Demand oriented Calibration of 5-Axis Machine Tools

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Abstract

The metrological calibration of 5-axis machines requires a huge effort. The Fraunhofer IPT investigates the reduction of these efforts by developing demand oriented measurement strategies. For this the geometrical axis errors will be modelled mathematically and evaluated systematically in order to identify the relevant errors, which have to be indentified. Furthermore the utilization of available measurement systems for the metrological calibration task will be analyzed. The aim is to design calibration strategies tailored to specific 5-axis machine types. Within this paper the principle approaches of this project will be presented.

1 Introduction and motivation

To ensure an efficient production process many metrological devices and methods are available for the geometrical calibration of machine axes. However for the specific needs of 5-axis calibration several gaps can be identified:

- Most of the available measurement systems focus on single linear axis.
- A full 5-axis calibration requires the sequential use of different metrology.
- The complex interaction of errors causes a huge effort for the identification.

Consequently the goal is to reduce the necessary effort without decreasing the achievable improvement of the machining accuracy. To meet this challenge a concept for demand oriented calibration will be elaborated. The basis of this concept is the systematic analysis of the relevant error budget.

2 Error models of single axes

For the metrological calibration, for systematic analysis as well as evaluations and for controller based compensation, the geometrical errors within a machine tool have to be modelled. According to [1] and [2] the real position of a reference point on a linear machine axis, represented by a vector L, is determined by six single errors according to the six degrees of freedom and can be modelled as

$$\vec{x}(x) = \vec{N}(x) + \Delta\vec{T}(x) + \Delta R(x)\cdot\vec{L} \qquad (1)$$

In this equation the 3x1 vector ΔT(x) represents the translational axis errors, the 3x3 matrix ΔR(x) the rotational errors and the 3x1 vector N(x) the nominal axis position. For a rotary axis the basic error equation, where N(x) represents the 3x3 matrix of the nominal rotation, is

$$\vec{x}(x) = \Delta\vec{T}(x) + \Delta R(x)\cdot N(x)\cdot\vec{L} \qquad (2)$$

3 Error models of 5-axis machine tools

3.1 Full error budget and models of a 5.axis machines

The accuracy of a 5-axis machine will be influenced (neglecting the spindle) by 43 single errors (6 errors per axis, 3 orientation errors of the linear axis system, 2 orientation errors per rotary axis and 3 position errors (position in linear axis system) per rotary axis). Accordingly to equation (1), for each of the 5 axis an error equation can be formulated. To model a complete 5-axis machine, the single equations have to be linked by regarding the orientation errors matrix O(x) and the position error vector P(x). For a 5-axis machine with C-A-Y-X-Z axis configuration, the model is

$$\begin{aligned}&\vec{x}(x,y,z,a,c) = \\ &\Delta O(y)\cdot\left[\vec{N}(y)+\Delta\vec{T}(y)+\Delta R(y)\cdot\Delta O(x)\cdot\left[\vec{N}(x)+\Delta\vec{T}(x)+\Delta R(x)\cdot\Delta O(z)\cdot\left[\vec{N}(z)+\Delta\vec{T}(z)+\Delta R(z)\cdot\vec{L}(z)\right]\right]\right] \\ &-\Delta O(a)\cdot\left[\vec{P}(a)+\Delta\vec{T}(a)+\Delta R(a)\cdot N(a)\cdot\Delta O(c)\cdot\left[\vec{P}(c)+\Delta\vec{T}(c)+\Delta R(c)\cdot N(c)\cdot\vec{L}(c)\right]\right]\end{aligned} \qquad (3)$$

Here L(z) represents the tool geometry and L(c) a local position of the work piece.

By expanding equation (3), the relative deviation between TCP and work piece (machining accuracy) is described by a 3x1 vector including 447 summands composed of the 43 single errors and the parameters describing the machine geometry. However the error model can be reduced significantly without decreasing the validity of this model. Furthermore it can be evidenced that, depending on the axes configuration and dimensions, not every error has to be considered.

