Journal of Machine Engineering, 2018, Vol. 18, No. 2, 64-73
ISSN 1895-7595 (Print) *ISSN 2391-8071 (Online)*

Received: *20 November 2017* / Accepted: *22 March 2018* / Published online: *25 June 2018*

machine tool calibration,
step diagonal measurement,
integrated calibration system

Philipp DAHLEM[1*]
Benjamin MONTAVON[1]
Martin PETEREK[1]
Robert H. SCHMITT[1]

ENHANCING LASER STEP DIAGONAL MEASUREMENT BY MULTIPLE SENSORS FOR FAST MACHINE TOOL CALIBRATION

The volumetric performance of machine tools is limited by the remaining relative deviation between desired and real tool tip position. Being able to predict this deviation at any given functional point enables methods for compensation or counteraction and hence reduce errors in manufacturing and uncertainties for on-machine measurement tasks. Time-efficient identification and quanitification of different contributions to the resulting deviation play a key role in this strategy. The authors pursue the development of an optical sensor system for step diagonal measurement methods, which can be integrated into the working volume of the machine due to its compact size, enabling fast measurements of the axes' motion error including roll, pitch and yaw and squareness errors without significantly interrupting the manufacturing process. The use of a frequency-modulating interferometer and photosensitive arrays in combination with a Gaussian laser beam allow for measurements at comparable accuracy, lower cost and smaller dimensions compared to state-of-the-art optical measuring appliances for offline machine tool calibration. For validation of the method a virtual machine setup and raytracing simulation is used which enables the investigation of systematic errors like sensor hardware misalignment.

1. INTRODUCTION

Machine tools used in the manufacturing industry must operate within accepted tolerance limits in order to meet the required product quality. Due to new technologies and increasing quality demands of customers, these tolerance limits are becoming ever tighter. At the same time, increased availability of production machines is a fundamental requirement for maintaining the competitiveness of companies. Since maintenance efforts of machine tools are made at the expense of production time, they are in conflict with endeavor to higher machine availability. Shagluf et al. derivate a cost model of CNC

---

[1] Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Chair of Production Metrology and Quality Management, Aachen, Germany
[*] E-mail: p.dahlem@wzl.rwth-aachen.de
DOI: 10.5604/01.3001.0012.0928

machine tool accuracy maintenance, which can support the decision-making on maintenance strategies for arbitrary scenarios [1]. However, they claim that the time-effort for calibrating actions as well as personnel costs for trained operators are one of the most critical factors for the maintenance total costs. They differ between quick check tests with a typical duration of around 30 minutes and full calibration actions taking 2 to 5 days. Taking into account the fact that a shorter maintenance interval keeps the machine performance constantly high and drastically reduces the risk of manufacturing non-conforming parts, the added value of performing a full calibration within the typical time of a quick check test becomes obvious. Therefore, the authors investigate an enhanced version of the laser step diagonal method as a candidate for such a fast calibration method.

The deviation between the actual and ideal functional point in the working volume of machine tools is one fundamental limiting factor to the part quality. The maximum range of the deviation per axis defines the volumetric accuracy of the machine tool, which in turn determines its volumetric performance. Different error sources influencing position and orientation of the tool and leading to a superposed deviation can be identified [2-4]:

- Kinematic errors;
- Thermo-mechanical errors;
- Loads;
- Dynamic forces;
- Motion control and control software.

These phenomena are subjected to change over time and hence ought to be checked regularly through machine tool calibration in order to anticipate tolerance mismatch.

The developed concept will focus on the time-efficient measurement of the kinematic errors due to imperfections of geometry of the machine components and the later configuration in the machine tool structural loop [4]. These component errors lead to six deviations from an ideal linear or rotational movement. Assuming a systematic and full rigid body behaviour these deviations can be expressed as functions of the axis movements. Additional location errors of the axis will influence the relative position and orientation between axis pairs in the machine coordinate system, resulting in a total of 21 error parameters for Cartesian three-axis machine tools [3].

