euspen's 19th International Conference & Exhibition, Bilbao, ES, June 2019
www.euspen.eu

Optimal design of artefacts for machine tool calibration

Gorka Aguirre, Beñat Iñigo, Julen Cilla and Harkaitz Urreta

IDEKO S. Coop., Elgoibar, Spain

gaguirre@ideko.es

Abstract
Measuring the accuracy of a machine tool is an open challenge in the industry, and a wide variety of technical solutions are available, such as interferometers, collimators, levels, calibration artefacts, laser trackers, etc. All solutions have advantages and disadvantages concerning which errors can be measured, the achievable uncertainty, the ease of implementation, possibility of machine integration and automation, the equipment cost and the machine occupation time. An added challenge is thus the selection of the optimal solution for each application, which, for example, will probably be different for the full volumetric calibration of a large 5 axis milling machine, and for the integration on a mid-size 3 axis machine of a fast and automatic verification system that detects and corrects changes in the squareness between two axes.
The need to ensure accuracy during the whole lifetime of the machine and the availability of monitoring systems developed following the Industry 4.0 trend are pushing the development of measurement systems that can be integrated in the machine to perform semi-automatic verification procedures that can be performed frequently by the machine user to monitor the condition of the machine. A reasonable approach is based on measuring calibrated artefacts with the machine and extracting the required information on the accuracy of the machine. Measurement time is critical in these applications, and therefore the possibility to adapt the artefact design and the measurement procedure to the specific requirements of each customer can be of great advantage.
This article will discuss the development of a software that can simulate the whole calibration process (machine, artefact, model estimation, uncertainty propagation, etc.) and apply optimization strategies for finding the best measurement strategy for each application. The use of this software will be demonstrated by analysing the influence of the main design parameters of an artefact for the calibration of a 3-axis machine tool.

Metrology, Optimisation, Simulation, Uncertainty

1. Introduction

Volumetric accuracy in machine tools was defined as the ability of the machine to produce accurate 3D shapes [1]. The development of volumetric calibration or error mapping strategies, and the compensation of the measured systematic errors, has been the focus of many research projects over the time [2].

The main challenge in this field has been the development of measuring devices and procedures able to map the main errors of the machine in their whole workspace within a reasonable time and with sufficiently low uncertainty. Calibrated artefact-based solutions were developed first, and in the last years laser tracker-based solutions have been proposed.

There is a trend towards the integration of verification and self-diagnosis systems in machine tools following "Industry 4.0" principles, and the verification and recalibration of volumetric accuracy is one of the key requirements. Artefact based calibration systems find here an important advantage due to their much lower cost, and there are therefore ongoing developments aiming at the integration of this kind of solutions in machine tools. The use of 1D ball bars will be discussed here (see Figure 1).

The optimization of the integration of artefact-based verification and calibration solutions will determine the success of this approach, with aspects such as the design of the artefact, the measurement strategy and the machine occupation time to be considered.

A software tool has been developed which allows for the simulation of the measurement and compensation process, including tools to analyse different possible process configurations and evaluate the calibration uncertainty of each of them [3]. The use of this software for the optimization of the design of the artefact will be demonstrated here.

In the following, in Section 2 the simulation software is described briefly. In Section 3, the implementation of the virtual machine and calibration models is presented. In Section 4, the design of the artefact and the measurement strategy are described. Finally, in Section 5, the simulation software is used to analyse the influence of the main design parameters of the artefact on the error mapping uncertainty, and then some conclusions are drawn.

Figure 1. 1D calibration artefact in machine tool

2. Calibration optimization software

The architecture of the software is presented in Figure 2. A virtual machine model simulates the volumetric error of the machine at any point in the workspace, considering effects such as geometric errors, thermal influences, elasticity, etc. This model, together with models of the artefact and measuring probe, are used for simulating the measurement process.

The result of the measurement is used to fit a compensation model, which is based on the same virtual machine but with a different implementation, since a reduced number of effects can be identified/compensated within reasonable characterization time.

