On-Machine Coordinate Measuring for In-Situ Quality Control

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Abstract

The capability of a computer numerical control (CNC) machine tool equipped with direct computer control coordinate measuring software and high accuracy contact probing is validated for in-situ machine health monitoring and in-situ part quality control. The validation conforms to international standards for performance evaluation of commercially available coordinate measuring machines (CMMs). The capability of the CNC system to perform CMM-type measurements is demonstrated via a case study. The equivalency between part dimensional measurements obtained directly from the use of the CNC machine tool as a CMM and from part dimensional measurements performed using commercially available CMMs is established via a correlation study.

Keywords: machining, CNC, coordinate measuring, CMM, first article inspection, in-situ quality control.

1. Introduction

This work was aimed at the development of a procedure to combine production, machine monitoring and part dimensional measurement using computer numerical control (CNC) machine tools equipped with in-situ, self-validated probing systems, to be utilized in the aerospace manufacturing sector, specifically at Spirit AeroSystems. A methodology in which the machine tool completes the required part operations, and then functions as a coordinate measuring machine (CMM) is laid out, to eliminate the need to perform long and expensive ex-situ CMM measurements. The novel, in-situ probing procedure is especially attractive for the completion of automated, daily machine health checks and first article inspections that are regulated by international standards (SAE AS9102B: Aerospace First Article Inspection Requirement 2014). The advantages are reduced operating cost due to reduced inspection labor/time and part rework requirements, and increased conformance to part quality specifications. The procedure aids in the certification by aerospace quality audit criteria (NADCAP Audit Criteria for Measurement and Inspection 2013).

A qualification method is applied to verify that the machine tool can be used as a CMM with sufficient accuracy and repeatability, and to ensure that the daily machine performance and first article inspections conducted with the in-situ CMM probing system are accurate. The qualification method is based on the standards that apply to commercial CMMs. That is, standards ANSI/ASME B89.4-1997 (Hook 2001), including addenda ANSI/ASME B89.4a-1998 and ANSI/ASME B89.4b-2001, and ISO 10360-2:2009 (ISO/TC 2009). These standards are henceforth referred to as ASME B89.4 and ISO 10360-2.

To operate the machine tool as a CMM, a high precision spherical probe (Renishaw Rengage, model RMP600 (RMP600 radio machine probe 2008) is mounted directly on the machine head, to trigger the reading of machine X, Y and Z coordinates, which are taken as the coordinates of the point of interest. The methodology is validated following a case study involving the drilling of holes on a family of aircraft floor beams using a computer numerical control (CNC) machine tool – a Bavius 5-axis machining center. The holes are located at various locations on the long faces of the floor beams. A picture illustrating the Bavius CNC machining center and the definition of its axes is shown in Figure 1.

Figure 1. A picture of the Bavius CNC machining center.
The machine coordinate system is superimposed on the picture.
When the machine rotary axis A = 0°, the spindle is vertical as shown.

2. Goals of the research study

The research study presented herein was aimed at establishing a comparison a via round robin-type study between measurements reported by the in-situ CMM probing system and conventional, commercially available, probing systems including laser trackers, laser scanners and point probing (Zhao, Xu and Xie 2009).

After a brief background of the literature in the field of CMM probing, the machine tool qualification method, including daily machine performance check and first article inspection procedures are described. Then, details of the round robin experimental setups are presented, and the results are analyzed via correlation. Finally, concluding remarks are given.

3. Background

Qualification of the use of the CNC machining center as a CMM is performed following two procedures. Thes are: 1) volumetric testing and 2) interim performance evaluation (daily checks).