If the kinematic errors are known, it is possible to calculate the resulting deviation at each functional point in the working volume using a mathematical model of the machine tool kinematic. The data can be used for the compensation of systematic errors [5, 6].

Numerous calibration methods, ranging from conventional material normals and dial gauges to modern optical multi-sensor systems, are available to determine kinematic machine errors. In particular, for the calibration of large machine tools, optical measuring principles have prevailed [7, 8]. Kwasny et al. give a comprehensive overview of the various calibration methods, also pointing out their strengths and limitations depending on the measurement task [9]. With the conventional measuring methods, calibration is a time-consuming and cost-intensive intervention, which requires an interruption of the production process as the methods are defined for tests under no-load or quasi-static conditions. Additionally, high planning and setup efforts are required with low potential for automation or permanent integration. Kwasny et al. also mention the laser vector method (also known as step diagonal measurement as referred to in this article) as medium time and cost-consuming for medium-sized three-axis machine tools, but not going far into detail as there is no system available on the market. In this context, an enhanced step diagonal method for machine tool calibration will be discussed, mathematically modelled and simulated.

2. STEP DIAGONAL MEASUREMENT – POTENTIALS AND LIMITATIONS

This article examines the step diagonal measurement, an indirect measurement method first described by Wang which can be applied to Cartesian three-axis kinematics [10, 11]. The measuring strategy is based on interferometric distance measurements along the body diagonals of the cuboid measurement volume. Wang claimed to identify all relevant kinematic errors with measurements of at least three different diagonals with assuming angular deviations are negligible small. The decisive difference to conventional diagonal measurements, which only allow qualitative analysis of the volumetric performance, are the non-simultaneous step by step movements of the axes [12]. After each step a measurement point is recorded. Due to the resulting “zig-zag course” along the diagonal, the reflector needs to be a flat mirror large enough to reflect the beam along the entire path of the measurement (Fig. 2). The hardware setup causes some difficulties that are already discussed [12]. The vast majority of machines show angular error motions for linear axes, which are not addressed in the discussed calculations. Moreover, misalignment of the setup may cause significant systematic errors influencing the calculated volumetric accuracy.

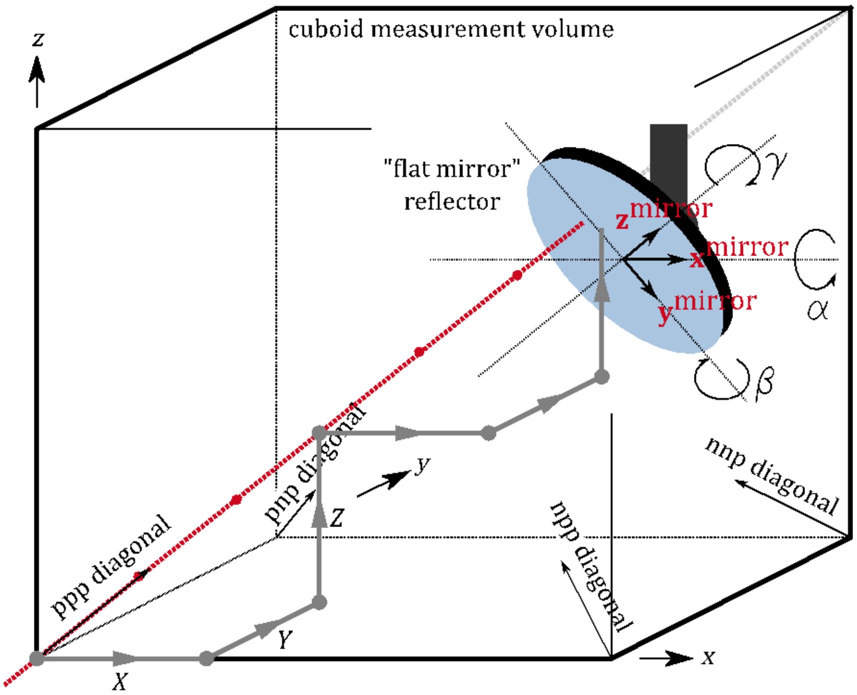

Fig. 1. Reflector orientation on the “zig-zag course” of the ppp diagonal with tilt angles and local coordinate system along with the nomenclature of the other diagonals of the cuboid measurement volume

