

# MODEL BASED CALCULATION OF THE TOOL-PATH SMOOTHING TOLERANCES

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## INTRODUCTION

Smoothing the tool path and the tool orientation within a certain tolerance is a common approach for reducing the mechanical excitation of a machine tool [1]. This is normally done by insertion of  $C_n$ -continuous polynomial-functions like NURBS or B-Splines assuming a constant value for the smoothing tolerance along the whole tool path. This value has to be smaller than the final tolerance value which is obtained for the finished part because of additional machining errors during the manufacturing process. These errors consist of geometric, dynamic and thermal errors as the effect of follow-up errors of the axis drives [2]. Non-regarding these errors causes a very small and constant value for the smoothing tolerance. This leads to higher curvatures of the tool path and finally to a higher mechanical excitation of the machine tool for a given path velocity. Figure 1 illustrates the effect of different path tolerances on the resulting curvature for corners having an angular range between 0 (straight) and 120 degrees.

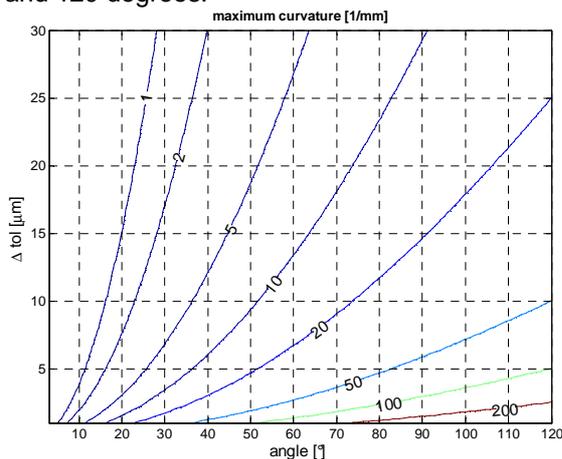


FIGURE 1. Resulting curvatures for a smoothed corner depending on the smoothing tolerance and the angular range of the corner.

There are several ways known for measuring and modeling the machining errors in order to

compensate them [3]. Regarding the smoothing of the tool path and the tool orientation current smoothing-algorithms are not able to predict the diversity of the machining uncertainties along the tool path. Here, a simple tolerance model for the prediction of geometric uncertainties along the tool path for a given work piece and a given machine is presented and applied for the two and five axis case.

At first, the geometrical errors of the linear axes and the resulting uncertainties for 3-axis machine tool movements are shown. Next, the geometric uncertainties of rotational axes and their contributions to the resulting uncertainties at the Tool-Center-Point (TCP) are added. In a final step the calculation results of the available smoothing tolerance are shown.

## GEOMETRICAL UNCERTAINTIES OF A 3-AXIS MACHINE TOOL

In this section the calculation and merging of geometric uncertainties is shown for the example of a movement of 3 cartesian axes. As defined in ISO 230-1 [4] there are 6 element deviations defined for each linear axis listed for the example of a linear X-axis:

- EXX: positional deviation
- EYX: linear deviation
- EZX: linear deviation
- EAX: roll deviation
- EBX: pitch deviation
- ECX: yaw deviation

The resulting 18 element errors for 3 linear axes and the 3 squareness errors

- C0Y: out of squareness between X and Y
- B0Z: out of squareness between X and Z
- A0Z: out of squareness between Y and Z

yield to 21 geometric errors for a 3 axis machine. All these error contributors are merged to the axis-wise geometric standard uncertainties  $U_x$ ,  $U_y$  and  $U_z$ , so by knowing the geometric errors, the tool path and the part dimensions for every position of the trajectory the geometric uncertainties can be calculated. Depending on

the regarded machining process there exists a relevant direction for the uncertainty. For the example of 2D laser cutting Figure2 shows the effective uncertainty in lateral direction for a 2D work piece. In this case, for a quite small work piece and when only two axes are involved in the movement, the resulting uncertainties only slightly differ along the path.

