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AACMM Performance Test: Influence of Human Factor and Geometric Features

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Abstract

Articulated Arms Coordinate Measuring Machines (AACMMs) have spread out in the manufacturing industry thanks to their flexibility and reduced cost. Nevertheless, their performance has been barely studied unlike traditional coordinate measuring machines. Therefore, a lack of traceability and reliability have been found AACMM field. AACMM performance is affected by many factors which are partially studied and compensated. Among them, human factor is one of the main factors with a significant impact on AACMM performance, however it is not considered in current evaluation or calibration methodologies. In this work, a new methodology is presented in order to calculate operator contribution to AACMM errors. Furthermore, operator behavior changes according to the measured feature and type of tolerance. For this reason, a *features-based* gauge capable of materialize a wide range of tolerances types has been designed and built for using with this methodology. Test results provide with a reasonable basis for performing both operator and AACMM qualification.

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Keywords: Coordinate Measuring Arms; CMA; AACMM; operator qualification; coordinate metrology; dimensional gauge

1. Introduction

AACMMs have broadened inspection tasks into a more flexible activity of manufacturing process. They not only avoid meticulous measurement planning but also work on quite different environments and tasks such as, production

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lines, workstation, part assembly places, reverse engineering, etc. Their flexibility and portability bring great advantages; nevertheless, they also bring additional error sources that have a deeper impact in AACMM performance than in traditional CMMs. Operator factor reveals as an important error source that contributes to AACMM uncertainty. However, this error source is not considered in current evaluation or calibration methodologies.

Vrhovec et al. [1] listed the main error sources and their approximated contribution to AACMM performance. Kinematic and encoder errors are pointed as two of the main error sources followed by thermal errors and elastics deformations. While kinematic errors are dealt by new calibration methodologies in order to improve the kinematic model, manufacturers develop lighter structures and high resolution encoders for reducing encoder errors. Santolaria et al. [2] improved AACMM performance in terms of distances and point repeatability by measuring a ball bar. Furutani et al. [3] calibrated their AACMM with several ball bar combinations. Kovac et al. [4] proposed a linear gauge with an interferometer for AACMM calibration. Gao et al. [5, 6] applied neural networks to their calibration process with kinematic seats. These calibration methodologies involve an overall error optimization, that is, kinematic errors and encoder errors. Also, elastic and thermal errors than happen during calibration are included in the calibration results. Thermal errors were also controlled by Santolaria et al. [7] who carried out their calibration methodology at several temperatures. Consequently, a set of kinematic parameters is calculated according to the environment temperature.

Regarding to elastic deformation, weight of AACMM components and contact force remain as non-controlled error sources. Vrhovec et al. [1] also proposed a laser sensor that detects deflection on AACMM links. In a previous work, Cuesta et al. [8] proved a greater contribution of the operator factor in AACMM performance that the one stated by Vrhovec previously. They also identified a considerable impact of other parameter such as part geometry or probe type. In fact, operator factor has a different behavior depending on the measured feature [9, 10] and it should be evaluated.

International standards [11, 12] define several tests capable of quantifying AACMM performance at some extent and, therefore, they establish reference values for evaluation over time and comparison with other AACMMs. Both standards provide with similar performance tests which consist of measuring a ball bar within the AACMM workspace. In other tests, a calibration sphere or a kinematic seat are used in order to evaluate point repeatability or the sphere diameter obtained with the AACMM. Piratelli et al. [13, 14] proposed a similar to ASME standard by using a virtual sphere gauge, bar and plate. In addition, in a previous work [15] it was developed a similar methodology with virtual circles instead of virtual spheres. In any case, a positive result of the evaluation would guarantee the validity of subsequent measurement, assuming that the rest of features (cylinders, planes …) are included into the evaluation. However, all these tests are carried out by only one operator, thus the impact into the evaluation could lead to a miscalculation of the AACMM performance. In addition, if the evaluation is carried out by another operator, it would probably bring different results according to his experience, training or measurement ability that could lead to a false acceptance of subsequent measurements.