Wang claimed the need for additional measurements if the assumption is not valid and suggested performing three linear displacement measurements with different Abbe offsets on each axis to determine the pitch and yaw angular errors. The mirror alignment issue can be solved by using an additional retroreflector [11]. Soons described another method to estimate the five relevant angular errors by executing several step diagonal measurements with different step sequences [13]. Ibaraki et al. tested this setup and solved the alignment errors, including laser alignment, with separately performed measurements for the determination of positioning errors EXX, EYY and EZZ, which is less time-consuming compared to the different step sequences [14].

Regarding time efficiency as a key benefit of step diagonal measurements and the unsolved problem of the effect of angular error motions, the suggested adjustments are still unsatisfactory and deteriorate the method advantages over existing multilateration calibration techniques [4]. This issue is addressed by the here presented optical sensor which measures multiple quantities simultaneously evaluated by an enhanced model of the step diagonal measurement.

3. MATHEMATICAL MODELLING

In the first step, it should be distinguished between constant alignment errors, including laser and reflector misalignments, changing reflector alignment caused by angular error motions, as well as the general contribution of angular deviations at the functional point. Constant alignment errors lead to linear trends in measured positioning deviations (cf. 1b and 1c in Fig. 5). To compensate for these effects, the separate measurement of linear positioning errors suggested by Ibaraki et al can be increased in efficiency [14]. It is sufficient to measure only the slope of the positioning errors with just two measurement points per axis and apply it to the evaluation of the step diagonal measurement.

Changing reflector alignment affects the measurements of positioning and straightness error motions (cf. 1a and 2a in Fig. 5). With the information of the relative reflector angle and the effective lever arm (distance from reflector rotation center to intersection point of laser and reflector) the measured distance can be corrected at every measurement. Furthermore, angular error motions cause significant deviations at the functional point in presence of long axes lengths. To compensate for both effects, angular measurements of the mirror plane are necessary.

The idea is to extend the method and hardware setup to measure the tilt of the mirror plane around two principal axes (cf. α and β in Fig. 1). The information of at least three diagonals will lead to an over-determined system of equations, because the reflector tilts equally for all four diagonals due to the systematic nature of the angular error motions of the linear axes. Hence the tilt of the mirror at each measuring point can be calculated also for the third orthogonal axis because of the multiple perspectives.

$$\mathbf{R}_{\alpha\beta\gamma} \approx \begin{pmatrix} 1 & -\gamma & \beta \\ \gamma & 1 & -\alpha \\ -\beta & \alpha & 1 \end{pmatrix}; \qquad \boldsymbol{r}^{mirror} := \begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} \tag{1}$$

Assuming the angular movements are of small absolute values, trigonometric functions can be approximated to the linear order of their Taylor series expansion ($\cos(\alpha) \rightarrow 1,\ \sin(\alpha) \rightarrow \alpha$). Herewith rotations around different axes become commutative and can be summarized in a single matrix $\mathbf{R}_{\alpha\beta\gamma}$:

The defined vector $\boldsymbol{r}^{mirror}$ is an eigenvector of the matrix $\mathbf{R}_{\alpha\beta\gamma}$, hence coordinate transformations can be reduced to the matrix multiplication of a vector. For the sense of direction, the right-hand rule applies. The conversion into the machine axis system is a coordinate transformation with the following transformation matrices for the four diagonals (*ppp*, *npp*, *pnp*, *nnp*).

