# APPLICATION ON-THE-FLY MEASUREMENT OF CNC MACHINE TOOLS

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The publication describes an on-the-fly tracking experiment using a self tracking interferometer on a small three-axis machining center. On-the-fly based on continuous measurement, you can get much more measured points while reducing the time required for machine tool calibration than using Trigger or time measurements. The present publication compares the time required for calibration of the machine, and compares measured and evaluated data with each other. At the end the results are presented for calibration and verification of volumetric compensation with self tracking interferometer. In addition, the results obtained were verified by a circular test ISO 230-4.

**KEYWORDS**
machine tool, compensation, geometric accuracy, volumetric accuracy, tracking interferometer

## 1 INTRODUCTION

Increase the requirements for productionaccuracy of machine tools forces the machine tool manufactures and suppliers to develop new technologies to achieve these goals.

The production accuracy of machine tools is influenced by working precision, volumetric accuracy, positioning and geometrical accuracy of the machine tools. At present, multiple approaches are used to increase production accuracy. These include increasing geometering accuracy, for example, robot machining [Kubela 2016] or implementation volumetric compensation to machine tools. This compensation already addresses the precision of positioning and the geometric accuracy of the machine.

[Eman 1987] stated that quasi-static errors constitute 60 – 70% of the final error and affect the machine tool repeatability. Undisputedly, other error sources presented in a machine tool depending on factors such as kinematics, stiffness, cutting conditions, workpiece material, etc. affect the accuracy of a workpiece too. However, these sources are not inclued.

Volumetric accuracy for machining centres is described by geometric deviations. For kinematics of five-axis machining centre, it is 42 errors [Brecher 2012] and for the kinematics of three-axis vertical centre, it is 21 errors [Holub 2014].Eliminating all 21 of geometric errors can achieve significant improvement of individual errors and the resulting volumetric errors.A volumetric error in the entire workspace improved from 51.1µm to 20.0µm, i.e. approximately by 60%. With the circular interpolation test,the parameters were improved in the plane of X-Y circularity by 48% and positional tolerance by 38%, in the plane of Y-Z circularity by 42% and positional tolerance by 49% and in the plane of X-Z circularity by 5% and positional tolerance by 52%.The total time of calibration and verification lasted approximately 6.5hours [Holub 2015A].

Increasing of the volumetric accuracy of the machine tool is devoted to a large number of publications. These are mainly the development of own algorithm designs and procedures for calculating machine errors and corrections. The authors use homogenus transformation matrix (HTM) in particular for designing the machine's kinematic model. The publication [Holub 2015B, Hrdina 2017] is used in the modeling of machine errors of so called dual numbers. The authors introduced a more efficient calculation of the geoemtrical errors of the machine tool. The tools for visualization in virtual reality are dealt with by authors in [Kovar 2017]. These tools could be used to visualize and clarify spatial mapping obtained from volumetric accuracy measurements. Author [Ibaraki 2011] used HTM to build an algorithm to create a 5-axis machining centre error map using the R-test. These methods lead to the identification of errors in CNC machine tools, their use for subsequent compensation.

## 2 MACHINE TOOL CALIBRATION

Calibration of machine tools is done to increase the geoemtrical accuracy of the machine. Machine manufacturers and users use redefined functions to apply compensation data. Machine tools are most often used to compensate for the ENC linear encoder, along with the Backlash Compensation function. In addition, deflection computations are available, and volumetric compensation is currently available as the last option. Compensation of linear encoder errors, becklash, and straigness errors can be measured by, for example, a laser interferometer. The publication [Holub 2016] addresses the use of a combination of different compensation approaches. In the experiment, the combination of gradual load-off of the offset in the order of positioning accuracy and the volumetric compensation was the best solution. With this solution, the best results were obtained, but with high demands on timing measurements. Positioning measurement is introduced for large machine tools in [Marek 2009]. As part of the further streamlining of the measurements, an experiment using On-The-Fly measurements was carried out. This approach to measuring machine tools and coordinate measuring machines is presented in [Schwenke 2009].

This approach is implemented in a further part of the publication on a three-axis machining machine to compare the achieved improvement in volumetric accuracy using trigger and On-The-Fly(OTF) mode.

## 3 EXPERIMENTAL

The publication presents the results of the three-axis milling machining center calibration using trigger and on-the-fly mode. The results are then evaluated by the test of circularity performed by Ballbar QC20-w. Measurement time savings should be confirmed to.

