DEVELOPMENT OF VIRTUAL BALL BAR FOR TESTING OF CMM PERFORMANCE

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Abstract. *Performance tests are frequently employed by users to verify Coordinate Measuring Machines (CMM) errors. These tests are described by standards like ISO 10360-2, American ANSI/ASME B89, German VDI/VDE and others, and it is always required a gauge to carry out the tests. In most cases, the artefacts are built with spheres having small geometric errors, increasing the cost and resulting in errors associated to least squares fitting. This work proposes the development of gauges with virtual geometries to determine the performance of CMMs. The proposed gauge has two groups of four holes each that are used to determine points of the spherical surfaces. These points are used to fit spheres using computational algorithms and to determine the distance between the centres of the spheres. This proposed gauge was called virtual ball bar and an application was performed to test the performance of an articulated arm CMM, using as reference the ANSI/ASME B89 standard. The results were compared with the application of this standard using a conventional ball bar and an additional experiment using fractional factorial design was carried out to compare these gauges. Results showed good agreement between the two approaches and it was observed a potential cost reduction compared to ball bar gauge.*

Keywords*: CMM evaluation, performance tests, CMM gauges*

1. INTRODUCTION

Performance tests are frequently employed by users to verify Coordinate Measuring Machines (CMM) errors. These tests are described by standards like ISO 10360-2, American ANSI/ASME B89, German VDI/VDE and some others. It must be pointed out that it is always required one gauge to carry out the tests. In most cases, these gauges are artefacts having spheres with small geometric deviations, as ball bar and ball plate ones. These high precision spheres increase the cost of the artefact and may introduce errors associated to the measurement task and to the least squares method used to fit these geometric entities (Bosch, 1995).

Some authors have been investigating other types of artefacts to check the performance of CMMs. Nardelli and Donatelli (2006) proposed a three-dimensional (3D) artefact that was built in aluminium alloy having one geometric plane with holes at each vertex. This four-hole plate had a structure with four bars linking the circular holes and the authors depicted advantages as low cost, low weight and ease of calibration over other gauges. Farooqui and Morse (2004) developed artefacts for evaluating scanning CMM performance. These artefacts were based on the superposition of a sinusoidal waveform profile over a flat surface of a linear or a circular part. Folkert *et al*. (2004) developed a ring gauge built in aluminium having wide grooves marked on internal and external diameter surfaces. This gauge was used to characterize the dynamic performance of CMMs.

The spreading use of Coordinate Measuring Arms (CMA), related to advantages like probe flexibility and portability, is asking for new or adapted methods to check their performance. CMA are largely used in automotive and aerospace industries to inspect discrete parts, and their construction involves some fixed length links coupled by rotary joints, having encoders at each joint to determine the angles between links. The position of a point on the extremity of the probe may be then calculated and transformed in Cartesian coordinates.

There are some works in literature related to performance evaluation of these types of CMMs. Kovac and Frank (2001) proposed the use of a high precision instrument to evaluate the performance and calibrate CMAs. Shimojima et al. (2003) presented a method to estimate the uncertainty of CMA, involving the use of three-dimensional ball plate gauge. This gauge was built having nine balls placed and fixed at different heights on the surface of a metallic plate. The authors reported that this method is suitable to determine the kinematical parameters of CMA.

The ANSI/ASME B89 standard (1994) proposed an adapted performance test to check accuracy and repeatability of CMA. A volumetric performance test was proposed requiring a calibrated 900 mm length ball bar having two spheres with diameters 25.4 mm. The volumetric performance of a CMA is presented in a graphic and the range and standard deviation of the volumetric errors displayed are considered as a performance indicators (ANSI/ASME B89.1.12M, 1994).

One of the simplest and cheapest gauges in use is the ball bar and its construction requires two precision spheres fixed at each side of the bar, as showed in Fig. 1. The advantages of this gauge are related to handling facilities, low weight and low cost in relation to others 2D or 3D gauges used to check performance of Coordinate Measuring Machines (CMMs). Ball bar gauge may be built by CMM owners, as originally ANSI/ASME B89.1.12M not requires a calibrated or fixed length gauge. Other requirement concerns the materials employed that should be chosen to prevent deflection when the CMM probe touch the sphere or under the action of the force of the gravity or vibrations. Materials having small thermal dilatation are decisive to minimize the effect of the temperature variation, as small density is required to provide a reduced weight and a high resistance against corrosion and friction efforts is demanded to provide a more lingering life.

