Technical Paper:

Automating Accuracy Evaluation of 5-Axis Machine Tools

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A wireless non-contact 3D measuring head is used to determine the accuracy of 5-axis machine tools. The measuring head is inserted in the spindle by the tool exchanger automating the measurement routine used. For checking the linear machine axes, a cross shaped artefact containing 13 precision balls is introduced, named Position Inspector, enabling the determination of positioning and straightness errors of two linear axes in one setup. The squareness error between both axes is also determined in this setup. This artefact can be mounted on a pallet system for automatic loading and is measured in a bi-directional run. This artefact can be measured in different orientations (i.e., horizontal, inclined, vertical) and is pre-calibrated with a CMM. The measurement sequence using this artefact is executed in eight minutes and its design and support system is addressed in this paper. The location errors and orientation errors of the axis average line (or pivot line) of both rotary axes are determined with the Rotary Inspector using the same measuring head with a single precision ball. For this, kinematic tests are used from ISO10791-6, e.g., the BK1 test, BK2 test which apply for trunnion or swivel table machines. Derived parameters can be used for machine correction resulting in a significantly improved machine accuracy. An example is given where this correction is performed automatically by implementing this measurement system in the machine's controller. Finally the machine tool is tested using the BK4 test. For this test all 5-axes are moved simultaneously and the measured displacements between the machine's spindle and table in *X*-, *Y*-, and *Z*-directions are compared to tolerance levels. This final test reveals the machine's overall accuracy and dynamic behavior.

Keywords: 5-axis machine tools, machine correction, metrology, non-contact

1. Introduction

In the course of machine tool accuracy investigations many methods have been developed [1–32]. This paper focuses on those methods suitable for automation to stimulate industrial application. A high degree of automation is obtained by using the tool-changer and pallet systems for (de-)mounting the hardware of the measurement equipment and the needed software runs on the controller (see Section 4.6).

Fig. 1. Photo of wireless 3D measuring head equipped with three non-contact sensors.

Calibration of 5-axis machine tools is complex as a very large number of errors can contribute (i.e., 54 or more) [12–15, 17–23, 25, 30]. Instead of determining all these errors individually a volumetric approach is used here to determine directly the 3D error vector between machine's table and spindle [9, 18, 22].

For this a measuring head is inserted in the machine's spindle that can measure the *X*-, *Y*-, and *Z*-positions of a 22.000 mm diameter precision ball. The calibrated measuring range is 1 mm with a measurement uncertainty of less than 1 μm at 1 kHz.

This head is shown in **Fig. 1** and equipped with three inductive non-contact sensors which are immune for liquids (i.e., oil, cooling liquid) and is stored in the machine's tool magazine. A tool changer inserts this head in the spindle and puts it back in the tool magazine right after the measurements.

A cross shaped artefact containing 13 balls is used with this measuring head to measure the 3D position of each ball to evaluate the accuracy of the machine's linear axes.

This artefact can be mounted on a pallet system to enable automatic loading by robot and this is discussed in Section 3.

For evaluating the impact of the machine's rotary axes on the machine's accuracy, the same measuring head is used with a single precision ball mounted on another pallet. This measuring system determines the location errors and squareness errors of the average line of each rotary axis using 3-axis tests (i.e., BK1, BK2 test) and this is explained in Section 4. After this, this system is finally used for the final 5-axis test to check the machine's overall accuracy (i.e., BK4 test).

To enhance industrial application, any machine operator can execute the required measurements.

2. Checking Linear Axis Performance

2.1. Classic Methods

Laser interferometers are commonly used to calibrate the linear axes of machine tools [24, 27, 31]. This instrument can measure five degrees of freedom such as E_{XX} (positioning error X-axis), E_{YX} and E_{ZX} (straightness error X-axis), E_{BX} and E_{CX} (i.e., pitch and yaw error X-axis). The remaining roll error E_{AX} is measured with two electronic levels. Despite that these instruments are well known and used, the required measuring time is considered as problematic for application in industry. Another issue is that such measurements cannot be automated, require an expert, and protection covers have often to be removed to gain access.

2.2. Indirect Method

For indirect methods the volumetric 3D error between table and spindle is assessed by using an artefact with known geometry. This geometry is determined with a CMM. Machine errors are then obtained by comparing measured values with known values.