### 3.1 *Demonstrator*

The case study was conducted on the MCV 754 QUICK. Measurement in trigger mode is described in [Holub 2016]. On-the-Fly mode connection is schematically shown in the figure 1. The Sinumerik control system is a recorded NC program that is controlled by the PC instruction. A signal is sent to the machine from the PC (1). During the movement of the machine, LaserTRACER (LTc) simultaneously transmits the measured length (2) and the trigger gives digital pulses to store the current machine position (T). After measuring one line, all measured data from machine positions to the PC (3) is sent via the Ethernet cable. At the same time, the LTc controller sends the data to the PC (4), where the data is evaluated together. If the data is evaluated as correctly measured, another position is measured.

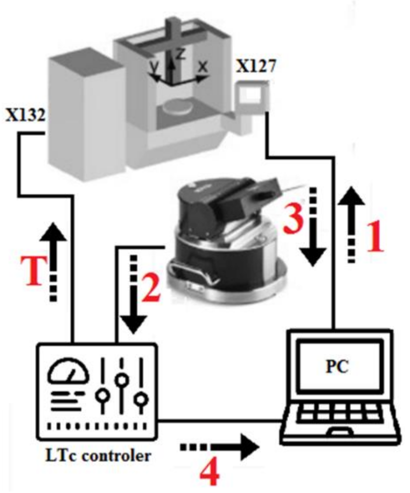


**Figure 1.** Diagram of machine tool connection with TRACER laser.

The demonstrator's kinematic chain and the corresponding geometric errors are shown in the figure 2.

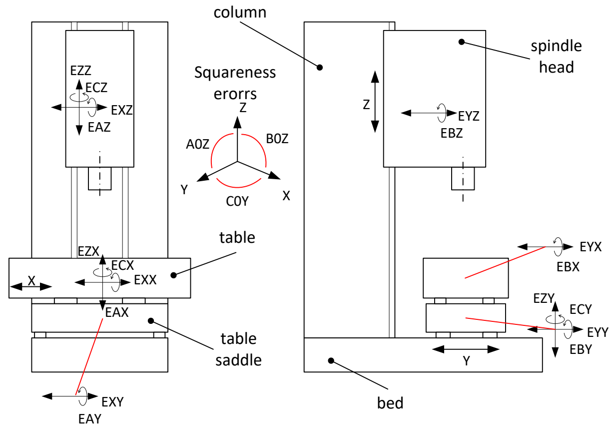


**Figure 2.** Geometric errors of three-axis vertical machining centre [Holub 2015A]

### 3.2 *Measurement strategy*

A full rigid body model (FRB) was selected to identify 21 machine geometry errors. The measurement strategy includes 6 LaserTracer measuring positions. The schematic of the position of the LaserTracer in position 6 is shown in the Fig. 3.

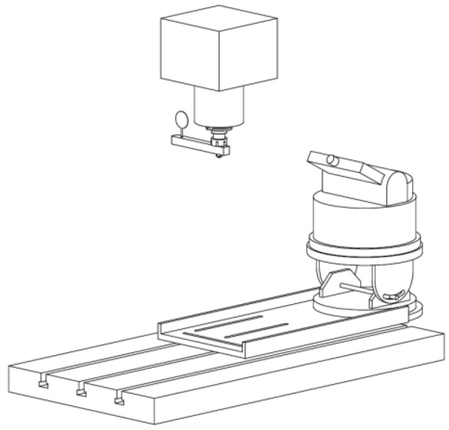

**Figure 3.** Scheme of measurement positions 6.

As part of the design of the measurement strategy, it is necessary to define the calibrated machine space. This is described in Table 1.

| Axis | Start axis /start mapping [mm] | End axis/ end mapping [mm] | Length [mm] |
|---|---|---|---|
| X | 0/150 | 500 / 754 | 350 |
| Y | 0 / 0 | 500/ 500 | 500 |
| Z | -550/ -400 | 0 / 0 | 400 |

**Table 1.** The measured area is defined according to the table.

### 3.3 *Trigger measurement*

In the first step, calibration measurements were performed using trigger mode. The results of 21 geometric errors obtained with LaserTARCER measurements are shown in the following table.

| Parameter | Value | Uncertainty |
|---|---|---|
| EXX [µm] | 15.3 | 0.2 |
| EYX [µm] | 5.6 | 0.5 |
| EZX [µm] | 1.8 | 0.3 |
| EXY [µm] | 1.3 | 0.1 |
| EYY [µm] | 12.7 | 0.5 |
| EZY [µm] | 1.8 | 0.2 |
| EXZ [µm] | 7.6 | 0.1 |
| EYZ [µm] | 1.7 | 0.1 |
| EZZ [µm] | 6.3 | 0.3 |
| EAX [µrad] | 9.2 | 1.2 |
| EBX [µrad] | 20.2 | 0.4 |
| ECX [µrad] | 19.4 | 0.3 |
| EAY [µrad] | 13.6 | 1.1 |
| EBY [µrad] | 16.7 | 0.3 |
| ECY [µrad] | 24.7 | 1.2 |
| EAZ [µrad] | 11.5 | 1.2 |
| EBZ [µrad] | 51.4 | 1.3 |
| ECZ [µrad] | 23.7 | 0.8 |
| C0Y [µrad] | 37.6 | 0.7 |
| B0Z [µrad] | -64.5 | 0.5 |
| A0Z [µrad] | 38.9 | 0.4 |