In this paper, a new evaluation methodology capable of revealing operator contribution to the measurement process uncertainty is proposed as well as a true value for AACMM performance. This methodology is based on the considered feature, so evaluation will show the capability of AACMM to measure different features, the mos common in actual manufacturing parts.

Table 1. AACMM ROMER Omega technical specifications.

Technical specification	Value
Model	Romer Omega (6DOF)
Range	1800 [mm]
Repeatability, Sphere test	0.010 [mm]
Point repeatability, Cone test	0.018 [mm]
Length Accuracy, Volumetric accuracy test	0.025 [mm]

2. Materials and test setup

A new methodology capable of evaluating operator effect as well as AACMM performance for several part features has been developed. This methodology is based on repeatability and reproducibility studies. This survey was performed with an AACMM ROMER, Omega series, 2018 model with a measurement range of 1800 mm (Fig. 1a). A "hard probe" of 50 mm long with a ruby sphere 6 mm in diameter was used. At the beginning, the AACMM and the probe were qualified with the manufacturer's software (Table 1).

In order to evaluate AACMM and operator performance for each type of tolerance, a *features-based* gauge was designed and manufactured, Fig. 1b. It includes most common geometrical characteristics: planes, spheres, inner and outer cylinders which can materialize different geometric and dimensional tolerances. This gauge consists of a main length of 1000 mm with T-inverted section. Along this length, 12 parallel planes are determined by 6 crenels. Each plane has enough surface area (about 2 cm^2) and accessibility for a proper manual measurement with AACMM. Furthermore, the gauge includes 5 spheres on crenels top. In each crenel 6 inner cylinders have been machined (drilled and bored). In addition, 4 cylindrical parts have been machined and then assembled in the main structure of the gauge. These parts contain 4 outer cylinders and 4 inner cylinders. The *features-based* gauge was made of aluminum alloy with hard anodized treatment to increase surface hardness.

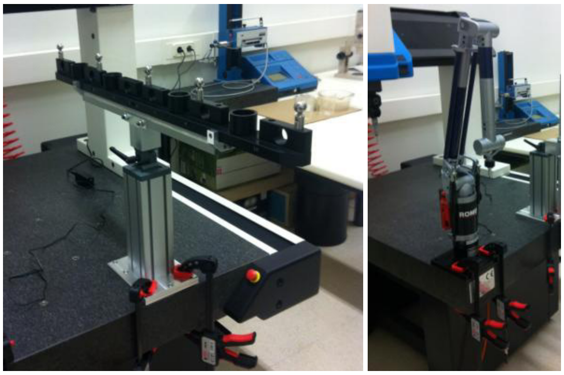

Fig. 1. a) Geometric "*features-based*" gauge; b) portable measuring arm used.

Geometric features and their combinations provide a wide range of geometric and dimensional tolerances. Table 2 shows tolerance types measured for this study and the associated dimension. The *features-based* gauge was previously measured with a DEA Global Image 091508 CMM, whose expanded uncertainty is given by MPE_E = 2.2+3L/1000 [µm]. These measurements are used as reference values for this work since its repeatability level is far better than AACMM's repeatability (MPE_p < 2.2 µm).

Table 2.Geometric features and tolerances included in the study.

Geometric features	Number of elements	Geometric tolerance	Dimensional tolerance
Spheres	2	Sphericity	Diameter (20 mm)
			Distance between spheres (960 mm)
Outer cylinders	2	Cylindricity	Diameter (50 mm)
			Distance between outer cylinders (700 mm)
			Parallelism between outer cylinders
Inner cylinders	2	Cylindricity	Diameter (30 mm)
			Distance between inner cylinders (900 mm)
			Parallelism between inner cylinders
Parallel planes	2 pair	Flatness	Distance between planes (1000 mm)
			Parallelism between planes
Perpendicular planes	1 pair	Flatness	Perpendicularity between planes
Inclined planes	2 pairs	Flatness	Angularity between inclined planes

PCDMIS software was used to control measurement of AACMM and CMM. Additionally, AACMM and the *features-based* gauge were mounted on a CMM table at fixed positions. Test measurements were carried out in the CMM laboratory where temperature is controlled within a range of 20 ± 1 ºC.