Several artefact shapes and configurations have been realized (ball bar, ball plate, ball cube, ball tetrahedron, etc.) in metrology research [6, 7, 9, 12, 19, 23, 27]. In this paper, a cross shaped artefact is introduced and used (see **Fig. 2**).

3. Position Inspector

This innovative measurement system combines a 3D measuring head with a pre-calibrated cross-shaped artefact containing 13 balls. The nominal ball spacing distance equals 75 mm and the balls span a length of 450 mm in X- and Y-directions.

The size of the artefact should cover the machine's working volume as good as possible and should not exceed 1 m to keep its use practical (i.e., transport case handling, weight and CMM availability for artefact calibration).

The artefact can be measured up to inclinations of 40°.

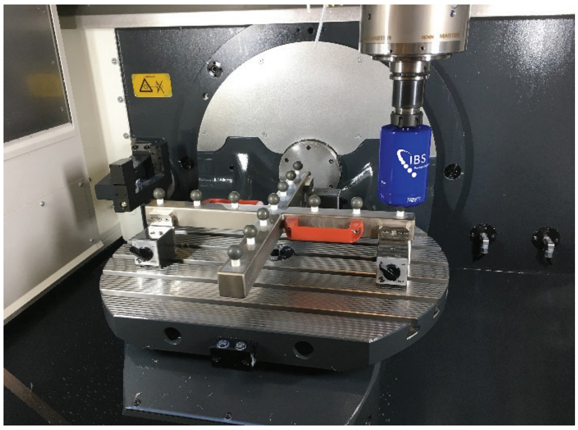

Fig. 2. Cross-shaped artefact containing 13 precision balls mounted on machine's work piece table.

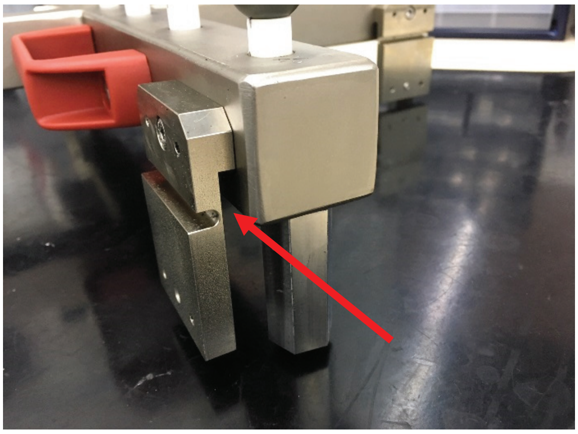

Fig. 3. Leaf spring element (see arrow) to clamp magnet to avoid frame deformation due to mounting.

The position of the balls of the artefact is measured in a single bi-directional run (e.g., forwards and backwards) to capture any potential play or backlash present. Machines equipped with a swiveling table are also measured with the artefact tilted 40° to check the errors of the Z-axis.

3.1. Design and Mounting

To obtain a thermally stable artefact an invar is used as frame material (i.e., CTE $= 2 \times 10^{-6}$ /K). This artefact can be mounted on a pallet or directly on the machine's table with three pillars. A magnet nearby the pillar clamps a leaf spring construction shown in **Fig. 3** pulling the artefact to the surface.

This leaf spring construction prevents bending moments and/or forces due to mounting to enter and deform the artefact. The geometry of the artefact must be stable at micrometer level to avoid frequent CMM re-calibration. This artefact is typically calibrated once a year.

Measuring forces are absent as the measuring head uses non-contact sensors.

The bottom of the pillar has an alignment pin that is pushed into the edge of the center slit in the machine's workpiece table. A bracket is provided that can