**Table 2.** Results of calibration measurement in trigger mode.

In the experiment, the ballbar QC20-w was performed test of circularity.The following table shows selected machine date without activated volumetric compensations.

| | Value |
|---|---|
| Circularity [µm] | 10.6 |
| Squareness [µm/m] | 55.5 |
| Straightness X [µm] | 12.3 |
| Straightness Y [µm] | 0.3 |
| Scaling error X [µm/m] | 41.8 |
| Scaling error Y [µm/m] | 36.9 |
| Position tolerance [µm] | 49.9 |

**Table 3.** Results of the test of circularity.

The following figure shows the test of circular interpolation for two runs. Dynamic reversal errors can be seen in the image, and there is a large squareness error and scaling errors.

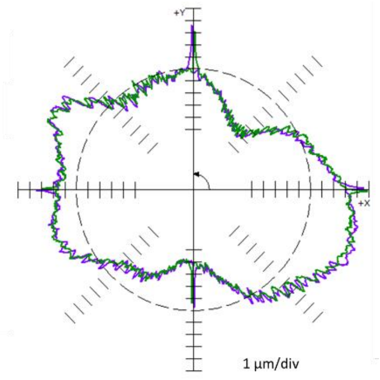


**Figure 4.** Results test of circularity without VCS compensation

The following table shows the results of the verification test with LaserTracer in trigger mode. Here, a significant improvement in most errors can be observed.

| Parameter | Value | Uncertainty |
|---|---|---|
| EXX [µm] | 2.5 | 0.3 |
| EYX [µm] | 2.0 | 0.7 |
| EZX [µm] | 2.0 | 0.3 |
| EXY [µm] | 2.4 | 0.1 |
| EYY [µm] | 13.1 | 0.5 |
| EZY [µm] | 6.1 | 0.3 |
| EXZ [µm] | 0.4 | 0.1 |
| EYZ [µm] | 0.5 | 0.1 |
| EZZ [µm] | 5.8 | 0.3 |
| EAX [µrad] | 6.4 | 1.7 |
| EBX [µrad] | 10.9 | 0.5 |
| ECX [µrad] | 7.7 | 0.4 |
| EAY [µrad] | 22.6 | 1.1 |
| EBY [µrad] | 4.1 | 0.3 |
| ECY [µrad] | 39.1 | 1.4 |
| EAZ [µrad] | 17 | 1.2 |
| EBZ [µrad] | 86.9 | 1.0 |
| ECZ [µrad] | 24.7 | 1.0 |
| C0Y [µrad] | 4.6 | 0.8 |
| B0Z [µrad] | -8.1 | 0.6 |
| A0Z [µrad] | 10.6 | 0.4 |

**Table 4.** Results of verification measurement in trigger mode.

In fig. 5 shows the results of the circularity test after the introduction of the volumetric compensations. It can be seen from the figure that dynamic reversal errors have remained. Other geometric errors have been improved. This is especially the problem of squareness. The results are shown in Table 9.

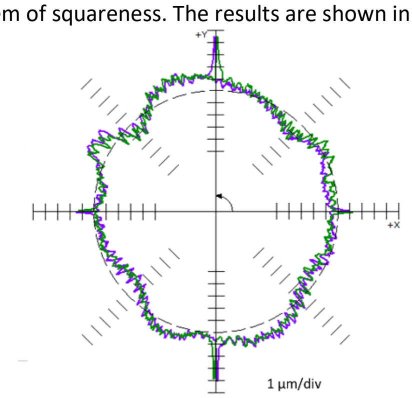


**Figure 5.** Results test of circularity with VCS compensation - trigger

The following table shows the times for the each LTc positioning. In addition, the total time required to measure in trigger mode was determined. The measurement time of the MCV 754 was 58 min.

| Position | Start [Time a.m.] | End [Time a.m.] | Time [min] |
|---|---|---|---|
| 1 | 9:06 | 9:15 | 0:09 |
| 2 | 9:30 | 9:43 | 0:13 |
| 6 | 10:00 | 10:08 | 0:08 |
| 5 | 10:13 | 10:23 | 0:10 |
| 4 | 10:38 | 10:48 | 0:10 |
| 3 | 10:57 | 11:05 | 0:08 |
| | | | 0 :58 |