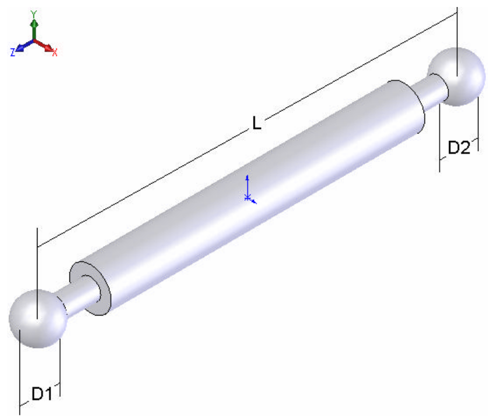

Figure 1 – Ball bar gauge with length L

Careful attention is directed to the spheres of ball bar gauges once the determination of the length of a ball bar is made by calculation of the distance center-to-center of the spheres. Then, they should present an excellent superficial finish and a small error of sphericity (about 0.1 m). Materials reported as used are the tungsten carbide and ceramics (Piratelli-Filho, 1997).

Attention should be deposited also on the number of positions required to carry out a volumetric performance test. The ANSI/ASME B89 (1994) requires 24 position and orientations to place the ball bar and perform measurements. Some works in literature reported the use of techniques of design of experiments (DOE) to carry out these tests in conventional CMMs. Piratelli-Filho and Giacomo (2003) reported a volumetric performance test performed with a ball bar gauge positioned according to a DOE experimental array to verify a moving bridge CMM. Feng *et al* (2007) reported a similar application involving DOE techniques to investigate parameters of a CMM when measuring the diameter and location of a hole.

This work introduces the development of gauges with virtual geometries to determine the performance of CMMs. The proposed gauge has two groups of four holes each that are used to determine points of the spherical surfaces. These points are used to fit spheres using computational algorithms and to determine the distance center-to-center of the spheres. This gauge was named virtual ball bar and an application was performed using this gauge to test the performance of an articulated arm CMM, using as reference the ANSI/ASME B89 standard. The results were compared with the application of this standard using a conventional ball bar and an additional experiment using fractional factorial DOE array was carried out to compare these gauges.

2. VIRTUAL BALL BAR GAUGE

In spite of ball bar be considered a low cost gauge when compared to other gauges, precision spheres having excellent superficial finish and very small sphericity errors (about 0.1 μm) is still problematic as it increases the gauge cost. It is observed that when determining a sphere by taking the coordinates of many points on a spherical surface, the probability of some of them be positioned incorrectly, for instance having no contact, exists and it can produce a systematic error in diameter and center location. Besides, as sphericity deviation increase, a higher number of points should be determined to accurately determine the center of the sphere.

An option to avoid these drawbacks is the development of gauges having conic holes to locate points of a perfect sphere in substitution to the real spheres. The holes drilled on the surfaces of the gauge are seats for CMM probe positioning during measurement and reference to capture the points that will be used to fit the virtual spheres. As well known, four points are required to fit a sphere and the virtual ball bar must have four non-coplanar points at each side. Figure 2 shows a hybrid gauge having a virtual ball bar and a ball bar, built having about 200 mm length.

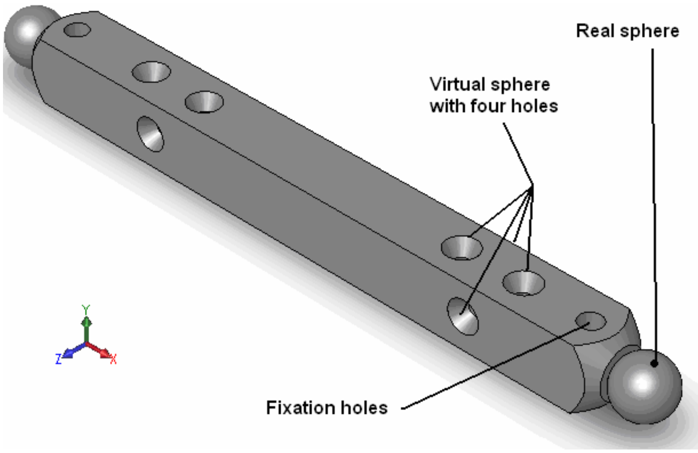

Figure 2 – Hybrid gauge having a virtual ball bar with four holes by side and a ball bar.