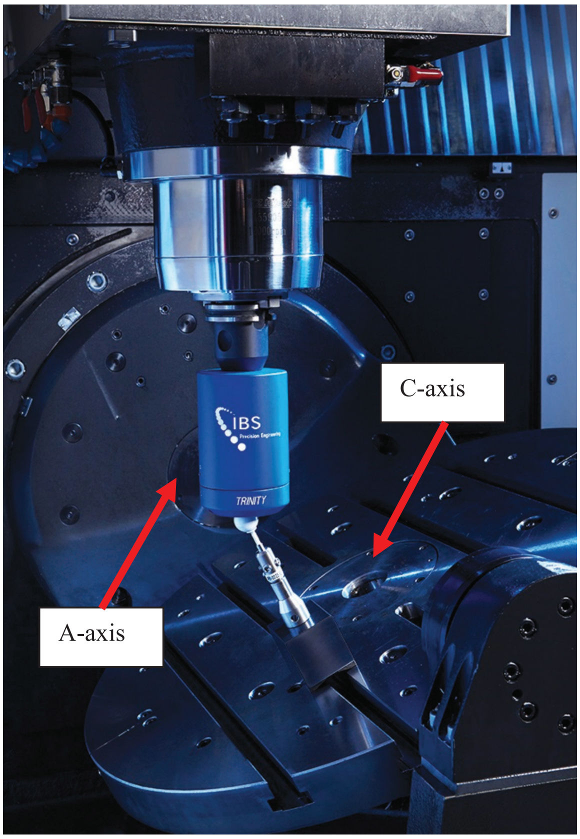

Fig. 4. Photo of measurement setup of the Rotary Inspector on a trunnion table machine with an A- and C-axes.

be mounted to the frame enabling repeatable mounting of the artefact within 0.1 mm on a classic T-slot table.

For quickest use the artefact is preferably mounted on a pallet system which is repeatable at micrometer level.

3.2. Artefact Calibration

A CMM is used to determine the position of the 13 balls of the artefact. Sag errors due to gravity are eliminated by measuring the artefact in the same orientation (e.g., horizontal, vertical) on the CMM as on the machine to be measured. The measurement uncertainty of the CMM used is less than 2 μm.

3.3. Application 1: Horizontal Artefact

In this example, a trunnion table milling machine is measured and discussed (see **Figs. 2** and **4**). First the measuring head is inserted in the spindle by the tool exchanger. Secondly the artefact is mounted on the machine's table. After this, a specific NC file is loaded that is prepared at system setup, commanding the machine to measure each artefact ball position in X-, Y-, and Z-directions in a bi-directional run.

A laptop running Position Inspector software is used to store the measurement data of the measuring head.

The execution of this NC file lasts four minutes and results are presented in a standard two page report. This measurement reveals seven errors (see **Table 1**).

Table 1. Measured errors of linear axes (X and Y).

Axis	Deviation	Value
X	Positioning error [E_{xx}max–E_{xx}min]	5 μm
X	Straightness hor. [peak to peak]	8 μm
X	Straightness vert. [peak to peak]	6 μm
Y	Positioning error [E_{yy}max–E_{yy}min]	13 μm
Y	Straightness hor. [peak to peak]	5 μm
Y	Straightness vert. [peak to peak]	12 μm
XY	Squareness [E_{COY}]	$-0.001°$

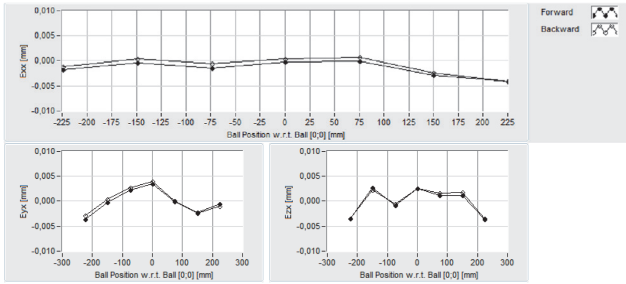

Fig. 5. Positioning error and straightness errors of the X-axis.

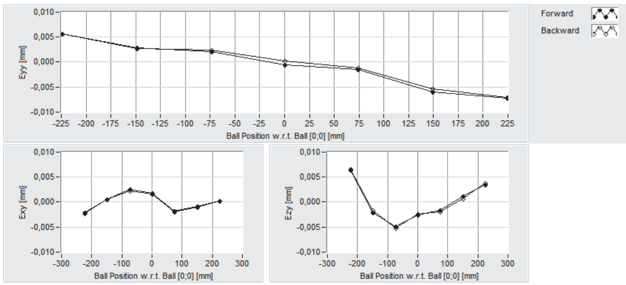

Fig. 6. Positioning error and straightness errors of the Y-axis.

