METHODS, PRACTICES, AND STANDARDS FOR EVALUATING ON-MACHINE TOUCH TRIGGER PROBING OF WORKPIECES

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ABSTRACT
This paper presents work being performed by NIST to evaluate test methods prescribed by the new draft standard for determination of on-machine measuring performance of numerically controlled machine tools [1]. The measuring performance of a machining center, equipped with a strain gage style touch trigger probing module, is evaluated according to this standard in order to validate the proposed test methods and to generate a baseline set of data to be used in the development of on-machine measurement uncertainty budgets. Probing repeatability, two-dimensional (2D) and three-dimensional (3D) probing errors and errors in identifying the workpiece coordinate system (WCS) in the machine coordinate system (MCS) are evaluated and the results presented.

INTRODUCTION
Using computer numerically controlled (CNC) machine tools as inspection platforms by employing on-machine touch trigger probing systems has become increasingly more attractive to many machine tool users. The most common uses of touch trigger probing systems on CNC machine tools include establishment of the WCS in the MCS in preparation for the subsequent machining operations as well as on-machine inspection of the machined workpiece. In some cases, probing is used to quickly validate machine geometric and/or thermal deformations by measuring a standard artifact located in the machine work volume [2-4]. Key benefits of implementing this technology include fast and accurate setups and the detection of machining errors, thus reducing scrap and rework. However, concerns exist over the fact that the machine structure and position feedback systems used to manufacture workpieces are the same systems used for measuring workpieces, and thus the errors that occur during machining may also occur during measuring, preventing the detection of errors on the workpieces. Therefore, this “error coupling” must be considered and assessed carefully for any on-machine measurement application.

A draft international standard, ISO/DIS 230-10, has recently been developed to help users of on-machine touch trigger probing systems evaluate the measuring performance of their machine tools [1]. The standard describes test methods designed to evaluate the combined effects of the probe, the probing hardware and software, signal transmission system, signal conditioning hardware, the environment, and the machine tool, on measuring performance. We evaluated several test methods described in this draft standard by measuring the performance of a CNC machining center (Fig. 1) equipped with a strain gage style touch trigger probing module. Descriptions of the tests performed, the measurement results, and a description of how this data will be used in the development of on-machine touch trigger probing uncertainty budgets are provided in the following sections.

PROBING SYSTEM
The probing system used with this machine is a commercially available strain gage style touch trigger probe. The probe, with a 100 mm long carbon fiber stylus and 6 mm diameter ruby sphere tip, is mounted in the machine spindle. It can be driven along the ± *X*-, ± *Y*-, and –*Z*-axes. Communication between the probe and machine controller is via a wireless optical transmission system and a wired machine interface module. The effective radius and effective length of the probing system, as calibrated for these tests,

 The full descriptions of the procedures used in the paper require the identification of certain commercial products and their suppliers. The inclusion of such information should in no way be construed as indicating that such products or suppliers are endorsed by NIST or are recommended by NIST or that they are necessarily the best materials, instruments, software or suppliers for the purposes described was 5.879 mm and 268.886 mm, respectively. A nominal probing feedrate of 300 mm/min was used for each test.

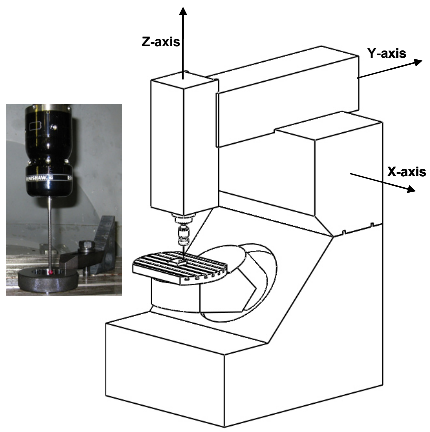

FIGURE 1. Schematic of the machining center used in this evaluation of ISO/DIS 230-10

REFERENCE ARTIFACTS

Three reference artifacts, a 50.8 mm grade B gage block, a 45.7 mm diameter ring gage, and a 25.4 mm diameter calibration sphere were used in this evaluation. Each artifact was allowed to thermally equilibrate in the machine shop environment before any tests were performed.

TEST METHODS

We conducted tests designed to evaluate probing repeatabilities, probing errors, feature size measurement errors, and the errors in determining workpiece location and orientation. These tests assess the capability of the machine to make measurements with varying degrees of complexity. Such complexity ranges from detecting a contact point along a single axis of motion, to detecting a feature involving motion along vectors in space and processing the collection of contact point data. The tests evaluated were performed with the prescribed artifacts located at different positions in the MCS from the position where probe calibration occurred. Descriptions for each test are provided below.