**Table 5.** Determination of partial measurement times and total time.

### *3.4 On-the-fly measurement*

In the second step, calibration measurements were performed using the OTF mode. The results of 21 geometric errors obtained with LaserTARCER measurements are shown in the table 6.

| Parameter | Value | Uncertainty |
|---|---|---|
| EXX [µm] | 16.1 | 0.2 |
| EYX [µm] | 6.4 | 0.6 |
| EZX [µm] | 1.1 | 0.3 |
| EXY [µm] | 2.7 | 0.2 |
| EYY [µm] | 17.9 | 0.5 |
| EZY [µm] | 1.4 | 0.2 |
| EXZ [µm] | 8.4 | 0.1 |
| EYZ [µm] | 3.4 | 0.1 |
| EZZ [µm] | 6.3 | 0.3 |
| EAX [µrad] | 8.0 | 1.3 |
| EBX [µrad] | 21.2 | 0.5 |
| ECX [µrad] | 20.2 | 0.3 |
| EAY [µrad] | 14.6 | 1.1 |
| EBY [µrad] | 21.0 | 0.3 |
| ECY [µrad] | 32.2 | 1.4 |
| EAZ [µrad] | 6.8 | 1.2 |
| EBZ [µrad] | 70.4 | 1.1 |
| ECZ [µrad] | 13.5 | 0.7 |
| C0Y [µrad] | 40.2 | 0.7 |
| B0Z [µrad] | -71.3 | 0.6 |
| A0Z [µrad] | 48.9 | 0.3 |

**Table 6.**Results of calibration measurement in OTF mode.

The next table show results from verification measurement.

| Parameter | Value | Uncertainty |
|---|---|---|
| EXX [µm] | 1.9 | 0.2 |
| EYX [µm] | 2.1 | 0.5 |
| EZX [µm] | 1.2 | 0.3 |
| EXY [µm] | 1.8 | 0.2 |
| EYY [µm] | 3.7 | 0.5 |
| EZY [µm] | 1.4 | 0.3 |
| EXZ [µm] | 1.5 | 0.1 |
| EYZ [µm] | 1.4 | 0.1 |
| EZZ [µm] | 5.8 | 0.3 |

| | | |
|---|---|---|
| EAX [µrad] | 3.1 | 1.3 |
| EBX [µrad] | 7.0 | 0.4 |
| ECX [µrad] | 3.5 | 0.3 |
| EAY [µrad] | 4.6 | 1.3 |
| EBY [µrad] | 3.1 | 0.3 |
| ECY [µrad] | 24.0 | 1.4 |
| EAZ [µrad] | 11.5 | 1.1 |
| EBZ [µrad] | 63.2 | 1.1 |
| ECZ [µrad] | 22.6 | 0.7 |
| C0Y [µrad] | -7.4 | 0.8 |
| B0Z [µrad] | 4.7 | 0.6 |
| A0Z [µrad] | -4.9 | 0.4 |

**Table 7.** Results of verification measurement in OTF mode.

Figure6 shows the results of the circularity test after the introduction of the on-the-fly volumetric compensations. It can be seen from the figure that dynamic reversal errors have also remained. Other geometric errors have been improved. This is especially the problem of squareness. The results are shown in Table 9.

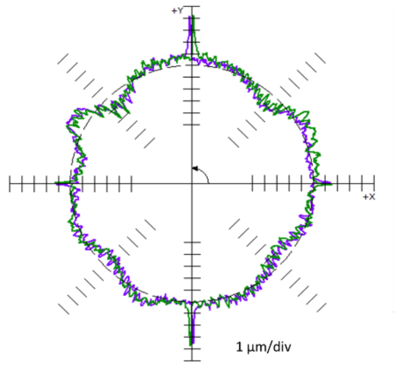


**Figure 6.** Results test of circularity with VCS compensation - OTF

The following table shows the times for the each LTc positioning. Furthermore, the total time required for OTF measurement was determined. The measurement time of the MCV 754 was 33 minutes. This is a time saving of approx. 57%.

| Position | Start [Time a.m.] | End [Time a.m.] | Time [min] |
|---|---|---|---|
| 1 | 9:40 | 9:44 | 0:04 |
| 2 | 10:19 | 10:25 | 0:06 |
| 6 | 11:30 | 11:37 | 0:07 |
| 5 | 11:53 | 11:58 | 0:05 |
| 4 | 12:15 | 12:20 | 0:05 |
| 3 | 12:31 | 12:37 | 0:06 |
| | | | 0:33 |