The quality of the error mapping process can be evaluated by comparing the machine model and the compensation model at several points distributed in the workspace of the machine.

The uncertainty of the volumetric calibration and compensation is estimated by performing Monte Carlo simulations [4] where the uncertainties of the machine, measurement tools and environment are propagated through the model estimation and validation process.

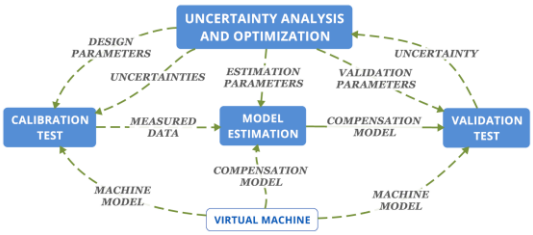

Figure 2. Software structure

3. Virtual machine model

In the following, the use of the virtual optimization tool for artefact-based calibration of machine tools will be demonstrated by applying it to the error mapping of a 3-axis milling machine with a 1D ball array.

A cantilever-type travelling column machine has been selected for the demonstration:

Kinematic chain: Tool-Z-Y-X-Bed-Workpiece

Workspace: X (0-3000), Y (0-1500), Z (0-1300)

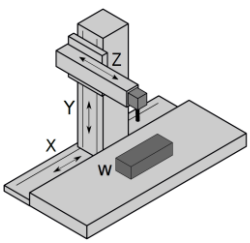

Figure 3. Machine kinematic structure

Two virtual machine models are required in the implementation of the virtual calibration software. One model is used to simulate the real machine M, and can include as many effects as needed to be considered in the analysis. For the compensation model C, only the effects that want to be identified as a result of the calibration process are included, since adding effects to it will require more extensive measurement procedures. The same virtual machine module is used for both models, only selecting different parameters in each case.

The virtual machine models VM provide the position of the tool centre point (TCP) in the machine´s main coordinate system, in function of the programmed axis positions *X(x, y, z)*, the tool offset *t*, and any other effect that may deviate it, such as guiding errors, backlash, thermal effects, etc., which are parameterized in the model by a set of parameters E.

The machine model and the compensation model are defined by different sets of parameters, E_M and E_C respectively.

$$\begin{cases} \mathrm{M} = \mathrm{VM}(\mathrm{X}, t, E_M) \\ \mathrm{C} = \mathrm{VM}(\mathrm{X}, t, E_c) \end{cases}$$

Both models are implemented as kinematic models based on homogeneous transformation matrices and the errors are modelled following ISO 230 definition of six geometric errors for each linear axis, considered as a rigid body: linear position error (EXX), straightness errors (EYX, EZX) and angular errors (EAX, EBX, ECX) [3].

3.1. Machine model

A key element to the success of the optimization software presented here is the proper definition of the model that represents the machine to be calibrated. The magnitude of each error, their shape, how fast they change within the workspace, the relevance of thermal and flexibility errors determine aspects such as the number of measurements needed or the order of the compensation model. The experience and engineering judgement of the user of the software is thus important for defining a proper machine model. In this work, only geometric errors will be considered in the machine model and in the compensation model, which is sufficient for the demonstration of the feasibility of the virtual optimization of a calibration process.

The geometric errors of the machine have been modelled here based on the following function.

$$E(x) = a_0 + a_1 x + \sum_n (b_n \sin n\pi x + c_n \cos n\pi x)$$

a_0, a_1, b_n and c_n are the model parameters, and x is the axis position, here normalized to $[-1,1]$ range. The model is defined here by assigning a uniform probability distribution to each parameter variation range (e.g. $[-a_0, a_0]$).

Table 1 shows the parameter values that have been used in the analyses shown in this paper.

In Figure 4, some EXX error functions generated with these parameters are shown.