These special virtual sphere features demand the use of probes having stylus with spherical tip to be placed on the gauge hole. Once coordinates of the four points are determined, the sphere radius and center are calculated by software algorithm. It may be argued that probe access to the conic holes of the gauge is somewhat difficult, specifically on CMM having bridge type structure. But some special types of probes like star type or motorized probes may be used to perform the tests. On the contrary, the probe access of CMA probe is easier as probe flexibility is a natural advantage of CMA type of measuring machines. Figure 3 shows virtual spheres determined with four points (holes) of the gauge.

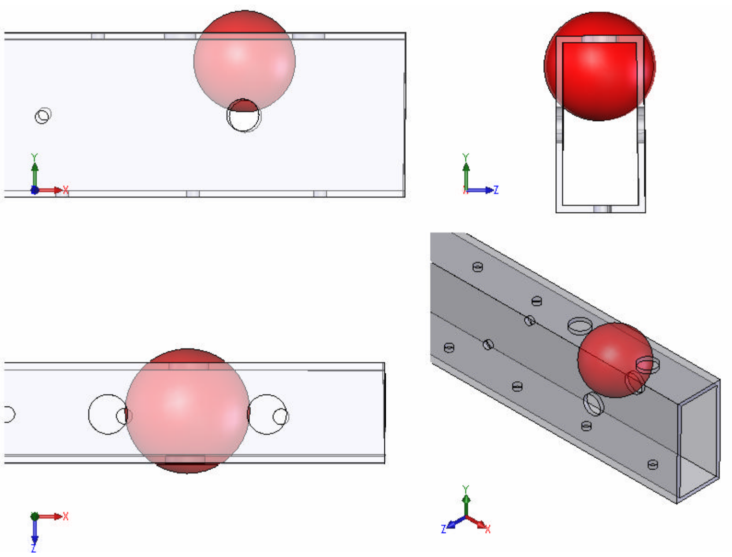

Figure 3 – Virtual spheres determined with four point (holes) of the gauge

Some other questions must be pointed out when dealing with determination of the points on the holes to determine virtual spheres. One is related to the modification of the diameter of probe sphere tip that a priori do not change the distance center-to-center of the virtual spheres. However, the conic holes may have an inclination in relation to the normal plane of the gauge surface, as showed in Fig. 4 at hole B and C, and a systematic error (bias) in center-to-center distance will be present when changing probe sphere tip. It is important to use the same probe tip diameter during and at different tests carried out in a given machine to have a comparison reference and avoid this source of error. Other issue is related to the modification of the probe axis orientation, as showed in Fig. 5, and it must observed that it has no influence on the position of the center of the sphere. A random error may appear in point coordinates unless careful placement of the probe is conducted during measurement, as it is unavoidable changing the probe orientation during measurements in CMA.

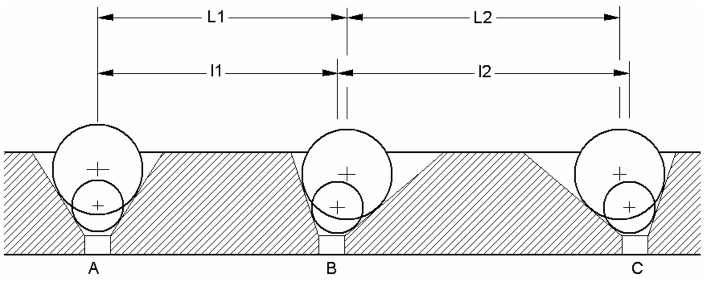

Figure 4 – Sources of errors when taking coordinates of gauge holes

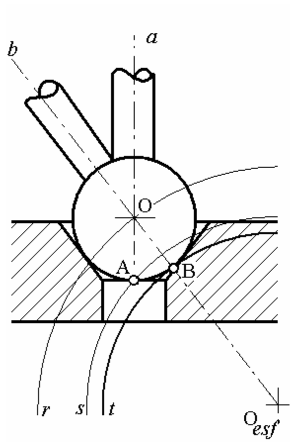

Figure 5 – Effect of different orientations of the probe axis

The software algorithm of the virtual ball bar gauge must perform calculations of the radius, the coordinates of the center and the distances between the centers of the spheres. A brief review of the steps performed to determine these characteristics is presented as follows. A sphere can be fitted taking any four different points in tridimensional (3D) space, with the only safeguard that each one is non-coplanar to the others. Taking three points A, B and D, it is defined a circle having O_1 as the center, as showed in Fig. 6. The center O_1 can be determined by taking the straight lines r_1 and s_1, orthogonal and passing by the halfway of the segments AB and BD, respectively.