The results are presented in graphs (**Figs. 5** and **6**) and are compared to tolerance values. It is intended for use as a quick check to support go/no-go decisions in production and machine maintenance.

3.4. Application 2: Inclined Artefact

To check the accuracy of the machine's Z-axis, the artefact could in principle be mounted vertically and the measuring head horizontally. For this, an adapter would be needed to mount the measuring head in the spindle in this orientation but this is not feasible due to the tool exchanger (e.g., collision).

Instead the machine's table is inclined 40°, tilting the artefact. In this mode, the measured errors are projected to the Z-axis ignoring the Y-axis. Here it is assumed that these Y-axis errors are negligible, which can be checked in the former horizontal measurement sequence (see **Fig. 7**).

The execution time for inclined measurement equals four minutes, so the total measurement time for the Position Inspector is eight minutes.

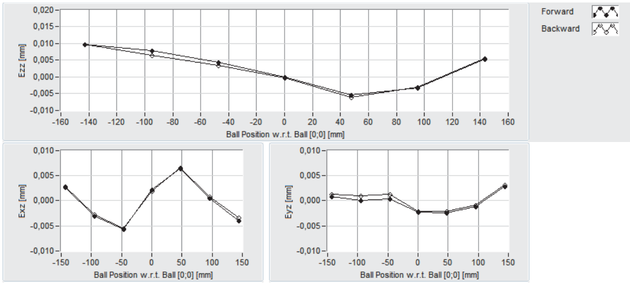

Fig. 7. Positioning error and straightness errors of Z-axis.

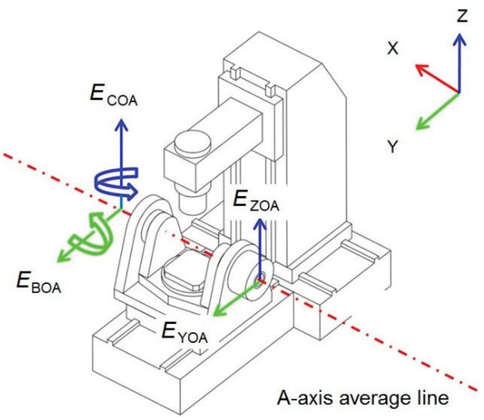

Fig. 8. A-axis average line location errors E_{YOA}, E_{ZOA} and squareness errors E_{BOA}, E_{COA} (each parameter is detailed in **Table 2**).

Table 2. A-axis average line location and squareness errors.

A-axis parameters	Description
E_{YOA}	Location error axis average line in Y-direction
E_{ZOA}	Location error axis average line in Z-direction
E_{BOA}	Squareness error axis average line to Z-axis (in latest ISO edition $E_{B(OZ)A}$)
E_{COA}	Squareness error axis average line to Y-axis (in latest ISO edition $E_{C(OY)A}$)

In this case, the largest error measured equals 16 μm (peak to peak for E_{ZZ}) and both straightness errors are smaller than 5 μm.

In this way, the Position Inspector is optimized for use in an industrial environment due to the high degree of automation and a limited measuring time for checking all three linear axes.

4. Checking Rotary Axis Performance

After checking the accuracy of the linear machine axes, the rotary axes are checked [15, 17–22, 25, 26, 30]. Instead of determining the error motions of a rotary axis itself [29], the location and orientation of the rotary axis average line are measured here (see **Fig. 8** and **Table 2**). After that the total machine accuracy is determined with a 5-axis test (e.g., BK4) [28].

Due to machine assembly errors and thermally induced drift, these location and orientation errors of rotary axes are often dominant for the machine's overall accuracy.

To measure the location error and orientation error of the axis average line, the Rotary Inspector has been developed. Here the squareness error is denoted as in ISO230-1, p. 15 (2012).

4.1. Rotary Inspector

The same measuring head is used in combination with a single precision ball for this application. This ball is positioned on the table (or pallet) such that the distance between the ball's center and the axis average line is at least 50 mm, typically close to the edge of the table to enable large circular paths to be executed.

Due to this distance, the squareness error of the rotary axis relative to the other machine's axes can be determined by considering the ball's "movement-out-of-the plane" relative to the circular path.

To measure the axis average line location error, the center position of the circular path is determined by least square circle fitting.