Volumetric testing involves measuring the displacement of the CNC machine drives using a calibrated instrument of sufficient range, accuracy and repeatability, twice a year. In general, the machine is to be commanded to move its head along several paths, over a volume that matches the regular operating volume of the CMM. The selected paths include space diagonals requiring 3-axis interpolation (p.32 of ASME B89.4 and p. 8 of ISO 10360-2). Presumably, 3-axis interpolation motion is the most inaccurate kind of machine motion (Suh, et al. 2008). The diagonals illustrated in Figure 2 represent the paths to be implemented during the volumetric testing described herein. The machine head is stopped at predetermined distance intervals, to permit several measurements of actual head position along the length of each diagonal. As per the ASME B89.4, for large CMMs of the size and axis aspect ratio of the Bavius CNC machining center, at least ten (10) measurements should be performed on each diagonal (p. 37 of ASME B89.4). As per the ISO 10360-2, at least five (5) measurements should be performed on each diagonal, distributed evenly over the length of the diagonal (p. 6-7 of ISO 10360-2).

An interim performance evaluation is used to determine the likelihood that a CMM is working within its accuracy and repeatability, between full volumetric tests. As per the ASME B89.4 and ISO 10360-2 standards, the goal of the interim test is to identify and stop CMMs that are out of accuracy and repeatability, before a significant number of bad parts are accepted or good parts rejected. The interim test should be applied frequently to increase confidence in the CMM's performance. It may be based on measurements made on a test workpiece of the same family that the machine is to test regularly or on measurements made on an artifact specifically designed for CMM testing. After a full volumetric test, ten (10) consecutive interim tests should be conducted, and the mean deviations from the artifact's nominals used to establish a baseline value for the artifact, with the range of deviations taken as an indication of the expected, typical variation from nominals. Deviations from the artifact's nominals should also be within the accuracy and repeatability tolerances of the CMM. Historical data from regular interim tests should be within the range of deviations established by the ten (10) initial interim tests.

4. Volumetric Testing of the Bavius CNC Machining Center

Volumetric testing is adapted from standard procedures described in the background and involves measuring the displacement of the CNC machine drives using laser tracker (API R-50 Radian, serial number 60166) traceable to NIST, twice a year. In general, the machine is to be commanded to move its head along several paths, over a volume illustrated in Figure 2. This matches the regular operating volume of the CNC machine. To qualify the Bavius CNC machining center for the parts to be produced with it, the volumetric testing involved taking diagonal motion measurements every 14.5 in of machine head travel. This produces a total of 10 measurement positions along each diagonal. The Bavius CNC machining center is compensated for ambient temperature, using a built-in sensor and compensation algorithm (Wu, et al. 2012). Therefore, displacement commands represent part lengths at the standard temperature of 68 °F. The drives are set at feed rate equal to the feed rate to be used during the regular operation of the CNC machine as a CMM.

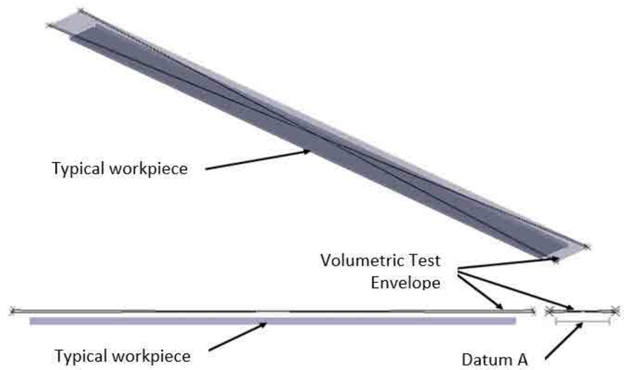
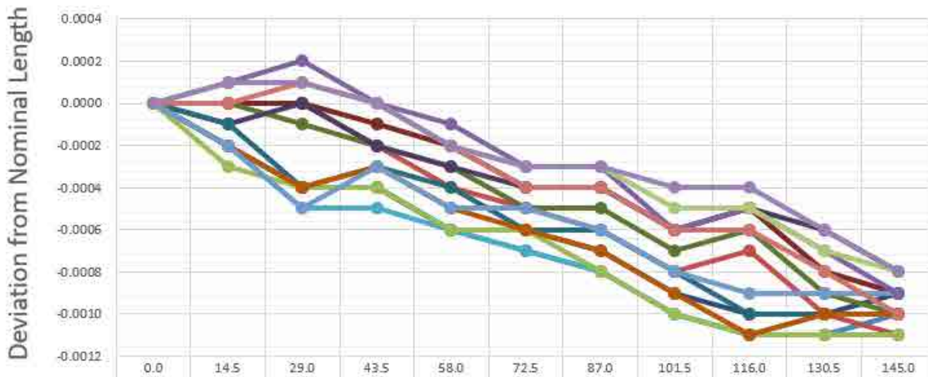


Figure 1. Illustration of a typical workpiece processed by the Bavius CNC Machining Center and the volume over which the volumetric test is to be applied.