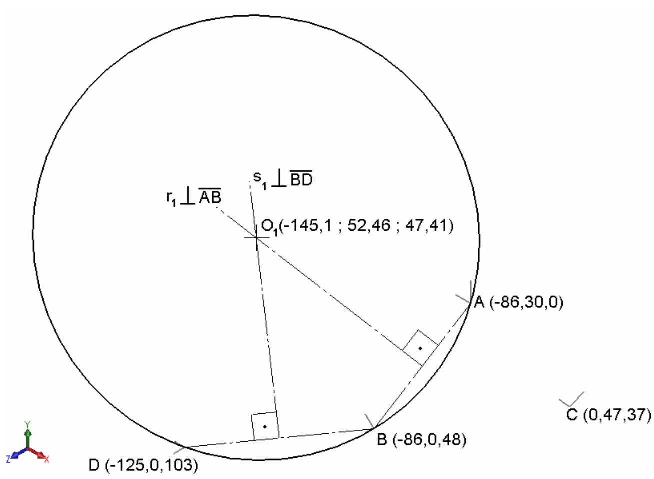

Figure 6 – Circle defined by three points in space

Using the equation to determine the distance between two points in Cartesian space, it is found that, as the center of the circle O_1 is at the same distance r_{O_1} from all points on the circle, its coordinates are determined solving the equations system showed in Eq. (1).

$$\begin{cases} \left(X_A - X_{O_1}\right)^2 + \left(Y_A - Y_{O_1}\right)^2 + \left(Z_A - Z_{O_1}\right)^2 = r_{O_1}{}^2 \\ \left(X_B - X_{O_1}\right)^2 + \left(Y_B - Y_{O_1}\right)^2 + \left(Z_B - Z_{O_1}\right)^2 = r_{O_1}{}^2 \\ \left(X_D - X_{O_1}\right)^2 + \left(Y_D - Y_{O_1}\right)^2 + \left(Z_D - Z_{O_1}\right)^2 = r_{O_1}{}^2 \end{cases} \tag{1}$$

Solving the system of Eq. (1) results in one straight line t_1, that is normal to the plane passing trough the center of the circle. Similarly to straight lines r_1 and s_1, t_1 may be interpreted as the group of all possible points that, at any given hypothetic point Q on t_1, the relation $\overline{AQ} = \overline{BQ} = \overline{DQ}$ applies. It must be observed that once the vector normal passing trough a first point (point A, for example) is parallel to the vector of the origin O and has coordinates (a_1, a_2, 1), then it could be imposed three equations as presented by Eq. (2).

$$\begin{cases} a_1 \cdot (X_B - X_A) + a_2 \cdot (Y_B - Y_A) + (Z_B - Z_A) = 0 \\ a_1 \cdot (X_D - X_A) + a_2 \cdot (Y_D - Y_A) + (Z_D - Z_A) = 0 \\ a_1 \cdot \left(X_{O_1} - X_A\right) + a_2 \cdot \left(Y_{O_1} - Y_A\right) + \left(Z_{O_1} - Z_A\right) = 0 \end{cases} \tag{2}$$

The same procedure follows to the points A, B e C. As the points A, B, C and D belongs to the sphere, thus the centre of the sphere is the point halfway from these two surfaces and the straight lines t_1 e t_2 fulfil this criterion for each circle, having the intersection O_{esf} as the centre of sphere, as showed in Fig. 7.

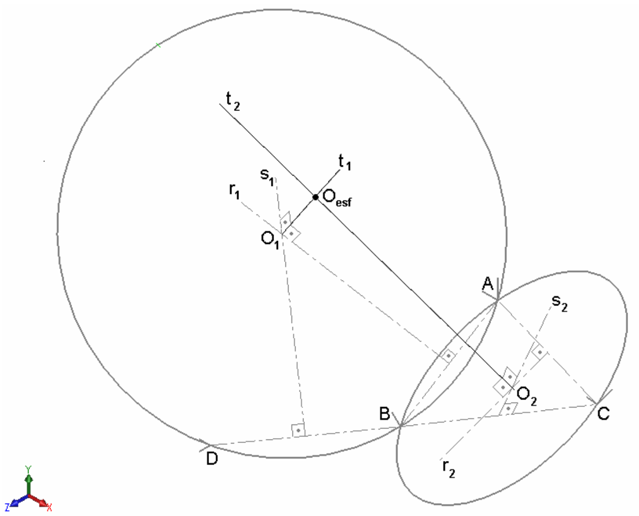

Figure 7 – Center of sphere (O_{esf}) found at intersection of the straight lines t1 and t2, normal to the circle plane and passing trough the origin