3.2 Reduced error budget and models of 5-axis machines

Most of the 447 summands are composed of products of two or more axis errors. It can be presumed, that the impact of these products is minor than the impact of the summands composed of one single error or one single error combined with a geometry parameter. By disregarding these error products, the number of summands decreases to 58. Whereas the validity of the model will not be reduced: Assuming a representative set of axis errors for all five axes, the error caused deviation between TCP and work piece within performing a 5-aixs circle movement (figure 1), deviates maximal 0.01 % considering the full and the reduced model. Furthermore the impact of different geometry parameters like the tool length can be discussed by means of this model. Table 1 shows that the error reduction do not influence the validity of the model, however the tool length has to be considered for the machine calibration. Analyzing varying parameter setups, the goal of the simulations is to reduce the calibration effort by identifying superior and inferior errors for different axis configurations.

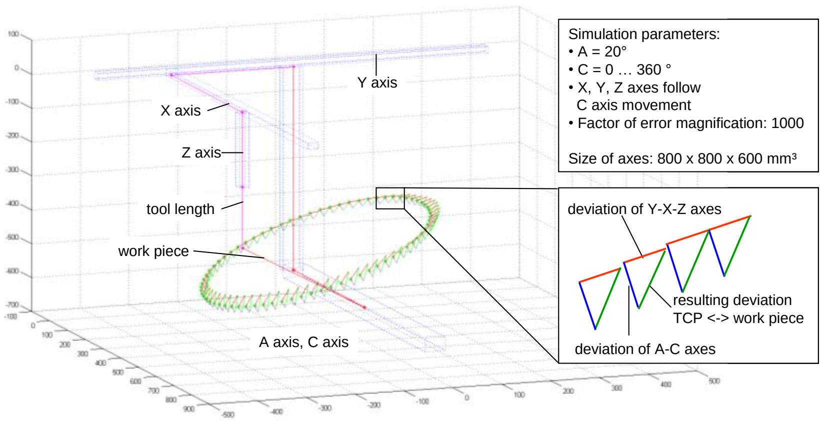

Figure 2: Error impact simulation, based on developed 5-axis model

Table 1: Impact of different tool geometries

Tool length [mm]	0	180	320
Deviation to full model [%]	0.0059	0.0017	0.0041
Deviation to zero tool length [%]	-	25.3	15.9

4 Demand oriented calibration

A reduced error budget and model tailored to real needs of accuracy improvement is the basis for the development of demand oriented calibration strategies. Comparing the analyzed error budget of different 5-axis configurations and the capabilities of the available metrology, an effective allocation of the metrology to the machine systems can be realized. As a first simple conclusion it can be stated, that for machines with a

C-A-X-Y-Z configuration and small axis ranges, the impact of the translational axis errors is bigger than that of the rotational errors. Consequently the utilization of a MT-Check [3] system appears more efficient than the use of a Lasertracer [4]. In contrast for the calibration of large Y-X-Z-C-A machines the Lasertracer seems to be the better system. Here the rotational errors are superior errors.

Moreover the demand oriented strategies for the capture of the measurement data can be developed by using the model as a linear system of equations and defining the necessary data input for its solution.

The elaboration of the demand oriented strategies will not be limited only on the actual available functions of the measurement systems. A lot of the considered systems have still potential. The possibilities to identify errors by means of novel measurement applications and evaluation methods have not been fully exhausted yet.

5 Summary and outlook

Within this paper an approach for a modular and flexible mathematical error model was presented, with which different types of 5-axis machines can be modelled automatically. By means of this model the relevant error budget of 5-axis machines will be identified. Based on these, measurement systems, with which an effective identification of the error budget is possible, will be allocated to the different types of machines. Finally demand oriented calibration strategies can be elaborated for the different 5-axis configuration. In the next steps the most common 5-axis machine types will be modelled and demand oriented calibration strategies will be developed as well as verified practically accordingly.

6 Acknowledgment

The authors would like to thank the German government (BMWi) and the foundation "Otto von Guericke" (AiF) for financial support of project N01022/10 "Opti5AchS".

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