The laser tracker's reflector is mounted on the tip of a tool holder inserted in the machine head, while the laser source/receiver unit is held stationary at a convenient location on the machine frame. The laser tracker is compensated for ambient temperature, atmospheric water pressure (air humidity), and atmospheric pressure, using built-in sensors and a compensation algorithm. Therefore, measurement values are true values at 68 °F. The start of each diagonal is taken as the zero-length reference. The difference between corresponding commanded and measured lengths are calculated. The measured length is the cumulated length along a diagonal. That is, the laser tracker is only zeroed at the start of a diagonal. The diagonal motions, and the measurements, are performed four (4) times. The start of each diagonal is taken as the zero-length reference. The difference between the four (4) measured lengths corresponding to the same location along a diagonal are calculated. For each measurement location, the range of the four measured lengths is calculated. The maximum range is taken as the machine repeatability index. This repeatability index can be used to assess machine performance over time. The difference between the most positive error and the most negative error, regardless of measured length, is taken as the machine accuracy index. Commonly applied industrial practice dictates that this accuracy index shall be at least four (4) times smaller than the smallest tolerance of the dimensions to be measured with the machine.

Figure 3 shows a plot of the deviation of the measured length with respect to the nominal length vs. the nominal length given as commanded motion to the Bavius CNC machining center, all along the four diagonals defined in Figure 2, including all repeat measurements. From Figure 3, the repeatability and accuracy indices of the Bavius CNC machining center are 0.0006 in and 0.0012 in, respectively.



	0.0	14.5	29.0	43.5	58.0	72.5	87.0	101.5	116.0	130.5	145.0
Error - Diagonal 1, Measurement 1	0.0000	-0.0002	-0.0004	-0.0004	-0.0006	-0.0007	-0.0008	-0.0010	-0.0011	-0.0011	-0.0010
Error - Diagonal 1, Measurement 2	0.0000	-0.0002	-0.0005	-0.0005	-0.0006	-0.0007	-0.0008	-0.0010	-0.0011	-0.0010	-0.0010
Error - Diagonal 1, Measurement 3	0.0000	0.0000	0.0000	-0.0001	-0.0002	-0.0004	-0.0004	-0.0006	-0.0005	-0.0008	-0.0009
Error - Diagonal 1, Measurement 4	0.0000	-0.0002	-0.0004	-0.0004	-0.0006	-0.0006	-0.0007	-0.0009	-0.0010	-0.0010	-0.0009
Error - Diagonal 2, Measurement 1	0.0000	0.0000	0.0000	-0.0002	-0.0004	-0.0005	-0.0006	-0.0008	-0.0007	-0.0010	-0.0011
Error - Diagonal 2, Measurement 2	0.0000	0.0000	0.0000	-0.0001	-0.0002	-0.0004	-0.0004	-0.0006	-0.0005	-0.0008	-0.0009
Error - Diagonal 2, Measurement 3	0.0000	0.0000	-0.0001	-0.0002	-0.0003	-0.0005	-0.0005	-0.0007	-0.0006	-0.0009	-0.0010
Error - Diagonal 2, Measurement 4	0.0000	-0.0001	0.0000	-0.0002	-0.0003	-0.0004	-0.0004	-0.0006	-0.0005	-0.0006	-0.0008
Error - Diagonal 3, Measurement 1	0.0000	-0.0003	-0.0004	-0.0004	-0.0006	-0.0006	-0.0008	-0.0010	-0.0011	-0.0011	-0.0011
Error - Diagonal 3, Measurement 2	0.0000	-0.0001	-0.0004	-0.0003	-0.0004	-0.0006	-0.0006	-0.0008	-0.0010	-0.0010	-0.0010
Error - Diagonal 3, Measurement 3	0.0000	-0.0002	-0.0004	-0.0003	-0.0005	-0.0006	-0.0007	-0.0009	-0.0011	-0.0010	-0.0010
Error - Diagonal 3, Measurement 4	0.0000	-0.0002	-0.0005	-0.0003	-0.0005	-0.0005	-0.0006	-0.0008	-0.0009	-0.0009	-0.0009
Error - Diagonal 4, Measurement 1	0.0000	0.0001	0.0002	0.0000	-0.0001	-0.0003	-0.0003	-0.0006	-0.0005	-0.0007	-0.0009
Error - Diagonal 4, Measurement 2	0.0000	0.0000	0.0001	0.0000	-0.0002	-0.0004	-0.0004	-0.0006	-0.0006	-0.0008	-0.0010
Error - Diagonal 4, Measurement 3	0.0000	0.0001	0.0001	0.0000	-0.0002	-0.0003	-0.0003	-0.0005	-0.0005	-0.0007	-0.0008
Error - Diagonal 4, Measurement 4	0.0000	0.0001	0.0001	0.0000	-0.0002	-0.0003	-0.0003	-0.0004	-0.0004	-0.0006	-0.0008