**Table 8.** Determination of partial measurement times and total time.

### 3.5 Results

From the measurements made, it can be stated that the On-The-Fly measurement mode provides a time saving of about 50%. For large machine tools where trigger measurement is a necessity to reserve a machine for 7 hours, this saving is very noticeable.

| Parameter | Value trigger | Value on-the-fly |
|---|---|---|
| EXX [µm] | 2.5 | 1.9 |
| EYX [µm] | 2.0 | 2.1 |
| EZX [µm] | 2.0 | 1.2 |
| EXY [µm] | 2.4 | 1.8 |
| EYY [µm] | 13.1 | 3.7 |
| EZY [µm] | 6.1 | 1.4 |
| EXZ [µm] | 0.4 | 1.5 |
| EYZ [µm] | 0.5 | 1.4 |
| EZZ [µm] | 5.8 | 5.8 |
| EAX [µrad] | 6.4 | 3.1 |
| EBX [µrad] | 10.9 | 7.0 |
| ECX [µrad] | 7.7 | 3.5 |
| EAY [µrad] | 22.6 | 4.6 |
| EBY [µrad] | 4.1 | 3.1 |
| ECY [µrad] | 39.1 | 24.0 |
| EAZ [µrad] | 17 | 11.5 |
| EBZ [µrad] | 86.9 | 63.2 |
| ECZ [µrad] | 24.7 | 22.6 |
| C0Y [µrad] | 4.6 | -7.4 |
| B0Z [µrad] | -8.1 | 4.7 |
| A0Z [µrad] | 10.6 | -4.9 |

**Table 9.** Comparison of geometric errors of verification measurements in trigger and On-The-Fly modes.

Table 10 shows the results of selected errors obtained from the circularity test. Here are the values for the trigger mode, On-The-Fly, and the calculated difference between these modes.

| | Value trigger | Value on-the-fly | difference |
|---|---|---|---|
| Circularity [µm] | 6.4 | 6.4 | 0 |
| Squareness [µm/m] | 5.0 | 5.0 | 0 |
| Straightness X [µm] | 1.0 | 0.6 | 0.4 |
| Straightness Y [µm] | 0.1 | -0.2 | 0.1 |
| Scaling error X [µm/m] | 6.1 | 9.5 | 3.4 |
| Scaling error Y [µm/m] | 11.6 | 8.9 | 2.7 |
| Position tolerance [µm] | 9.8 | 9.0 | 0.8 |

**Table 10.** Comparison of circular test results for trigger and On-The-Fly modes.

Figure 7 shows an EXX error pattern obtained by a calibration measurement in trigger (Table 2) and On-The-Fly modes (Table 6). From the course you can see deviations from the waveforms that are negligible. These deviations can be caused by the time lag of the individual measurements and are attributed to different temperatures on the production hall. It can be seen from the graph that the trigger and on-the-fly modes do not affect the resulting measurement accuracy.

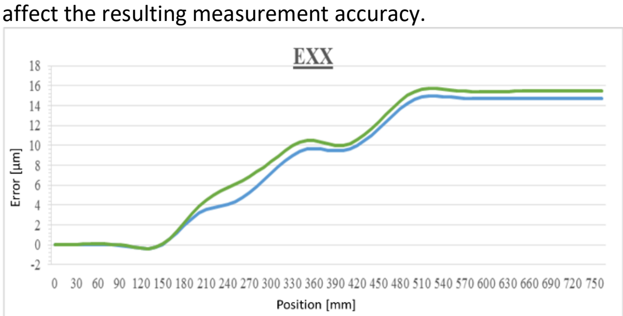


**Figure 7.** Graph showing EXX error patterns for Trigger (blue) and On-The-Fly (green).

## 4 CONCLUSIONS

Verification of suitability of volumetric compensation with LaserTracer in On-The-Fly mode was made in the publication. As a first result, we can say that this method can achieve significant time savings of around 50%. In addition, it can be concluded from the measurements that the continuous measurement by the On-The-Fly method does not affect the results of the geometric errors. This was confirmed by both the comparison with the trigger method and the circularity test (ISO 230-4). The biggest differences can be observed for scaling errors that are affected by ambient temperature. Since the tests were not carried out in a temperature-stable hall, these errors can be attributed to the distribution of temperatures. The main observed errors such as squareness, position tolerance, straightness and circularity showed minimal differences between calibrations performed in trigger and On-The-Fly modes. In conclusion, the On-The-Fly method has a great potential to control and compete for the integrity of machine tools.

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