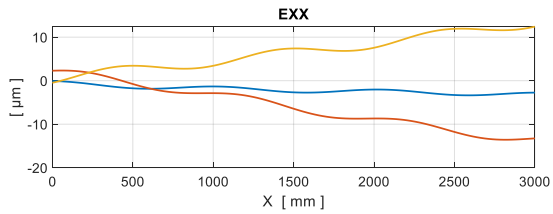

Figure 4. EXX error function examples

The volumetric error (defined later) evaluated at multiple points in the workspace by the families of machines derived from this definition shows the following probability distribution.

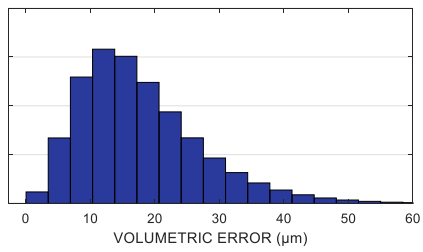

Figure 5. Volumetric error distribution

3.2. Compensation model

The compensation model must include only the errors that want to be identified. Including too many effects or a high model order requires a more detailed measurement process to be able

to separate all effects and identify all the parameters, and it has the added risk of overfitting, where the model estimation shows very good results (small residuals) but the extrapolation in the workspace is not good.

In this work, the compensation model includes the 21 error functions in the machine model, represented by Legendre polynomials in this case.

$$E = a_0 + a_1 x + \frac{a_2}{2}(3x^2 - 1) + \frac{a_3}{2}(5x^3 - 3x) + \cdots$$

Table 1 Error parameters for machine model

	a_0	a_1	n_1	b_1	c_1	n_2	b_2	c_2
EXX	0	40	0.5	20	20	3	10	10
EYX	0	0	0.5	30	0	3	3	3
EZX	0	0	0.5	15	0	3	3	3
EAX	10	20	0.5	10	10	3	5	5
EBX	10	20	0.5	10	10	3	5	5
ECX	10	20	0.5	10	10	3	5	5
EB0X	40	-	-	-	-	-	-	-
EXY	0	0	0.5	15	0	1	5	5
EYY	0	20	0.5	5	5	1	3	3
EZY	0	0	0.5	15	0	1	5	5
EAY	10	15	0.5	10	10	1	5	5
EBY	10	15	0.5	10	10	1	5	5
ECY	10	15	0.5	10	10	1	5	5
EA0Z	40	-	-	-	-	-	-	-
EB0Z	40	-	-	-	-	-	-	-
EXZ	0	0	0.5	15	0	1	5	5
EYZ	0	0	0.5	15	0	1	5	5
EZZ	0	20	0.5	15	15	1	3	3
EAZ	10	15	0.5	6	6	1	2	2
EBZ	10	15	0.5	6	6	1	2	2
ECZ	10	15	0.5	6	6	1	2	2

3.3. Validation criteria

The estimated compensation model is validated by comparing it to the virtual machine model that represents the machine that has been calibrated. In an ideal error mapping process, both models should provide the same TCP coordinates for any axis positions within the workspace of the machine.

The difference between them defines thus the volumetric error in the calibration process, and it can be evaluated in a set of X_i machine positions (60x20x20 in this work) distributed over the workspace:

$$e_i = \|C(X_i, t, E_C) - M(X_i, t, E_M)\|$$

The rms value of the volumetric calibration error vector e_i is used here as the quality measure of the calibration process. Secondary quality measures can be defined as validation results, such as the estimated measurement time for example, which need to be considered when looking for the optimal configuration.

4. Artefact design and measurement strategy

A calibrated ball artefact is used as measuring target in the error mapping process analysed here. The design of the artefact is mainly defined by the number of balls and the relative position between them. 1D artefacts are in principle not optimal for volumetric calibration, because the distances measured in one artefact position will all be aligned in the same direction. 2D or 3D artefacts allow the measurement of distances that are not aligned, and this brings a higher degree of decoupling between how each machine error affects each measured distance. This is of interest for the model estimation, requiring a lower number of measurements, but 2D and 3D artefacts are in general more difficult to handle and can pose limitations due to interferences with the machine.

4.1. Artefact design

In this work, a 1500 mm long 1D artefact with 11 balls is taken as a reference for the analysis, and the effects of its design parameters will be discussed. Regarding its design, small variations in the distribution of the balls are considered here, introducing small offsets in their positions, as shown in Figure 6.