Nominal length (motion commanded to the machine)

Figure 3. Results from a volumetric test performed on the Bavius CNC machining center. The plot shows the deviation of the measured length with respect to the nominal length vs. the nominal length given as commanded motion to the Bavius CNC machining center. All dimensions are inches.

4.1. Interim performance evaluation (daily checks)

Daily checks are adapted from standard interim performance evaluations described in the background, and involve the use of the high precision contact probe (Renishaw Rengage probe RMP600 (RMP600 radio machine probe 2008)) and a program written in a CNC/CMM software (CAPPS-NC), to command machine motions to the various probing points. The software complies with international standards traceable to the National Institute of Standards and Technology (NIST).

The interim performance evaluation described herein is designed to check the accuracy and repeatability of the X, Y, Z and A drives of the Bavius CNC machining center, which are involved in part processing and measurement. The machine tool and the definitions of its X, Y, Z and A drives are illustrated in Figure 1. The interim performance evaluation is to be conducted against two specially designed artifacts: A five (5)-sphere calibrated artifact (Figure 4) and two (2) calibrated bushings embedded on the hard tool (Figure 5).

These “checks” mimic measurement of location and diameter of holes made by the Bavius CNC machining center on XY and XZ planes of a specific family of parts. The Bavius CNC machining center is utilized to make holes on the XY and two XZ planes of parts of this family. Then, the Bavius CNC machining center is utilized to measure the location and diameter of these holes. The measurements are below the operating envelop of the Bavius CNC machining center. Thus, the interim testing complements the volumetric test measurements described in the previous section, which involved measurement along diagonals located above the operating envelope of the machine.

The five (5)-sphere calibrated artifact (Figure 4) is qualified using a standard CMM (Hexagon 152210-Chrome) traceable to NIST. During the qualification, the artifact is free from loads resulting from clamping against the metrology table. The artifact is glued to the table of the Bavius CNC machining center to keep it free from loads throughout the interim testing. The qualification is conducted in a controlled atmosphere at 68 °F. The artifact is made of the same material (same aluminum alloy) as the parts being processed on the Bavius CNC machining center. This enables thermal compensation, during the interim testing, using the standard procedure deployed by the Bavius CNC machining center for regular part processing. The artifact's nominals are taken from these qualifications. The nominals are average values of the X,Y, Z coordinates of the five (5) spheres, with local coordinate system as defined in Figure 4.

The two (2) bushings embedded on the hard fixture (Figure 5) are qualified using a laser tracker scaled against a linear laser (API XD1LSP) traceable to NIST. The qualification is conducted directly on the Bavius CNC machining center, but the temperature of the machine bed is measured, and the dimensions obtained from the qualification corrected for thermal growth due to temperature deviations with respect to 68 °F. The hard fixture holding the bushings are also made of the same material (same aluminum alloy) as the parts being processed on the Bavius CNC machining center. This enables using the standard procedure deployed by the Bavius CNC machining center for the thermal compensation. The artifact's nominals are taken from these qualifications. The nominal is the center-to-center distance from bushing 1 to bushing 2, with local coordinate system as defined in Figure 5.