Analytically, the coordinates of the centre of the sphere is calculated from solving the system of equations in Eq. (3). In this equation, X_i, Y_i e Z_i are the Cartesian coordinates of the known *i-th* point and r is the radius of the sphere (unknown). When i = 0, then X, Y and Z are the Cartesian coordinates of the centre. Determination of the coordinates of the centre and the diameter of the virtual spheres are accomplished by solving this system of equations.

$$\begin{cases} (X_A - X_O)^2 + (Y_A - Y_O)^2 + (Z_A - Z_O)^2 = r^2 \\ (X_B - X_O)^2 + (Y_B - Y_O)^2 + (Z_B - Z_O)^2 = r^2 \\ (X_C - X_O)^2 + (Y_C - Y_O)^2 + (Z_C - Z_O)^2 = r^2 \\ (X_D - X_O)^2 + (Y_D - Y_O)^2 + (Z_D - Z_O)^2 = r^2 \end{cases} \tag{3}$$

Future research efforts shall deal with the development of software for virtual ball bar having uncertainty estimative of the center of the virtual ball, as a result of the uncertainty related to the coordinates of the measured points. Monte Carlo Simulation may be suitable to implement this task.

3. EXPERIMENTAL APPROACH AND RESULTS

Experimentation was carried out using a Coordinate Measuring Arm manufactured by Romer, having six degrees of freedom and a hard probe with a 6 mm ball tip stylus. According to the manufacturer, the CMA accuracy was reported as 0.07 mm. The CMA software used to capture data was GPad and data points were stored in files to perform calculations. Experimental approach involved two kinds of tests using both virtual ball bar and ball bar gauges: the first was applied according to the recommendations of ANSI/ASME B89 standard; the second was applied using Design of Experiments (DOE) techniques. All measurements were performed at temperature 20±1ºC.

The ball bar gauge was built in the same material block as virtual ball bar gauge, but having two precision spheres located at each extremity, as showed in Fig. 2. This gauge was calibrated using a Universal Measuring Machine and the uncertainty in length was determined. The results showed a value of 214,290 ± 0,040 mm.

The virtual ball bar gauge was built having four holes drilled at each end to accommodate the probe stylus during measurement. The gauge was not calibrated to apply the test.

3.1. Volumetric performance test using ANSI/ASME B89 standard

The standard ANSI/ASME B89 proposes a volumetric performance test to be applied to CMA that has some differences in relation to conventional CMMs. The ball bar length required is 900 mm length and having balls with diameter 25.4 mm. The calibration of this gauge is demanded. There are four more positions to place the gauge during measurements than tests performed to CMMs (20 positions), besides of some alterations in other positions to accommodate the CMA within the work space. Figure 8 shows the positions required by the standard. The gauge is measured taking four points on each sphere surface, one at a pole and three at the equator. Analysis of volumetric performance is carried out by plotting a graph of the position against center-to-center length deviations. The range and the standard deviation, besides the bias, are considered as the parameters of performance.

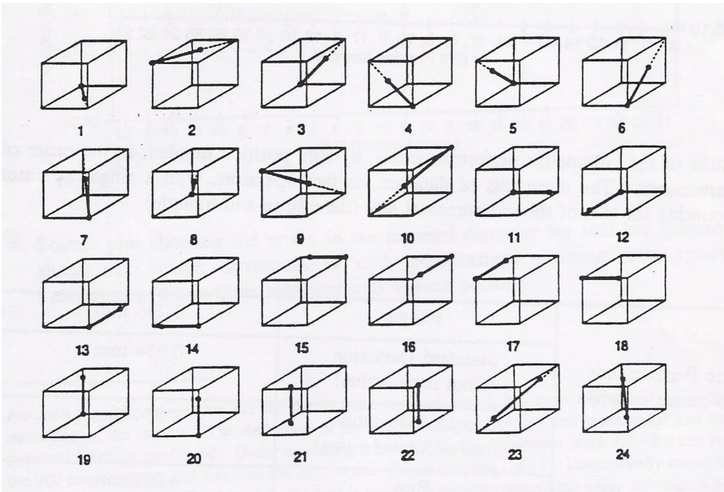

Figure 8 - Experimental array proposed by ANSI/ASME B89 (1994) for volumetric performance tests of CMAs