In Section 5, the influence of the number of balls *N* and the offsets *a* and *b* in the uncertainty of the error mapping process will be analysed.

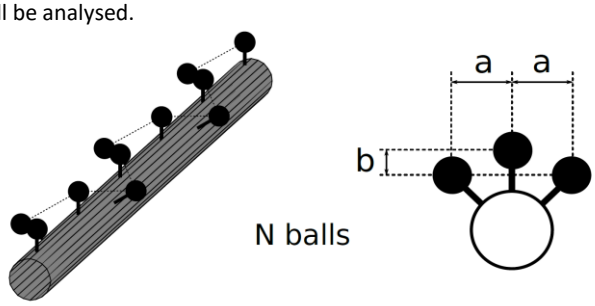

Figure 6. Artefact design and parameters

4.2. Artefact uncertainty

The calibrated lengths between the balls will be taken as true references for the comparison with distances measured by the machine. The uncertainty in the true distance between the balls needs to be considered in the virtual analysis of the error mapping process.

The main contributors to the uncertainty are the uncertainty of the machine where it is calibrated, the thermal effects and the deformation due to the inclination.

As a combination of these effects, the uncertainty in the reference distances between the balls is modelled here as a normal distribution with 2 µm standard deviation.

4.3. Measurement strategy

The calibration process is based on measuring the artefact in several positions to cover the workspace of the machine and provide enough information so that all the parameters of the compensation model can be identified with the expected uncertainty.

The influence of the different artefact positioning strategies was analysed in [3]. For the simulations presented here, the strategy shown in Figure 7 has been chosen. It is based on twelve diagonal positions distributed in the workspace.

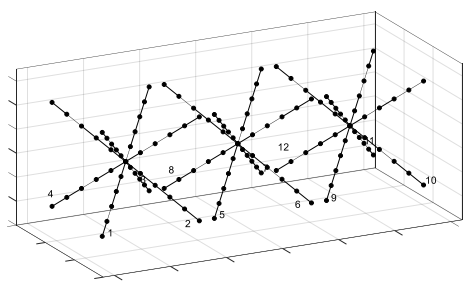

Figure 7. Artefact positioning strategy

5. Optimization of the artefact design

The influence of the main design parameters of the artefact is analysed next by performing simulations of the calibration process as described above. The number of balls *N*, the horizontal offset *a* and the vertical offset *b* will be considered (see Figure 6). A nominal value has been defined for the three variables, and variations of each parameter will be analysed independently (see Table 2).

Table 2 Design parameter values

	Nominal value	Analysed values
N	11	5-7-9-11-13-15-17
a (mm)	30	0-10-20-30-40-50-60
B (mm)	30	0-10-20-30-40-50-60

5.1. Number of balls

The number of balls in the artefact increases the measurement time, but adds measured distances and spatial resolution to the measurement, which in principle can help in identifying more error parameters. The nominal value of eleven balls leads to an axial distance between the balls of 150 mm. The artefacts with other number of balls are created keeping the total length in 1500 mm, and thus changing the distance between them.

The calibration and compensation procedure is simulated for the seven artefacts, and their reduction in volumetric error, as defined in Section 3.3, is shown in Figure 8.

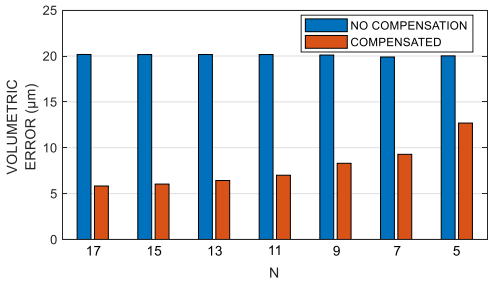

Figure 8. Volumetric error in function of number of balls in artefact *N*

The error probability distribution of the machine before and after compensation is shown in Figure 9, for artefacts of 5, 11 and 17 balls.