Probing Repeatability

Three tests were conducted to evaluate probing repeatability: 1) single-point surface location repeatability, 2) circle center location repeatability, and 3) sphere center location repeatability.

Single-Point Surface Location

In this test three surfaces of a reference block are aligned to the MCS. Surfaces normal to the *X*-, *Y*-, and *Z*-axes are individually and uni-axially probed ten times. The single-point surface location repeatability along each axis, $R_{SPT,X}$, $R_{SPT,Y}$, and $R_{SPT,Z}$, is calculated as the range of the individual coordinate values.

Circle Center Location

A reference ring is aligned paraxially to the machine *Z*-axis. A WCS is established at the ring center by probing the ring with four points equally spaced around the ring inner circumference. The ring center coordinates in the *XY* plane are calculated using a best fit circle algorithm and recorded. The measurement process is repeated ten times. Probing repeatability parameters, $R_{CIR,X}$ and $R_{CIR,Y}$, are calculated as the range of the recorded *X*- and *Y*- center values.

Sphere Center Location

A reference sphere is probed with one point at the pole and four points equally spaced around the equator. The measurement process is repeated ten times and the *X*-, *Y*-, and *Z*-axis sphere center coordinates for each measurement are determined using a least squares best fit sphere algorithm. Probing repeatability parameters, $R_{SPH,X}$, $R_{SPH,Y}$, and $R_{SPH,Z}$, are calculated as the range of the center coordinates along *X*-, *Y*-, and *Z*-axes, respectively.

2D Probing Error

A reference ring is probed with 25 points equally spaced around the ring circumference. The ring center is determined using a least squares best fit circle algorithm and the radial distances from the center to the measured points are determined. 2D probing error, $P_{FTU,2D}$, is calculated as the range of the measured radial distances.

3D Probing Error

A reference sphere is probed in the radial direction with 25 points spaced around the upper half of the sphere circumference. One probing point is located at the sphere pole, four points are equally spaced 22.5° below the pole, eight points are located 45° below the pole, four points are 67.5° below the pole, and eight points are 90° below the pole. The sphere center is determined using a least squares best fit sphere algorithm and the radial distances from the center to the measured points are calculated.

3D probing error, $P_{FTU,3D}$ is calculated as the range of the radial distances.

Workpiece Location and Orientation

This test assesses the capability of a machine to determine the location and orientation of a workpiece before it initiates machining operation. A reference block is mounted on the work table, skewed by approximately 1° about the *X*-, *Y*-, and *Z*-axes in the MCS. The WCS orientation and origin are determined by probing the reference block and recorded in the active work offset. Four points on the top surface of the block are then probed in the *Z*-direction of the WCS. $E_{PLA,Z}$, WCS reference plane identification error, is calculated as the range of the recorded *Z*-coordinates in the WCS. Next, two points are probed parallel to the *Y*-axis of the WCS on the surface aligned parallel to the WCS *XZ*-plane. $E_{LIN,Y}$, WCS orientation identification error, is calculated as the difference between the two *Y*-coordinates in the WCS. The reference block corner or WCS origin location coordinates, X_{COR}, Y_{COR}, and $Z_{COR,}$ are then measured by probing one point on each of the three reference block surfaces used to define the WCS origin. Last, the reference block size is measured. $E_{EST,Y}$, the effective stylus tip diameter error, is calculated as the difference between the measured size and the calibrated size of the reference block.

Feature Size Measurement Performance

The following three tests were conducted to evaluate feature size measurement performance.

Web Size

A reference block is aligned along the *X*-axis of the machine and its length is measured ten times. Then the block is aligned along the *Y*-axis and its length is again measured ten times. The measurement performance parameters, $E_{WEB,X}$ and $E_{WEB,Y,}$ are calculated as the average of the differences between the reference block calibrated length and the measured values along the *X*- and *Y*-directions, respectively. $R_{WEB,X}$ and $R_{WEB,Y}$, are calculated as the range of the measured values for each axis.

Circle Diameter

A reference ring is aligned paraxially to the machine *Z*-axis and its inner diameter is measured by probing four points equally spaced around its circumference. The ring diameter is calculated using a least squares best fit circle algorithm. The measurement is repeated ten times and the performance parameter, $E_{CIR,D}$, is calculated as the average differences between the ring calibrated diameter and the measured diameter values. $R_{CIR,D}$, is calculated as the range of the recorded diameter values.

