of the calculated tool positions (tool tip and axis position), unpredictable behavior may occur when the tool traverses some positions of the workspace. At these positions, called singular positions, the orientation of the tool must be abruptly changed, and we observe incoherent and very rapid movements of one of the rotation axes. This involves great correction displacements of the translation axes, and an important reduction of the feedrate. As a result, the specified feedrate is not respected which is critical within the context of HSM. With native polynomial interpolation, the singularity problem is localized on a portion of the tool trajectory whereas with linear interpolation, the problem is localized on a single point. The treatment of the singularity must be handled during the tool path calculation stage. As the treatment is performed by the CAD/CAM system, the whole geometrical information is known, and it thus becomes easy to deform the tool path so that it does not traverse the singularity. The deformation of both curves is simply managed by the displacement of control points defining the curves.

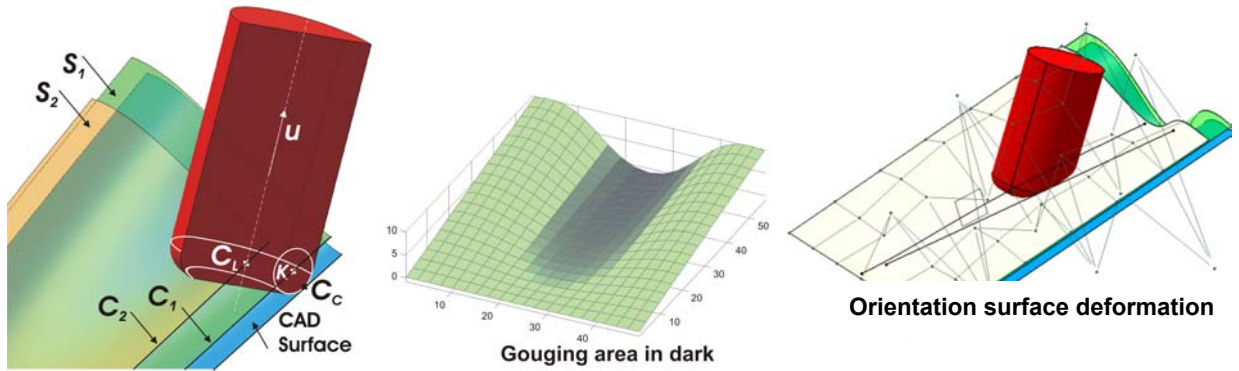
The last illustration is an extension of the previous described method: the deformation method allows the optimization of the dynamical behavior of the machine tool. It is well known that in five-axis machining, the rotation axes are critical in the field of HSM. They are much slower than translation axes. Our goal is then to optimize the tool trajectory in the rotation space so as to minimize the movements on these axes. If there are less solicitations of these axes, the feedrate can be reached and machining time reduced.

### **Tool trajectory as a surface**

We focus in this section on the opportunity to use the polynomial interpolation format to compute tool paths in 5-axis end milling. As seen above, the tool movement in 5-axis can be described by two B-Spline curves defining a ruled surface. The objective is now to extend the model from a curve to a

surface. Considering that the offset surface in 3-axis ball end milling is the representation of the tool path as a surface motivates this purpose. In 5-axis machining, we need to control at least two points of to set up the tool in the 3D space. That means that two surfaces allow the calculation of the tool trajectory.

We have already shown that the couple  $(C_L, \mathbf{u})$  commonly used to locate the tool in 5-axes is not well appropriate to conceive tool paths as surfaces in the case of the filleted end milling [4]. To solve this problem, we suggest to use the point  $K$  to set up the tool.  $K$  is defined as the offset point of  $C_c$  by an offset distance equal to the corner radius  $r$  of the tool. The point  $K$  plays a particular role for it remains fixed during the rotation movements of the tool when the tool is set in position. The definition of points  $K$ ,  $C_L$  and the normal vector  $\mathbf{n}$  is thus sufficient to position the tool in the 3D space.



**Figure 2.** Definition of the guiding and orientation surfaces defining the tool path

The tool path surface thus consists of two surfaces  $S_1$  and  $S_2$ , loci of the points  $K$  and  $C_L$  with:

$$S_1(u,v) = S(u,v) + r \cdot \mathbf{n}(u,v) \text{ and } S_2(u,v) = S(u,v) + r \cdot \mathbf{n}(u,v) + (R-r) \cdot \mathbf{v}(u,v) \quad (1)$$