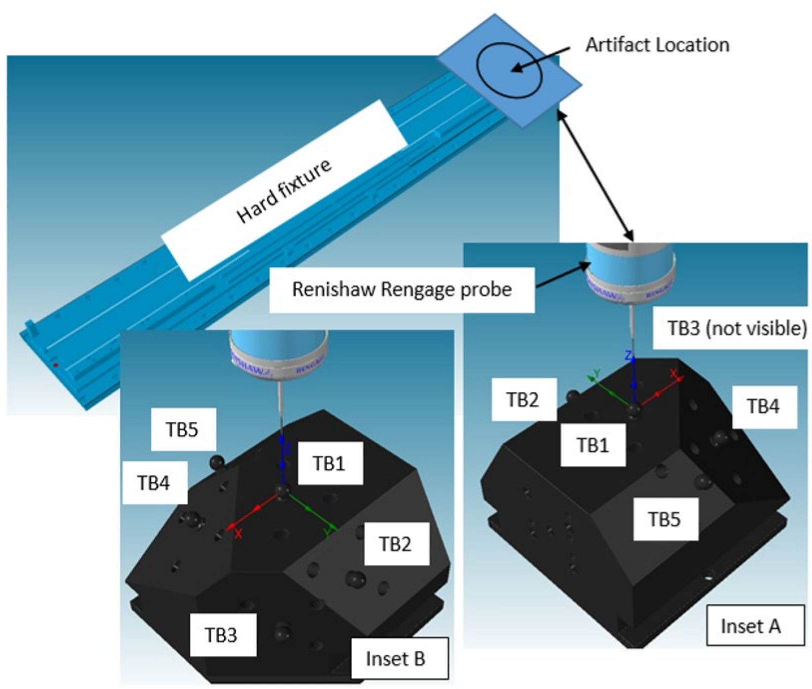


Figure 4. Schematic illustrating the arrangement of the five (5)-sphere calibrated artifact used to qualify the Bavius CNC machining center, by probing with the Renishaw Rengage probe. Inset A shows the artifact in regular

orientation. Inset B shows the artifact from "behind", to make all spheres visible. Spheres are labeled TB1 to TB5.

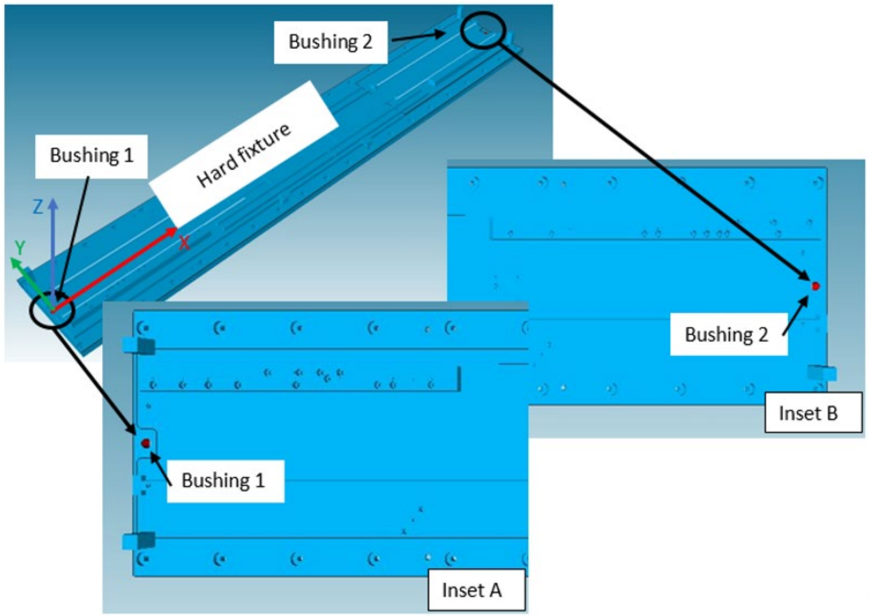


Figure 5. Schematic illustrating the arrangement of the two (2) calibrated bushings embedded on the hard tool to be used to qualify the Bavius CNC machining center, by probing with the Renishaw Rengage probe. Bushings are labeled as Bushing 1 (left) and Busing 2 (right). Insets A and B show close, top views of area surrounding the bushings.