Some modifications on this methodology were applied since the main target is to compare the two different gauges. A shorter gauge was used having nearly 214 mm long and it was constructed in the same material block as proposed virtual ball bar. Next, analysis was carried out plotting a graph of position against the deviations from the mean value. To apply the test, a mechanical support was prepared in squared aluminum tubes. The tubes were sectioned and welded to build a squared face of a box, as showed in Fig. 9 with the CMA used. An additional test was applied to check the repeatability according to the ANSI/ASME B89 standard, measuring 10 times a 15 mm diameter precision ball taking four points on the surface each measurement. The standard deviation and the range of the coordinates of the calculated center was a measure of the repeatability, and it was found respectively 0.020 mm and 0.104 mm.

The virtual ball bar gauge was fixed at the mechanical support, placed over a measurement table and besides the CMA. It was measured four points on each sphere to determine the center and the length between centers and this procedure was repeated three times by location. The sequence of positions measured was established at random. Figure 10 shows the results using a 6 mm probe sphere. It was observed a range of 0.372 mm and standard deviation of 0.073 mm.

Figure 9 - Experimental construction with gauge, support and CMA

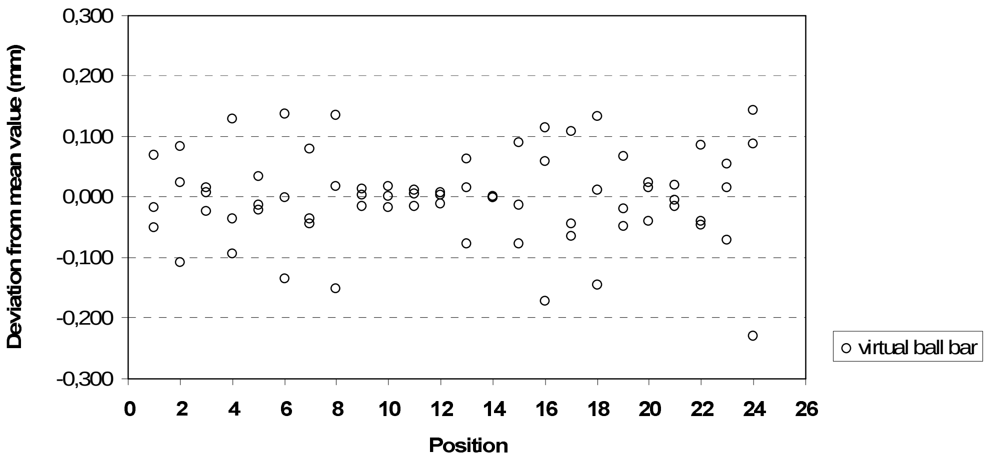

Figure 10 - Results of volumetric performance test using virtual ball bar and ANSI/ASME B89

The ANSI/ASME B89 was carried out using a ball bar as depicted before. The gauge was measured three times in each position according to Fig. 8. The results of deviation from the mean value of the center-to-center distance were determined and are showed in Fig. 11. The range of the results was 0.646 mm and the standard deviation was 0.101 mm. These results were close to ones obtained using virtual ball bar, but in two positions the values were greater than 0.2 mm (4 and 6) and in one it was lesser than -0.2 mm (18), explaining the bigger range.

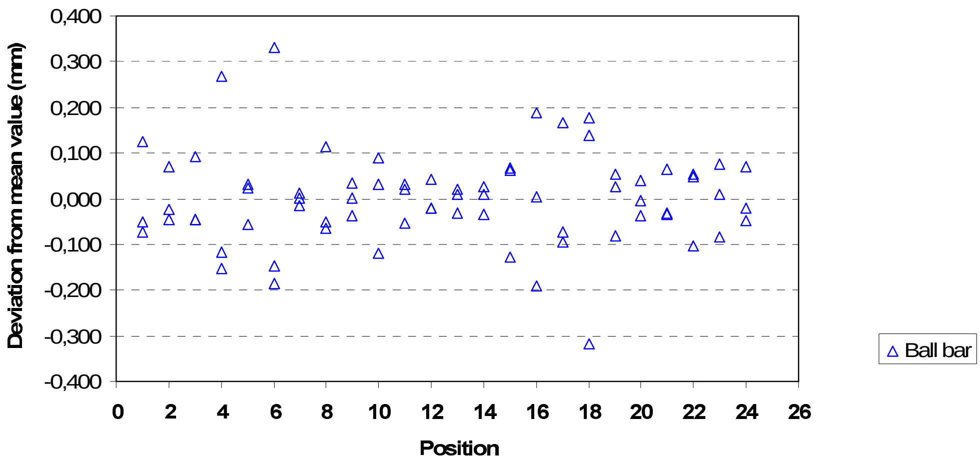

Figure 11 – Results of volumetric performance test using ball bar and ANSI/ASME B89