$S_1$  is called the guiding surface and  $S_2$  the orientation surface (Fig. 2). The guiding surface  $S_1$  is the offset surface of the CAD model surface  $S(u,v)$  by a value equal to the corner radius  $r$  of the tool. It is thus independent of the machining strategy. We can plan tool paths in its parametric space as in 3-axis ball end milling. The orientation surface  $S_2$  is the surface that gives the orientation of the tool axis according to the considered machining strategy. The orientation surface  $S_2$  is located between two limit surfaces  $S_{low}$  and  $S_{upp}$ . The upper limit corresponds to the case for which the tool axis orientation is parallel to the tool feed direction. The lower one corresponds to the case for which the tool axis orientation is parallel to the normal vector. We propose to build the guiding and orientation surfaces as multi-patch surfaces because  $S_1$  and  $S_2$  are generalized offset surfaces [9]. The precision obtained on surfaces  $S_1$  and  $S_2$  is proportional to the number of patches. From a point  $K$  on  $S_1$  one finds the corresponding point  $C_L$  on  $S_2$  with the assumption that parameter setting of  $S_1$  and  $S_2$  are identical. Thus the method generates approximations. The errors on the guiding surface  $S_1$  must be controlled because they cause local gouging between the tool and the nominal surface at the  $C_c$  point. On the other hand, errors on the orientation surface  $S_2$  present fewer disadvantages since the variations of orientation of the tool axis do not generate machining errors. The orientation surface is built according to the desired orientation of the tool all trajectory long.

We take advantage of this bi-parametric model of the orientation surface to prevent gouging. To illustrate our purpose, let us consider the machining of a surface according to the parallel plane strategy, we have set the angles of the tool axis according to the surface normal. The guiding surface can be modeled through an implicit or an explicit representation. Tool path are thus calculated on the guiding surface to ensure a maximum scallop height. The point  $K$  follows the curve  $C_1$ , intersection of the guiding plane and  $S_1$ , and  $C_L$  follows  $C_2$ , the curve built on  $S_2$  according to the tool axis angles

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(Fig. 2). If we use the linear interpolation format, we have to check for gouging and if needed, we must change the tool axis orientation successively in every sampled points [10]. The variation of the tool axis orientation is not continuous, affecting the dynamical behavior of the machine tool. Furthermore, the maximum scallop height can be affected so that the tool path has to be regenerated. When using the surface representation, the tool path on the part can be modified in real time and the tool axis orientation can evolve smoothly by deforming the orientation surface with usual CAD tools. The orientation surface might be set to avoid gouging between the tool and the part.

## Conclusion

In this paper, we have presented native polynomial formats for tool trajectory that improve the performance of the couple CAD/CAM system and NC unit within the context of HSM. Indeed, these models are at least  $C^2$  continuous which ensures a good dynamical follow-up by the numerical control unit during machining. Moreover, the so calculated tool path can be easily deformed to answer dynamical (avoiding the singular cone, avoiding gouging, ...), mechanical (integration of the tool deformation, ....) or geometrical constraints (limiting geometrical deviations, ...).

## References

- [1] Schultz H., High Speed Milling of dies and moulds, cutting conditions and technology, *Annals of the CIRP*, Vol. 44(1), (1995), pp. 35-38
- [2] [3] Dugas A., Lee J-J., Hascoët J-Y., High Speed Milling – Solid simulation and machine limits, *Integrated Design and Manufacturing in Mechanical Engineering*, Kluwer Academic Publishers (2002), pp. 287-294
- [3] Duc E., Lartigue C., Laporte S., Assessment of the description format of tool trajectories in 3 axis High Speed Machining of sculptured surfaces, *Metal cutting and High Speed machining*, Kluwer Academic Publishers (2001), pp 363-374
- [4] C. Tournier, E. Duc, C. Lartigue, A. Contri, The concept of the machining surface in 5-axis milling of free form surfaces, *IDMME'2000*, Kluwer Academic Publishers, pp. 279-286, 2002
- [5] Y. Altintas, K. Erkorkmaz, Feedrate Optimization for Spline Interpolation in High Speed Machine Tools, *Annals of the CIRP* 52(1) (2003) 297-302.
- [6] R.V. Fleisig, A.D. Spence, A constant feed and reduced angular acceleration interpolation algorithm for multi-axis machining, *Computer Aided Design* 33 (2001) 1-15.
- [7] C. Lartigue, E. Duc, A. Affouard, Tool path deformation in 5-axis flank milling using envelope surface, *Computer Aided Design* 35 (2003) 375-382.
- [8] A. Affouard, E. Duc, C. Lartigue, J.-M. Langeron, P. Bourdet, Avoiding 5-axis singularities using tool path deformation, *International Journal of Machine Tools and Manufacture*, in press
- [9] R.T. Farouki, The approximation of non degenerate offset surfaces, *Computer-Aided Geometric Design*, vol. 3, p. 15-43, 1986.
- [10] Y.S Lee, Admissible tool orientation control of gouging avoidance for 5-axis complex surface machining, *Computer-Aided Design*, vol. 29, no. 7, p. 507-521, 1997.