Sphere Diameter

A reference sphere is probed with five points in radial directions parallel to the machine axes. One probing point is located at the sphere pole and four are equally spaced around the sphere hemisphere. The sphere diameter is calculated using a least squares best fit sphere algorithm. The performance parameter, $E_{SPH,D},$ is calculated as the average of the differences between the reference sphere calibrated diameter and the measured diameter values. $R_{SPH,D}$ is calculated as the range of the measured diameter values.

MEASUREMENT CYCLES

Several CNC measuring cycles are provided with the machine control software, e.g., probing of a surface, a web, or a hole. Whenever applicable, these standard measuring cycles were used to perform a prescribed test method. The cycles used included:

- a cycle for measuring a surface normal to the axis of travel
- a cycle for measuring a hole with four points parallel to the machine axes
- a cycle for measuring a sphere with five points parallel to the machine axes
- a cycle for fitting a least squares best fit circle to four points.

For tests where the standard measuring cycles were not applicable, custom CNC programs were generated and analyses of the probing points were performed post-process on a personal computer. Custom CNC programs were generated for tests requiring the probing of a reference ring with more than four points and the probing of a reference sphere with more than five points. The circle fitting algorithm provided by the controller is limited to fitting a circle to a maximum of four points. Because of this limitation, analyses requiring a circular fit to more than four points and analysis requiring a spherical fit were performed via post-processing on a personal computer using least squares best fit methods.

MEASUREMENT RESULTS

The results from the above mentioned tests are given in Tables 1 – 3.

TABLE 1. Probing Repeatability & Error Results

Single Point	
$R_{SPT,X}$: 1.10 µm	$R_{SPT,Y}$: 0.70 µm
$R_{SPT,Z}$: 0.50 µm	
Circle Center	
$R_{CIR,X}$: 0.70 µm	$R_{CIR,Y}$: 0.80 µm
Sphere Center	
$R_{SPH,X}$: 0.40 µm	$R_{SPH,Y}$: 0.71 µm
$R_{SPH,Z}$: 0.43 µm	
Probing Error	
$P_{FTU,2D}$: 3.30 µm	$P_{FTU,3D}$: 3.82 µm

TABLE 2. Workpiece Location and Orientation Results

WCS Errors	
$E_{PLA,Z}$: 4.14 µm	$E_{LIN,Y}$: 1.0 µm
$E_{EST,Y}$: 21.7 µm	
WCS Location	
X_{COR}: 81 µm	Y_{COR}: 314 µm
Z_{COR}: 68 µm	

TABLE 3. Feature Size Measurement Performance Results

Web Size	
$E_{WEB,X}$: 16.8 µm	$R_{WEB,X}$: 1.10 µm
$E_{WEB,Y}$: 20.8 µm	$R_{WEB,Y}$: 0.70 µm
Circle Diameter	
$E_{CIR,D}$: -17.8 µm	$R_{CIR,D}$: 1.70 µm
Sphere Diameter	
$E_{SPH,D}$: 17.0 µm	$R_{SPH,D}$: 0.44 µm

DISCUSSION OF RESULTS

The measurement results suggest that probing repeatabilities for on-machine measurements are small, approximately 1 µm and below. However, the test results also suggest that significant errors exist in the probing systems ability to accurately determine the location of the workpiece in the MCS and to accurately measure feature size. The *X*-, *Y*-, and *Z*-axis linear positioning repeatabilities, as defined by standards [5], for this machine tool are 3.6 µm, 3.5 µm, and 5.1 µm, respectively. A comparison of the positioning repeatabilities and probing repeatabilities suggest that linear axis positioning repeatability may not be a good indication of the machine tool's probing performance, i.e., the probing performance may be better than the linear positioning performance. In addition, simulation of the 2D and 3D probing error tests with our virtual machine tool model based on the quasi-static positioning errors of the machine resulted in simulated probing errors of 1.4 µm and 1.7 µm, respectively. A comparison of the simulated and measured probing errors suggests that the machine's positioning errors may contribute as much as 44 % to the probing error.

CONCLUSIONS

The test methods prescribed by ISO/DIS 230-10 have been used to evaluate the measuring performance of a CNC machine tool equipped with a strain gage style touch trigger probing module. Each test method was efficiently performed and did not require the use of any expensive equipment. The measurement performance parameters obtained for various probing scenarios prescribed in the standard provided all necessary information to estimate the overall uncertainties of on-machine part probing with this system.

FUTURE WORK

The measurement results produced by this evaluation will be used in the development of measurement uncertainty budgets for measuring part specific features on machine tools using touch trigger probing. Simulations of the test methods using our virtual machine tool model will help us prioritize the contributors to the on-machine measurement uncertainty and, in the long term, will aid in the prediction of acceptable part features and tolerances to be manufactured with this system.

REFERENCES

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