$$\mathbf{D}_{ppp}^{mirror->machine}(X,Y,Z) = \begin{pmatrix} \frac{Y}{D_{XY}} & \frac{X\cdot Z}{D_{XY}\cdot D_{XYZ}} & \frac{X}{D_{XYZ}} \\ -\frac{X}{D_{XY}} & \frac{Y\cdot Z}{D_{XY}\cdot D_{XYZ}} & \frac{Y}{D_{XYZ}} \\ 0 & -\frac{D_{XY}}{D_{XYZ}} & \frac{Z}{D_{XYZ}} \end{pmatrix} \tag{2}$$

$$\mathbf{D}_{npp}^{mirror->machine}(X,Y,Z) = \mathbf{D}_{ppp}^{mirror->machine}(-X,Y,Z)$$
$$\mathbf{D}_{pnp}^{mirror->machine}(X,Y,Z) = \mathbf{D}_{ppp}^{mirror->machine}(X,-Y,Z)$$
$$\mathbf{D}_{nnp}^{mirror->machine}(X,Y,Z) = \mathbf{D}_{ppp}^{mirror->machine}(-X,-Y,Z)$$

$$D_{XY} = \sqrt{X^2 + Y^2}, \qquad D_{XYZ} = \sqrt{X^2 + Y^2 + Z^2} \tag{3}$$

The calculation of the angular deviations is split up per step, leading to a separate set of equations for each axis, here denoted with the indices *X*, *Y*, *Z*. The abbreviations EA, EB, EC refer to the angular deviations of the according axis and are the unknown variables. Transforming from machine to mirror coordinates can be done by transposing the matrices from the equations above. Herewith the following system of equations can be set up:

$$\begin{pmatrix} \mathbf{D}_{ppp}^{machine\rightarrow mirror} \\ \mathbf{D}_{npp}^{machine\rightarrow mirror} \\ \mathbf{D}_{pnp}^{machine\rightarrow mirror} \\ \mathbf{D}_{nnp}^{machine\rightarrow mirror} \end{pmatrix} \cdot \begin{pmatrix} EA \\ EB \\ EC \end{pmatrix}_{X,Y,Z} = \begin{pmatrix} \boldsymbol{r}_{ppp}^{mirror} \\ \boldsymbol{r}_{npp}^{mirror} \\ \boldsymbol{r}_{pnp}^{mirror} \\ \boldsymbol{r}_{nnp}^{mirror} \end{pmatrix}_{X,Y,Z} \tag{4}$$

Identifying the general form $\mathbf{A} \cdot \boldsymbol{x} = \boldsymbol{b}$ for a set of potentially over-determined linear equations, a least-square solution $\boldsymbol{x}^*$ can be obtained through the Moore-Penrose-pseudoinverse $\mathbf{A}^{\dagger}$:

$$\boldsymbol{x}^* = \mathbf{A}^\dagger \cdot \boldsymbol{b} \text{ with } \mathbf{A}^\dagger = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T \tag{5}$$

The variance of $\boldsymbol{x}^*$ and the angular deviations respectively can be obtained by multivariate propagation of uncertainties:

$$\mathbf{Cov}(\boldsymbol{x}^*) = \mathbf{A}^\dagger \cdot \mathbf{Cov}(\boldsymbol{b}) \cdot [\mathbf{A}^\dagger]^T \tag{6}$$

4. HARDWARE CONCEPTS

Small laser diodes, photosensitive sensors and multi-channel fiber interferometers enable the development of compact hardware setups capable of measuring distance and orientation of a reflective target simultaneously. To point out the benefit of using fiber interferometers Fig. 2 shows the application of the conventional step diagonal measurement in a small-sized machine tool, where most other hardware setups would fail because of their own size. Here, the working volume excluded from calibration is comparable to the unused volume during manufacturing tasks, due to the size of workpiece, fixtures and the tool length. In this case, the short axis length lead to negligible small angular effects, so that a conventional step diagonal measurement might be suitable.