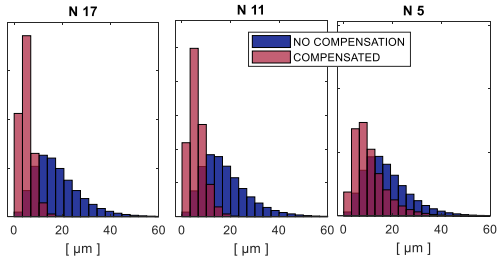

Figure 9. Volumetric error probability distribution for N 5, 11, and 17

As expected, the error is reduced with higher number of balls, but the improvement is less significant with higher number of balls, and considering the longer measurement time, 11 or 13 balls could be considered optimal in this case.

5.2. Horizontal offset

The next analysis looks at the horizontal offset in the position of the spheres (*a* in Figure 6). Seven different values have been simulated, and the results are shown in Figure 10.

The results show that the horizontal reduces the error mapping and compensation uncertainy. The offset does not affect measurement time, so the choice of the optimal value will be mostly based on constructive limitations of the artefact.

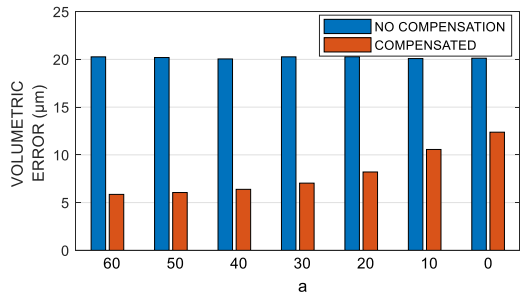

Figure 10. Volumetric error in function of ball horizontal offset *a*

5.3. Vertical offset

Finally, the effect of the vertical offset in the position of the spheres (*b* in Figure 6), is analysed. Seven different values have been simulated, and the results are shown in Figure 11.

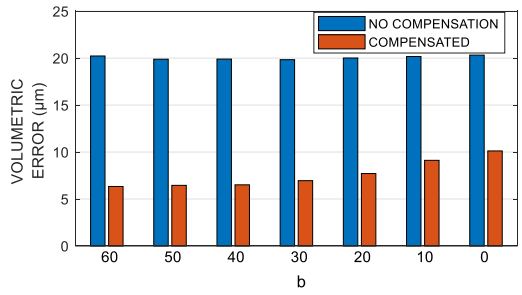

Figure 11. Volumetric error in function of ball vertical offset *b*

The vertical offset reduces the uncertainty of the error mapping process too in a similar way to the horizontal offset, and again, the choice of the optimal value will be mostly based on constructive limitations of the artefact.

6. Conclusions

A successful implementation of artefact-based calibration of machine tools depends greatly on finding an optimal design of the artefact itself, so that the expected calibration accuracy can be achieved with the minimum machine occupation time.

The use of a simulation software for the optimization of artefact-based calibration processes has been presented here. It has been applied on a 3-axis machine tool and the influence of the main design parameters of the artefact on the calibration result have been analysed.

It has been demonstrated that the simulation software is useful for the optimization of artefact based calibration processes. Experience is however critical in the definition of the expected machine errors in the virtual machine to ensure that the results are valid when the solution is implemented on a real machine. Other aspects such as thermal errors and structural flexibility need to be added to the analysis for a proper optimization of the error mapping process.

7. References

[1] McKeown PA, Loxham J. Some aspects of the design of high precision measuring machines. *CIRP Annals* 1973;**22**.

[2] Schwenke H, Knapp W, Haitjema H, Weckenmann A, Schmitt R, Delbressine F. Geometric error measurement and compensation of machines–An update. *CIRP Annals* 2008;**57**:660–75.

[3] Aguirre G, Iñigo B, Cilla J, Urreta H. Virtual optimization of artifact based calibration of machine tools, ASPE Annual Meeting, Las Vegas, USA: 2018.

[4] Evaluation of measurement data — Guide to the expression of uncertainty in measurement. Joint Committee for Guides in Metrology; 2008.