Any 5-axis machine tool can be measured with the Rotary Inspector but this paper is limited to trunnion table or swivel table machines. This means that these machines have two rotary axes at the table side (see **Fig. 4** for example).

4.2. Setup and Measurement Sequence

First the origin of the measuring head is aligned with the machine's spindle axis of rotation. This could be realized with adjustment screws but it is better to displace the measuring head's origin electronically by software. In principle any tool holder can be used for this application and the corresponding alignment parameters are re-loaded for each measurement.

Secondly the measuring head X-, Y-, and Z-coordinates are mapped with the machine's X-, Y-, and Z-axes. A rotation matrix is derived from this routine and applied instantly. Because the measurement axes of the measuring head coincide with the machine's axes, calculated errors can be transferred into the machine's controller directly.

4.3. BK1 Test

In ISO10791-6, kinematic tests are defined using three axes for trunnion table machines named BK1, BK2 [28]. For the BK1 test, the A-axis is commanded to move through its entire range (e.g., from 0° to $-90°$ to $+90°$ to 0°) while the linear Y- and Z-axes follow. For this, the TCP function is used in the controller.

The results of such a BK1 test are shown in time (see **Fig. 9**) and in space (see **Fig. 10**).

In **Fig. 10**, the same data is plotted in the YZ-plane. The measurement data is shown in dark blue in **Fig. 10** and the cyan circle represents the best fit circle, revealing the

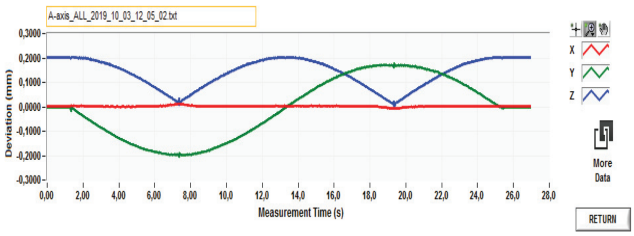

Fig. 9. BK1 measurement result of the A-axis: the displacement in X, Y, and Z are shown in time, 27 seconds.

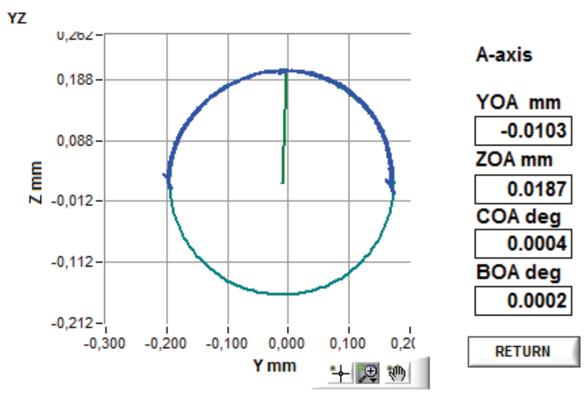

Fig. 10. BK1 measurement result of the A-axis shown in the YZ-plane.

Table 3. BK1 test: correction values A-axis.

A-axis average line parameter	Correction value
E_{YOA}	-10.3 μm
E_{ZOA}	18.7 μm
E_{COA}	0.0004°
E_{BOA}	0.0002°

location errors of the A-axis average line. From this the following error parameters are calculated (see **Table 3**). These errors can be used for machine compensation.

The data in the XY- and XZ-planes is available but omitted here to show the relevant YZ-plane better. These are included in the next example for the C-axis.

4.4. BK2 Test

For the BK2, three axes test the same is done for the second rotary axis: the C-axis is commanded to make a full circle clockwise and counter-clockwise while the X- and Y-axes follow. In **Figs. 11** and **12**, the results of such BK2 test are shown.

The same data is plotted in space in **Fig. 12**. These values can be used to correct the machine's kinematics: the C-axis average line is slightly displaced and rotated, i.e., due to a non-zero E_{AOC} (see **Table 4**). Due to this squareness error of the C-axis, the circle appears as an ellipse in the XZ-plane (centered graph in **Fig. 12**) and as an inclined line in the YZ-plane (graph on the right hand side in **Fig. 12**).