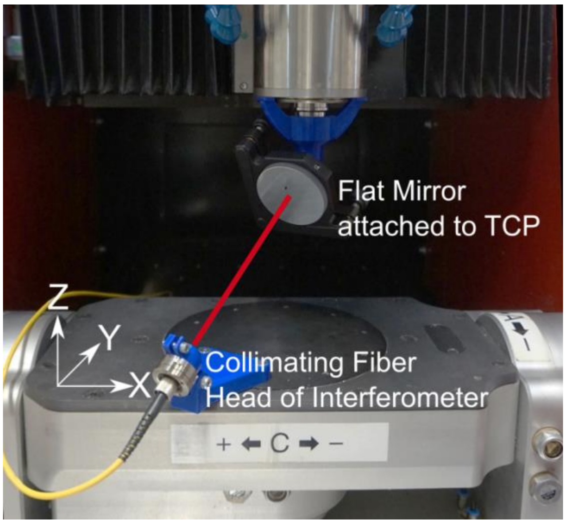

Fig. 2. Application of the conventional step diagonal measurement using the frequency-modulating fiber interferometer attocube IDS 3010, which enables to calibrate the working volume of 260 mm × 420 mm × 160 mm due to its small size

For more general purposes a simulation (Chapter 5) and first experiments were carried out using the hardware layouts sketched in Fig. 3.

In concept a) the angle is determined as ratio between the difference of individual length measurements and their perpendicular offsets. Reducing the latter distance also reduces the angular resolution. This drawback is not present in b). Here the critical point is the precise alignment of the position sensing device at zero angle ($\alpha = 0$, $\beta = 0$).

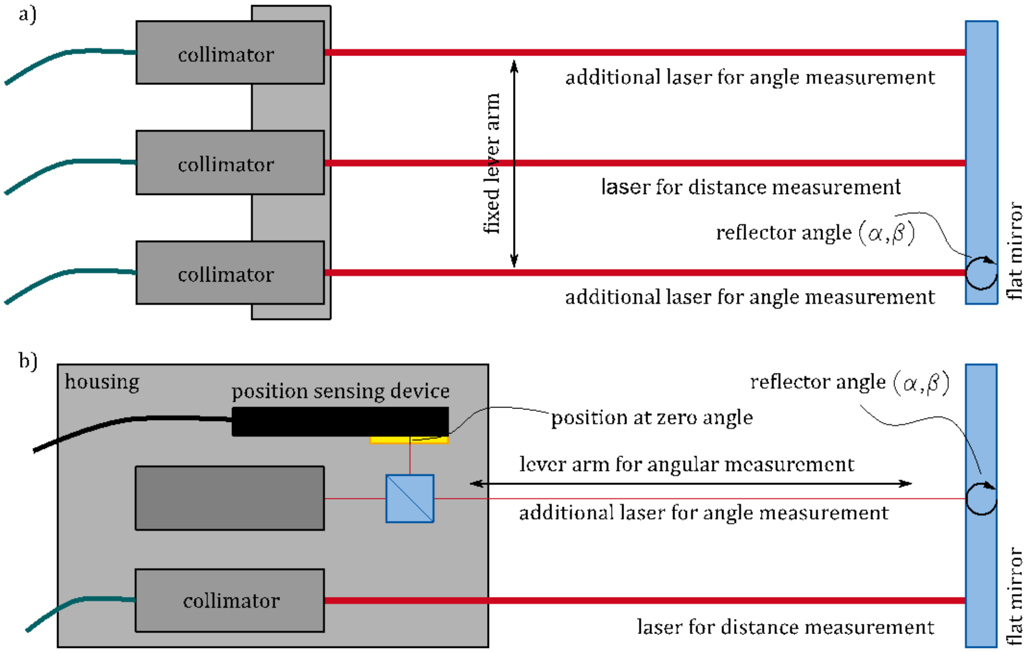

Fig. 3. Sketches of two different hardware layouts, either a) using multiple interferometric laser beams or b) using one interferometric beam and a conventional laser in combination with a position sensing device

Fig. 4. CAD-rendered model of a possible test setup using hardware layout (see Fig. 3b)

Through the use of fiber interferometers and subsequent minimization of setup sizes, permanent integration of the required hardware into the machine tool becomes a realistic scenario. Fig. 4 shows a CAD-rendered image of a possible hardware implementation. A promising idea is to install four compact base units to the lower corners of the machine tool working volume. A central laser source and control unit can be placed apart and multiplexed to one or multiple machines in order to save costs. Herewith the preparations for a measurement are reduced to exchanging the tool for a flat mirror.