5. Experimental Configuration

The FAIs involve the use of the high precision contact probe (Renishaw Rengage probe RMP600 (RMP600 radio machine probe 2008)) and a program written in a CNC/CMM software (CAPPS-NC), to command machine motions to the various probing points. The software complies with international standards traceable to the National Institute of Standards and Technology (NIST). The probing points are selected to define the position of the holes to be inspected. Figure 6 shows the probe performing an FAI on a generic part.

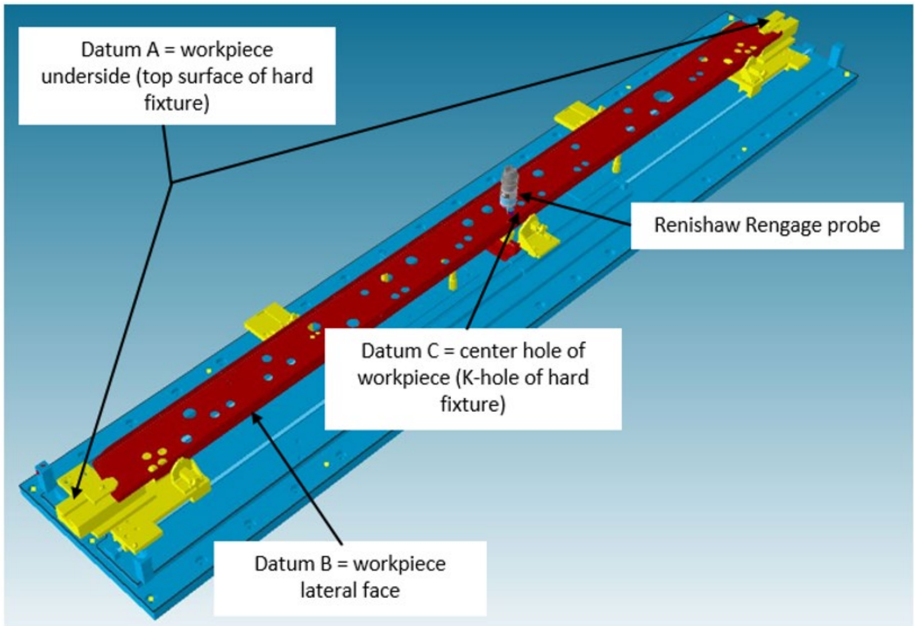
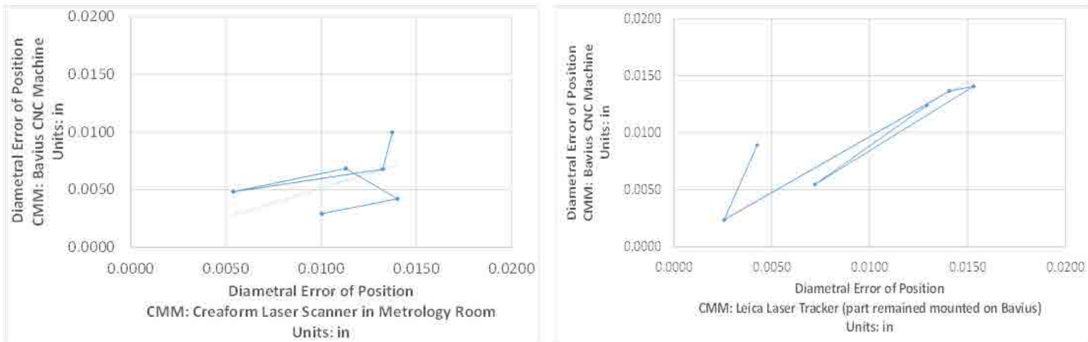


Figure 2. Schematic illustrating the arrangement of the machine bed of the Bavius CNC Machining Center. Milling floor of the hard fixture (blue), datums and clamps of the hard fixture (yellow) and a generic workpiece (red). The Renishaw Rengage probe is being used to measure the position of all the holes of interest, directly on the machine. Typical holes are on the horizontal or vertical long faces of the part.