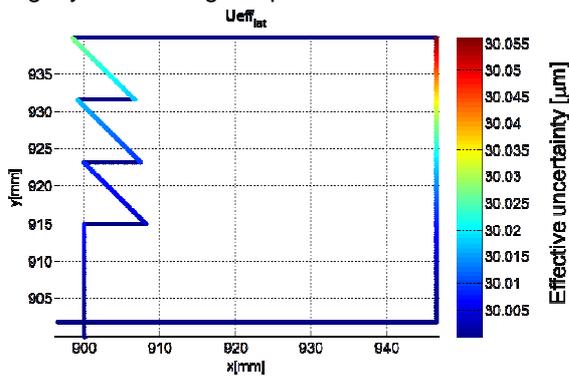


FIGURE2. Effective uncertainty in lateral direction for a 2D laser cutting work piece

### GEOMETRICAL UNCERTAINTIES OF A 5-AXIS MACHINE TOOL

Regarding a rotational axis there are 6 element deviations defined, listed for the example of a rotational C-axis:

- EXC: radial error motion
- EYC: radial error motion
- EZC: axial error motion
- EAC: tilt error motion
- EBC: tilt error motion
- ECC: positional deviation

Together with the geometric errors of the 3 linear axes, the component errors for 2 rotational axes and the additional location errors lead to the geometric errors for a 5 axis machine tool movement.

The resulting combined uncertainties are calculated as follows: The geometry of the tool consisting of translatoric and rotatoric set-point trajectories also including the orientation of the tool is defined at the TCP. After transforming the TCP into the Machine-Coordinate-System (MCS) the movements of the machine tool axes are known. After identifying the geometric errors for each axis [5] the geometric uncertainties can be calculated and merged as combined standard deviations for the TCP movement for each cartesian direction at the TCP.

For the example of laser cutting Figure3 shows a typical 3D-movement including changes of the orientation of the tool along the TCP-path. This

leads to large compensating movements of the linear axes which is shown in Figure2.

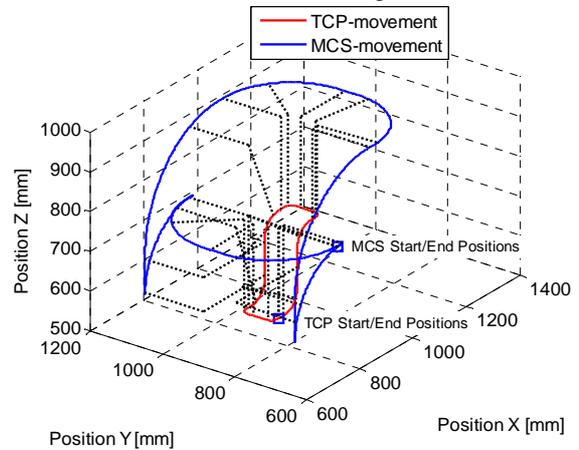


FIGURE3. 5-Axis movement shown for 5-axis laser-cutting.

Due to the increased number of axes, but also caused by the large compensating movements the uncertainties strongly increase. The deviations in x and y -direction which finally lead to the effective uncertainty in lateral direction are shown in Figure4-5. The deviation in z-direction has no influence on the effective uncertainty in lateral direction and is not regarded in this example. EXCTCP, EYCTCP, EX0XY and EY0XY in Figure4-5 are contributors caused by element and out of squareness errors of the involved rotational axes. Because of the large distance between the TCP and the rotation-center of these axes the resulting TCP uncertainties of these contributors are dominant.