5. VIRTUAL SENSOR AND MACHINE TOOL

The development of a virtual sensor and machine tool setup allowing for numerical simulation of step diagonal measurements is motivated by the need for a validation of the established mathematical model. As an approach for a virtual sensor, the measurement setup is interpreted as optical system consisting of a common environmental medium representing ambient air and homogeneous bodies with flat surfaces, representing the optical components.

The complete composition of ambient medium and virtual optical components is handled as scene for a raytracing algorithm [15, 16]. Refractive indices are assumed to be constant during one simulation sequence, modelling an experiment in stabilized, e.g. climatised environmental conditions. Refraction and reflection are the only phenomena taken into account to determine the propagation direction and hence the model of the step diagonal measurement is not used as a priori information.

The formulation of a virtual machine tool can be simplified to two coordinate systems: one fixed system representing the machine frame and a mobile coordinate system attached to the functional point which will be translated and rotated equivalently to the tool movement.

For the simulation of the sensor behavior, it is irrelevant if the tool movement is ideal or superposed with geometric errors. Hence the total error motion is added to the movement of the functional point before the raytracing scene is generated. For this purpose, a pre-generated map of the axes deviation in combination with the full-rigid-body model is used.

In contrast to practical tests, the simulation allows for a separated investigation of systematic disturbances. Herewith the identification of error sources such as misalignment and possible counteraction or corrections can be identified. An excerpt of simulation results for such a scenario can be seen in Fig. 6.

6. CONCLUSION AND FURTHER RESEARCH OUTLOOK

The presented enhanced step diagonal method can be used for a fast machine tool calibration measuring all 21 parameters of the rigid-body model for kinematic errors of Cartesian three-axis-machines, thus restrictions regarding tool offset corrections are avoided. The feasibility of the method using innovative hardware concepts was demonstrated by means of simulation, reproducing all virtually induced kinematic errors within floating point precision, even in presence of systematic errors.

The developed hardware concepts allow small sensor setups that can be permanently integrated into a machine tool working volume and enable time-efficient calibration run. The implementation of a real sensor setup and integration into a machine tool as test carrier are next steps in the outline of the research project. In addition, a modification of the method to measure along face diagonals instead of the body diagonals is planned. This modification tested by Bui C.B. [17] can lead to further reduction in measurement time. At the same time, the suggested multivariate propagation of uncertainty will be validated using a Monte-Carlo extension of the raytracing simulation mentioned in Chapter 5.