3.2. Volumetric performance test using DOE approach

Aiming to reduce the total number of measurements, the placement of the ball bar and the virtual ball bar in the work volume of the CMA was carried out by using a Design of Experiment (DOE) array, in substitution to the suggested positions of the ANSI/ASME B89 standard. The experimental array was selected after defining the input variables that affect CMA performance. It was adopted four variables having three levels each, showed in Tab. 1. All these variables refer to the gauge placed in work volume. A probe sphere having 6 mm in diameter was used to carry out measurements. Each measurement was repeated three times to have estimative of the experimental error.

Table 1 – Variables investigated and respective levels adopted

Variables	Level 1	Level 2	Level 3
A – Position along X axis	Left	Centre	Right
B – Position along Y axis	Front	Mean	Back
C – Position along Z axis	Low	Mean	High
D – Gauge orientation	Along X	Along Y	Along Z

Dealing with four variables having three levels each, the total number of runs or placements using a complete factorial design is determined by 3^4 generating 81 runs, as factorial design combines all variables in all possible levels. Reduction of this amount of runs was obtained using a fractional factorial design 3^{4-2}, having nine runs to combine the four input variables (Montgomery, 1991). This array is showed in Tab. 2.

Table 2 – Fractional factorial design 3^{4-2}

Run	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The experimental approach showing these gauge positioning and the orientations in work volume is presented in Fig. 12. It is observed that the CMA is located inside an imaginary cubic work volume in a way that the probe can reach all positions demanded by DOE runs. The mechanical support showed in Fig. 9 was used to fix the gauge before measurements take place.

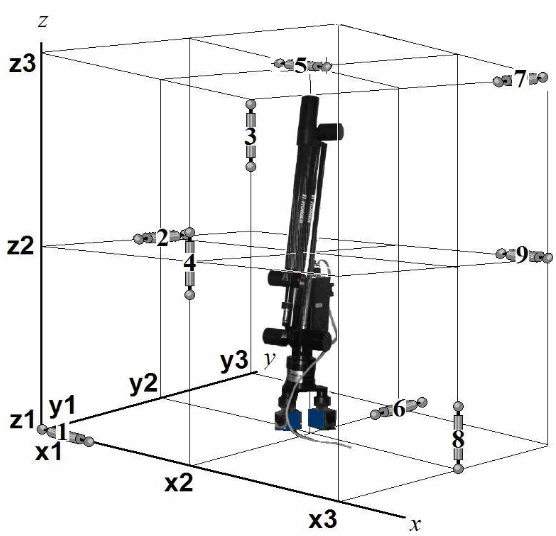

Figure 12 – Scheme of the experimental array with the positions demanded by 3^{4-2} DOE

Each run was executed three times in a random sequence. The results of the deviation from mean value of the length between spheres for the virtual ball bar and the ball bar are presented in Fig. 13 and 14. It was observed a standard deviation 0.095 mm and range 0.465 mm for the virtual ball bar and standard deviation 0,111 mm and range 0.411 mm for the ball bar. It was observed that some one point was greater than 0.2 mm (position 7). The results of the tests appear similar, as observed at the figures and by standard deviation and range.

When comparing the volumetric performance tests according to the ANSI/ASME B89 and DOE approach, it was observed that the results were similar to both gauges used. Some slight differences were present and the use of virtual ball bar produced smaller standard deviations in both approaches and range values showed error prone as sample of points increased.