One beam was processed by the Bavius CNC machining center by drilling holes that are required to be made at the center. The beam was run through an FAI procedure using the Bavius CNC machining center as a CMM, as described in the preceding sections. To validate the measurement procedure, the same beam was subject to measurements using several other standard CMMs and clamping methods. The results from this round robin test are shown and discussed in the following sections.

6. Experimental results

Figure 7A shows the relationship between measurements of the diametral error of position using the Bavius CNC machining center as a CMM vs. using a Creaform laser scanner in an environmentally controlled metrology room. Figure 7B shows the error relationship, but after measurement using the Bavius CNC machining center and a Leica laser tracker, without dismounting the beam between measurement runs with one device or the other. Note the equation of the linear regression line between errors reported by one measurement procedure and the other, and the coefficient of correlation (R), both given in the figure insets. When the beam is dismounted to be taken to metrology, the regression line fails to explain the relationship between errors measured by the Bavius vs. the laser scanner (R is high, but regression line constant is less than 1). However, when the beam is held on the machine tool and both the Bavius and the laser tracker are used to measure the errors of position, the regression line explains the relationship between the errors reported by these two measurement methods (R is high, and regression line constant is about 1).



A: Regression line Y = 0.51X, R = 0.94 B: Regression line Y = 0.96X, R = 0.98

Figure 3. A) Relationship between measurements of the diametral error of position using the Bavius CNC machining center as a CMM vs. using a Creaform laser scanner in an environmentally controlled metrology room. B) The error relationship, but after measurement using the Bavius CNC machining center and a Leica laser tracker, without dismounting the beam between measurement runs. Y and X are diametral position errors measured by the two methods compared, respectively. R is coefficient of correlation.

Moreover, as evident from Table 1, the regression line is found to explain the relationship between the position error measured by the Bavius CNC machine only when the part remains mounted on the it for the measurement run following the alternative method.

Test Set	Comparison between:	Regression line	R
1	Bavius CNC Machine vs. Creaform Laser Scanner in Metrology Room	Y = 0.5X	0.94
2	Bavius CNC Machine vs. Leica Laser Tracker (part remained mounted on Bavius)	Y = 1.0X	0.98
3	Bavius CNC Machine vs. Creaform Point Probe (part remained mounted on Bavius)	Y = 0.6X	0.99
4	Bavius CNC Machine vs. FaroArm Contact Point Probe (part remained mounted on Bavius)	Y = 0.8X	0.96
5	Bavius CNC Machine vs. Bavius CNC Machine (part remounted between measurement runs)	Y = 0.5X	0.82

Table 1. Results from round robin tests. Regression line and coefficient of determination between position error measurement procedures. Y and X are diametral position errors measured by the two methods compared, respectively. R is coefficient of correlation.

7. Concluding remarks

A CNC machining center was fitted with high resolution contact probing to enable drive position readings triggered by the probing to be utilized for part measurement. Standard volumetric and interim tests that apply to performance evaluation of conventional CMMs were adapted for performance evaluation of the CNC machining center when it is used as a CMM for automated machine tool health monitoring and for FAIs. Immediate advantages from this operating procedure were obtained on the shop floor, including reduced inspection labor/time and part rework requirements, and increased conformance to part quality specifications.

It was found, by round robin testing following measurement of drilled holes position error by several methods that proper part clamping is critical. Measurements of hole position error using the CNC machine tool itself ensures that part clamping is standard, thus measurements more repeatable.

The proposed use of the CNC machine as a CMM shall be a cost-effective method for metrology inspection whenever the measurement cycle time is a small fraction of the manufacturing cycle time. The method is particularly attractive in the aerospace sector, where low production volume is associated with high machine tool idle time. For these applications, in-situ probing results in minimally disruptive part measurement.

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