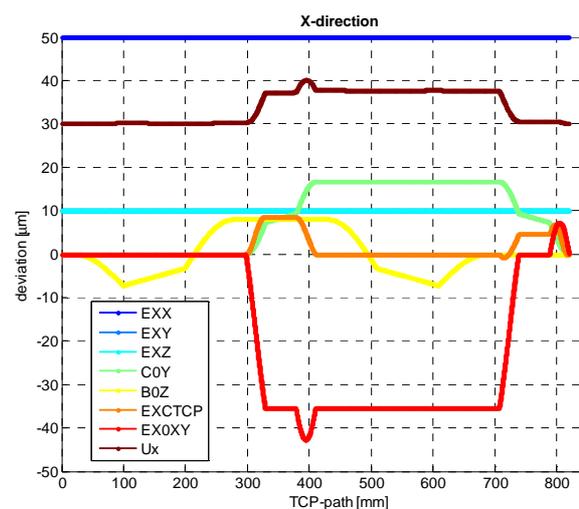


FIGURE4. TCP-deviations in x-direction along the TCP-path

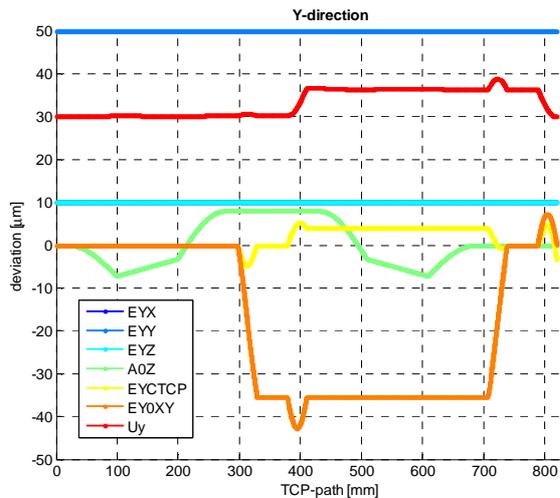


FIGURE5. TCP-deviations in y-direction along the TCP-path

The resulting effective uncertainty of the TCP in lateral direction is shown in Figure6.

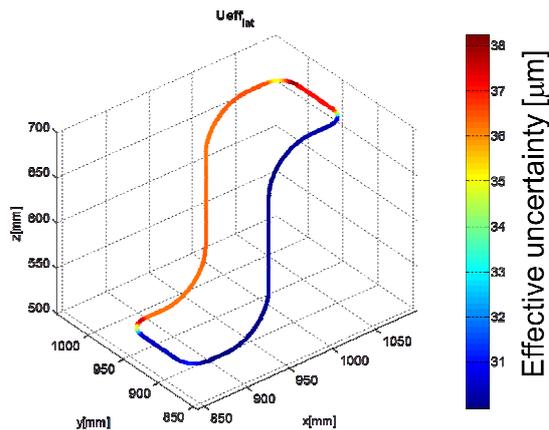


FIGURE6. Effective TCP-uncertainties for a 5-Axis movement shown for 5-axis laser-cutting.

- constant values for
  - thermal deviation
  - dynamic deviation
  - process deviation
- position dependent values for the geometric uncertainties

## CONCLUSION

A procedure for the elaboration of the available smoothing tolerances based on the geometric errors of a machine-tool has been shown for the two and five axis case. Depending on part geometry and the allowable range for application of path smoothing can be determined.

## REFERENCES

- [1] Hadorn, M. Optimal Set Point Generation for Machine Tools under Nonlinear Constraints ETH Zurich, Switzerland, 2007
- [2] Andolfatto, L.; Lavernhe, S. & Mayer, J. Evaluation of servo, geometric and dynamic error sources on five-axis high-speed machine tool International Journal of Machine Tools and Manufacture, 2011, 51, 787 – 796
- [3] Okafor, A. & Ertekin, Y. M. Derivation of machine tool error models and error compensation procedure for three axes vertical machining center using rigid body kinematics International Journal of Machine Tools and Manufacture, 2000, 40, 1199 – 1213
- [4] ISO 230-1: Test code for machine tools-Part 1: Geometric accuracy of machines operating under no-load or finishing conditions 1996
- [5] Treib, T., 1987, Error Budgeting-applied to the calculation and optimization of the volumetric error field of multiaxis systems, Annals of the CIRP Vol. 36/1/1987, Hallwag Bern

## CALCULATION OF THE AVAILABLE SMOOTHING TOLERANCE

The following 3 steps finally lead to the available smoothing tolerance:

1. Calculation of the so-called NC-tolerance based on the technical drawing and the tolerance value which is obtained for the finished part assuming an ideal machine tool with no deviations.
2. Calculation of the effective uncertainties based on component and location errors as illustrated before.
3. Reduction of the NC-tolerance calculated in step1 by