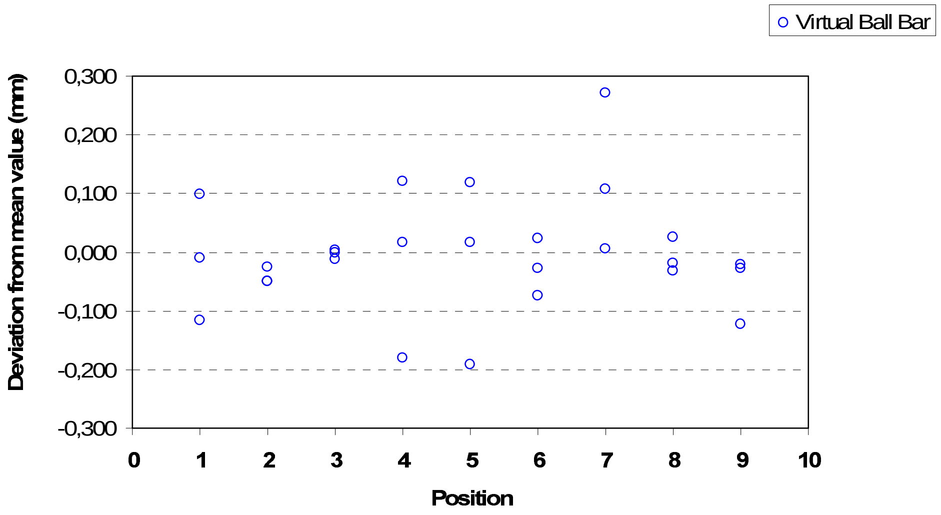

Figure 13 – Results of volumetric performance test using virtual ball bar gauge and DOE experimental array

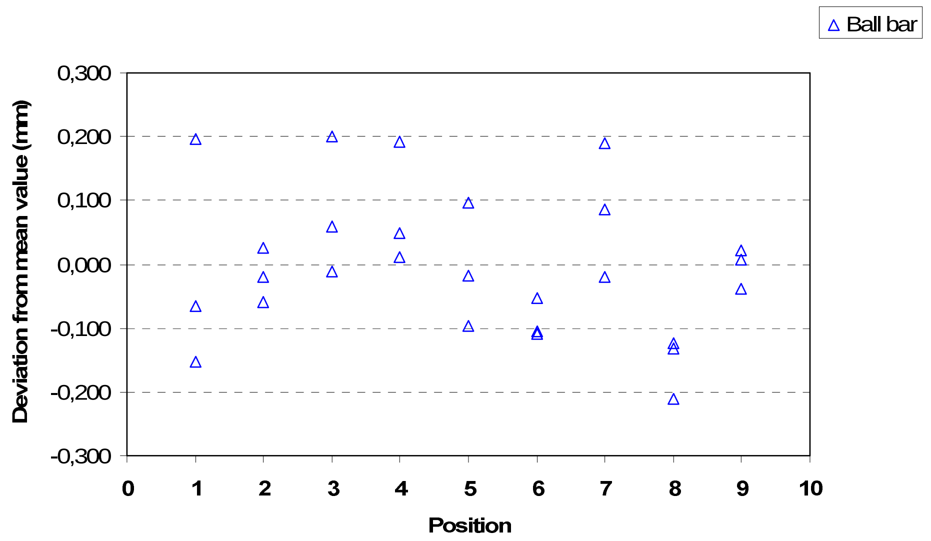

Figure 14 – Results of performance test using ball bar gauge and DOE experimental array

4. CONCLUSION

The virtual ball bar is a low cost gauge when compared to other gauges used to check volumetric performance of CMM and CMA. It involves the measurement of the coordinates of points located by holes in a bar and fitting a sphere to the data as a way to calculate the distance center-to-center of the virtual spheres. This particular way of construction is especially useful to check performance of CMA, as the probe of these machines has flexibility to access the holes at any direction in work volume, demanding different combinations of joints and scales positions of the machine.

Volumetric performance tests were carried out using ANSI/ASME B89 and a fractional factorial design 3^{4-2} to reduce the number of positions to measure, using a 6 mm probe stylus diameter. Data analysis was performed and the results proved similar for ball bar and virtual ball bar. Virtual ball bar proved to be less error prone in relation to conventional ball bar, since errors sources associated to the balls sphericity or to the measurement of points on spherical surface are absent.

Experimental approach using a design of experiment (DOE) fractional factorial was interesting as it was obtained nearly the same results at a reduced number of experiments (runs). It was observed that only one face of the imaginary cubic work volume built in aluminum was suitable to carry out all planned measurements.

New developments shall be investigated to substitute tri-dimensional gauges used to check performance of CMMs, like ball plate artifacts having high precision balls and a high cost associated.

5. ACKNOWLEDGEMENTS

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