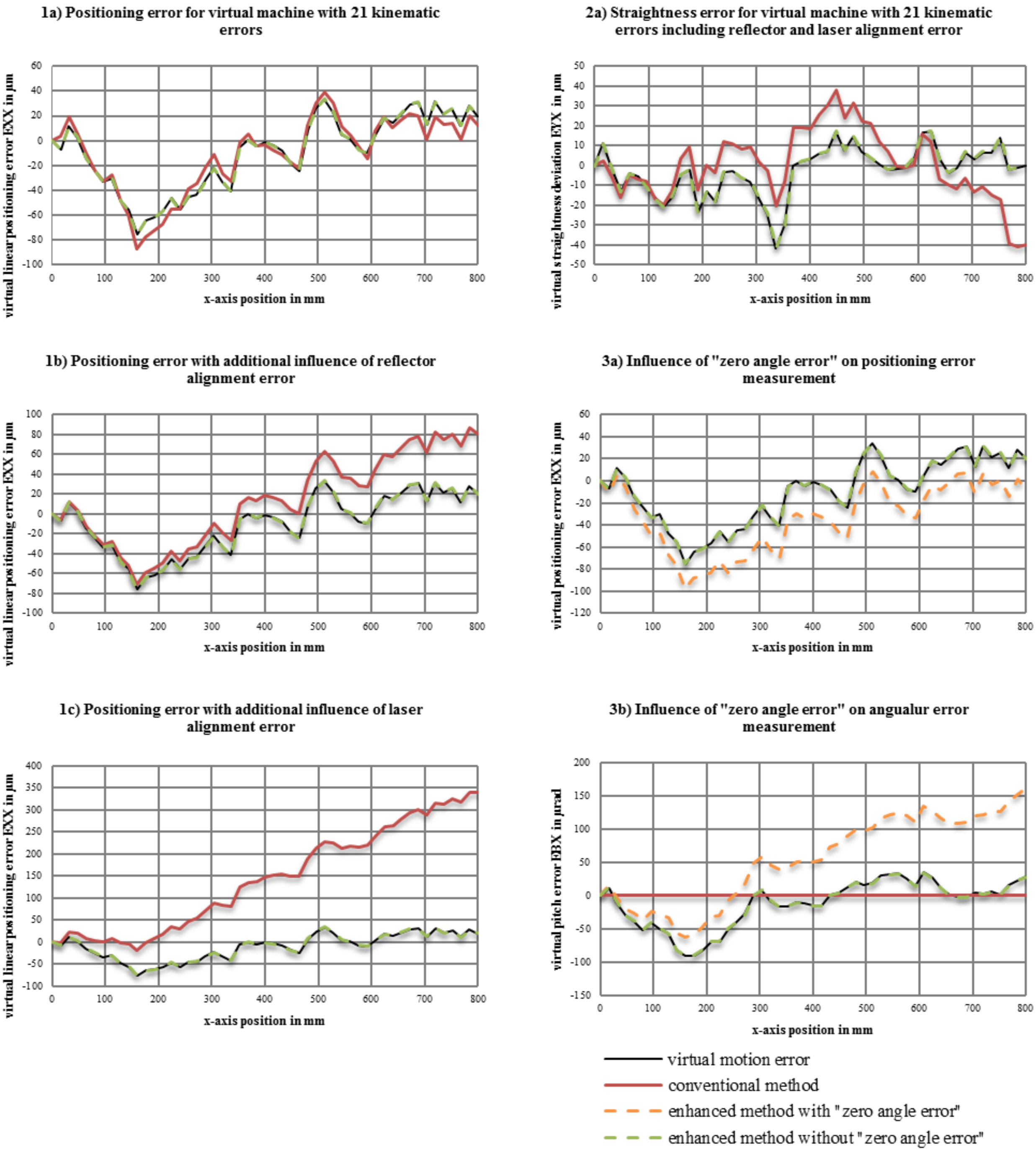

Fig. 5. Comparison of conventional and enhanced evaluation method considering axis and alignment errors (cf. Chapter 2, 3 [10])

Results of a simulated step diagonal measurement in a virtual 3-axis machine with x = 800, y = 600, z = 500 mm measurement volume using 50 points per axis. Apart from the 21 kinematic errors (1a, 2a), an additional reflector misalignment (1b, 2a) of $\alpha = 100$, $\beta = 300$ µrad and a laser misalignment (1c, 2a) of $\alpha = 700$, $\beta = 1000$ µrad were simulated. Especially the linear trend caused by imperfect alignment can be observed. The enhanced evaluation method (Chapter 3) is able to compensate for these effects and reproduce the used kinematic errors within floating point precision (black/green). The remaining deviations of the error curves when using this method are not visible due to the resolution of the diagrams and are within a range which is not critical for the calibration. Influences of wrong measured angular errors on the enhanced evaluation method are shown in 3a) and 3b). Here a zero angle error for hardware layout b) is simulated with a zero angle position deviation of $x = 1.5$, $y = 2$ mm on the position sensing device (cf. Chapter 4).