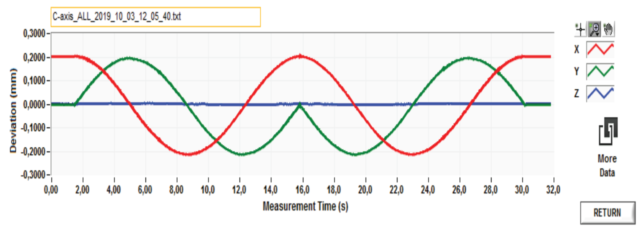

Fig. 11. BK2 measurement result of the C-axis: the displacement in X, Y, and Z are shown in time, 32 s.

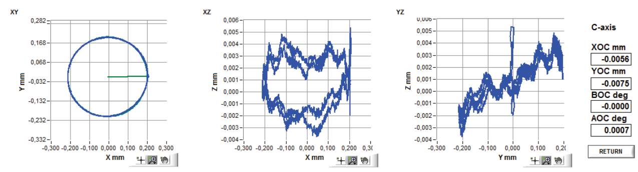

Fig. 12. BK2 measurement result of the C-axis shown in the XY-, XZ- and YZ-planes.

Table 4. BK2 test: correction values C-axis.

C-axis average line parameter	Correction value
E_{XOC}	-5.6 μm
E_{YOC}	-7.5 μm
E_{BOC}	0.0000°
E_{AOC}	0.0007°

A kind of wave pattern on this circle is observed and this is caused by the machine's dynamic behavior but should be absent for a perfect machine.

In **Fig. 12**, vertical spikes are present acting in Z-direction: these occur typically at start and stop of such measurement. Spikes can also appear at quadrant transitions caused by backlash (compensation) but are absent in **Fig. 12**.

Where a classic ball bar [6, 7, 9, 11, 12, 16, 31] detects spikes in radial direction only, it could not observe the vertical spike as observed in **Fig. 12**, because this acts in a plane perpendicular to the ball bar. The 3D measuring head detects any spike in any direction potentially caused by backlash, clamping, brakes, shocking protection cover motion, tubes, cables slaps, controller errors, etc.

4.5. Overall Accuracy Test BK4

Finally the BK4 test is executed using all five axes. The result of this test is shown in **Fig. 13**. For this test, the machine is commanded to rotate both rotary axes simultaneously while the three linear axes follow (see **Table 5**). The C-axis rotates with twice the speed of the A-axis and both move clockwise and counter-clockwise.

The displacement amplitude (i.e., maximum minus minimum value) in X, Y, and Z is to be reported and equals $dX = 22.6$ μm, $dY = 37.3$ μm, and dZ is 18.7 μm. The smaller the amplitude, the better the machine's accuracy in 5-axis mode.

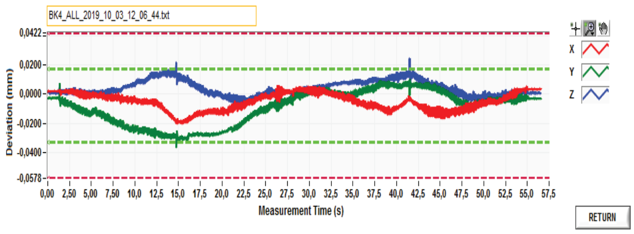

Fig. 13. BK4 measurement result: the displacement in X, Y, and Z are shown in time, 57 seconds.

Table 5. Description of BK4 test cycle.

A-axis angle	C-axis angle
$A = 0°$	$C = 0°$
$A = -90°$	$C = 180°$
$A = 0°$	$C = 360°$
$A = +90°$	$C = 180°$
$A = 0°$	$C = 0°$

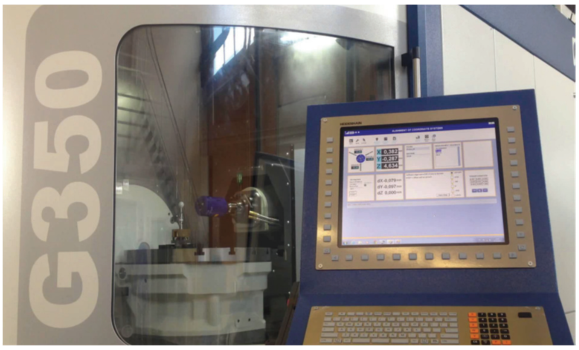

Fig. 14. Rotary Inspector software implemented on machine's controller.

Table 6. Compensation result.

Deviation	Before correction	After correction
dX	0.0734 mm	0.0165 mm
dY	0.0527 mm	0.0144 mm
dZ	0.0674 mm	0.0087 mm

These amplitudes can generally be decreased by correcting axis average line location errors and squareness errors (see Sections 4.3 and 4.4). The BK4 test is used as a final overall accuracy check.

4.6. Automatic Compensation

For automation the software of the Rotary Inspector can even be running on the machine's controller (see **Fig. 14**). This way all eight measured correction parameters (e.g., see **Tables 3** and **4**) can be directly implemented in the machine's kinematic chain.

After correction, the same BK4 test is repeated once again to check the results and degree of improvement (see **Table 6**). The degree of improvement is 3.6 times better in Y, 4.4 times better in X, and 7.7 times better in Z.

This example has been realized on a Heidenhain iTNC530 controller and automatic compensation for Siemens controllers is also available.

5. Summary

A non-contact 3D measuring head is used first in combination with a cross-shaped artefact containing 13 precision balls. The artefact is pre-calibrated on a CMM and measured in a bi-directional run on a machine tool. This measurement system, named Position Inspector, is used to check the accuracy of the three linear axes.

Secondly, this measuring head is used with a single precision ball to check the rotary axes. Measurements using three axes simultaneously can be used to correct axis average line location and squareness errors.

Finally the overall machine's accuracy is tested using the BK4 test, using 5-axes simultaneously. An example has been presented that shows the degree of improvement when applying error correction.

The measurement systems presented can even be implemented on the controller of the machine for optimal automation.

Acknowledgements

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2002 Received Doctoral degree (Mechanical Engineering) from Eindhoven University of Technology
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Main Works:
- Developing measurement systems and instruments for machine tools (5-axis machines, spindles)
- Provide training and system implementation
- ISO (TC39-SC2: Machine Tools – Test Conditions, Chair-person since 2016)

Membership in Academic Societies:
- European Society for Precision Engineering and Nanotechnology (euspen), Member of Scientific Committee
- International Academy for Production Engineering (CIRP)

Name:
Koen Houben

Affiliation:
IBS Precision Engineering BV

Address:
201 Esp, Eindhoven 5633AD, Netherlands

Brief Biographical History:
2017 Received Bachelor degree (Industrial Engineering and Management) from Fontys University of Applied Sciences (Eindhoven)
2017- Application Engineer, IBS Precision Engineering BV

Main Works:
- Manage and deliver optimal machine tool products
- Responsible for production of measurement systems
- On-site trainings and product demonstrations

Name:
Henny Spaan

Affiliation:
IBS Precision Engineering BV

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201 Esp, Eindhoven 5633AD, Netherlands

Brief Biographical History:
1990 Received Master of Science degree (Mechanical Engineering) from Eindhoven University of Technology
1993- Founder/President, IBS Precision Engineering BV
1995 Received Doctoral degree (Mechanical Engineering) from Eindhoven University of Technology

Main Works:
- Several patents on machine tool error calibration and compensation techniques
- (Ultra-precision) metrology
- Received Rien Koster Award (Dutch) in 2013 for his contribution to mechatronics and precision technology
- ISO (TC213: Metrology)

Membership in Academic Societies:
- International Academy for Production Engineering (CIRP)
- European Society for Precision Engineering and Nanotechnology (euspen)
- American Society for Precision Engineering (ASPE), former Board Member
- Mechanical Engineering Industry Association (VDMA) Electronics, Micro and New Energy Production Technologies (EMINT), Board Member

Name:
Theresa Spaan-Burke

Affiliation:
Innovation Director, IBS Precision Engineering BV

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Brief Biographical History:
1993-1999 Toshiba Research Europe / University of Cambridge
1994 Received Doctoral degree (Physics) from University of Kent
1999-2004 QinetiQ
2004-2012 CEO, European Society for Precision Engineering and Nanotechnology (euspen)
2012- IBS Precision Engineering BV
2013 Received Master degree (Global Business) from Oxford University

Main Works:
- Ultra-precision technologies
- Commercialization of precision technologies
- Leading numerous European and national funded projects
- Leading international team of national metrology institutes (define European Strategy for Nanotechnology)

Membership in Academic Societies:
- European Society for Precision Engineering and Nanotechnology (euspen)