ACKNOWLEDGMENTS

The depicted research has been funded by the German Research Foundation DFG as part of the Cluster of Excellence "Integrative Production Technology for High-Wage Countries". Project number 128.

REFERENCES

[1] FLETSCHER S., LONGSTAFF A.P., SHAGLUF A., 2015, *Derivation of a cost model to aid management of CNC machine tool accuracy maintenance*, Journal of Machine Engineering, 15/2, 17-43.

[2] IBARAKI S., KNAPP W., 2013, *Indirect Measurement of Volumetric Accuracy for Three-Axis and Five-Axis Machine Tools, A Review*, Kyoto.

[3] MAYR J., JEDRZEJEWSKI J., UHLMANN E., et al., 2012, *Thermal issues in machine tools*, CIRP Annals - Manufacturing Technology, 2, 771-791, DOI 10.1016/j.cirp.2012.05.008.

[4] DELBRESSINE F., HAITJEMA H., KNAPP W., et al., 2008, *Geometric error measurement and compensation of machines–An update*, CIRP Annals - Manufacturing Technology, 2, 660-675, DOI 10.1016/j.cirp.2008.09.008.

[5] ERTL F., LENZ K.J., *Beschreibung und rechnerunterstuetzte Korrektur der Fehler von mehrachsigen Maschinen*, Feinwerktechnik und Messtechnik, 85, 239-243.

[6] HOCKEN R. J., 1993, *Software Compensation of Pecision Machines*, A Report from Precision Engineering Laboratory UNC Charlotte to National Institute of Standards and Technology.

[7] ESTLER W.T., FORBES A., GALETTO M., et al., 2016, *Advances in Large-Scale Metrology – Review and future trends*, CIRP Annals–Manufacturing Technology, 2, 643-665, DOI 10.1016/j.cirp.2016.05.002.

[8] PETEREK M., SCHMITT R., 2015, *Traceable Measurements on Machine Tools–Thermal Influences on Machine Tool Structure and Measurement Uncertainty*, Procedia CIRP, 576-580, DOI 10.1016/j.procir.2015.06.087.

[9] KWASNY W., TUREK P., JEDRZEJEWSKI J., 2011, *Survey of machine tool error measuring methods*, Journal of Machine Engineering, 11/4, 7-38.

[10] WANG C., 2000, *Laser vector measurement technique for the determination and compensation of volumetric positioning errors. Part I, Basic theory*, Review of Scientific Instruments, 10, 3933, DOI 10.1063/1.1290504.

[11] LIOTTO G., WANG C., 2003, *A theoretical analysis of 4 body diagonal displacement measurement and sequential step diagonal measurment*, Laser Metrology and Machine Performance, VI, 44.

[12] CHAPMAN M.A., 2003, *Limitations of laser diagonal measurements*, Precision Engineering, 4, 401-406, DOI 10.1016/S0141-6359(03)00041-2.

[13] SOONS J.A., 2005, *Analysis of the step-diagonal test*, Metal Cutting Theory and Practice, Third Edition.

[14] HATA T., IBARAKI S., 2010, *A new formulation of laser step diagonal measurement – Three-dimensional case*, Precision Engineering, 3, 516–525, DOI 10.1016/j.precisioneng.2010.02.004.

[15] EDLÉN B., 1966, *The Refractive Index of Air*, Metrologia, 2, 71-80.

[16] SCHOTT North America Inc., 2014, *Refractive Index and Dispersion*, Duryea.

[17] BUI C.B., HWANG J., LEE C.-H., et al., 2012, *Three-face step-diagonal measurement method for the estimation of volumetric positioning errors in a 3D workspace*, International Journal of Machine Tools and Manufacture, 40-43, DOI 10.1016/j.ijmachtools.2012.03.005.