3. Methodology

The evaluation test intention is to calculate operator and AACMM uncertainty when measuring a feature in a part. Because of this, several operators are necessary to carry out the test and to extend the methodology to any kind of tolerance. This way, evaluation results will qualify certain operators for the measurement with a specific AACMM. Also, AACMM capability to measure each type of tolerance is finally determined, which assures AACMM reliability and traceability. Three operators measured the *features-based* gauge 5 times, with 10 repetitions each time.

Given the importance of operator factor, the test analysis use statistical techniques similar to repeatability & reproducibility studies which allow us to evaluate operators. Two ways ANOVA (analysis of variance) compare the mean of several measurement samples, classified into two categories by their variance study. As a result, this technique obtains if any factor is significant and, therefore, affects AACMM measurement. On the way, variance of factors are calculated and used to set the operator and AACMM uncertainty.

Measurement results were used to calculate the sum of squares for each factor or group of measurement, eq. 1-5. *Sum of squares of operator* (OSS) and *Sum of squares of gauge* (GSS) consider the variability associated to each operator or set of gauge measurements against the total mean. *Interaction between operator and gauge factors* (ISS) measures the variability of their combined effects. This value is used for comparison against the variability of each individual factor and the total mean. *Error sum of squares* (ESS) represents the variability which is non-explained by operator or gauge factor. At last, *total sum of squares* (TSS) shows the variability of the whole test measurements. Letters a, b and r are the number of operators (3 operators), the sets of measurements of the gauge (5 sets) and the repetitions (10), respectively.

$$OSS = \sum rb(\bar{X}_{operator} - \bar{X}_{total})^2 \quad (1)$$

$$GSS = \sum ra(\bar{X}_{gauge} - \bar{X}_{total})^2 \quad (2)$$

$$ISS = \sum\sum r(\bar{X}_{int} - \bar{X}_{op} - \bar{X}_{gauge} + \bar{X}_{total})^2 \quad (3)$$

$$ESS = \sum\sum\sum(X_{indiv} - \bar{X}_{group})^2 \quad (4)$$

$$TSS = \sum\sum\sum(X_{indiv} - \bar{X}_{total})^2 \quad (5)$$

These values of sum of squares are divided by the degree of freedom of each group in order to obtain the mean squares. The ratio for each mean square and the *Error mean squares* provides the F parameter. This parameter is introduced in the Fisher distribution to obtain the significance of the factors. The level of confidence is given by p values: p value lower than 0.05 (95% level of confidence) means that the factor is statistically significant. These significant p factors explain the measurement variability and prove that there are differences between operators performance. Table 3 shows the ANOVA methodology for the test analysis.

Table 3. ANOVA methodology for the test analysis.

Sources	Sum of squares	Degree of freedom	Mean squares	F	p
Operator	OSS	a-1	OMS=OSS/(a-1)	OMS/EMS	0.05
Gauge	GSS	b-1	GMS=GSS/(b-1)	GMS/EMS	0.05
Interaction	ISS	(a-1)(b-1)	IMS=ISS/(a-1)(b-1)	IMS/EMS	0.05
Error	ESS	ab(r-1)	EMS=ESS/ab(r-1)		
Total	TSS	abr-1	TMS=TSS/(abr-1)		

The non-explained variability due to operator or gauge is assumed as the AACMM contribution to the measurement uncertainty. The total variability is the sum of the variability of each factor. In addition the standard deviation was calculated for each factor so the true contribution of operator and AACMM to the measurement test is obtained.

4. Results

Two kinds of results were obtained: direct comparison among operator's measurements and contribution of operator and AACMM to measurement performance in terms of standard deviation. As example, Fig. 2 shows the test results for sphere diameter which includes diameter deviation and frequency of each diameter value. It is observed that each operator is characterized by a different behavior; whilst operator 1 and operator 2 achieve similar curves with different dispersion, operator 3 performance is considerably worse. These results show the most suitable operator for measuring sphere diameters and his measurement dispersion is determined.

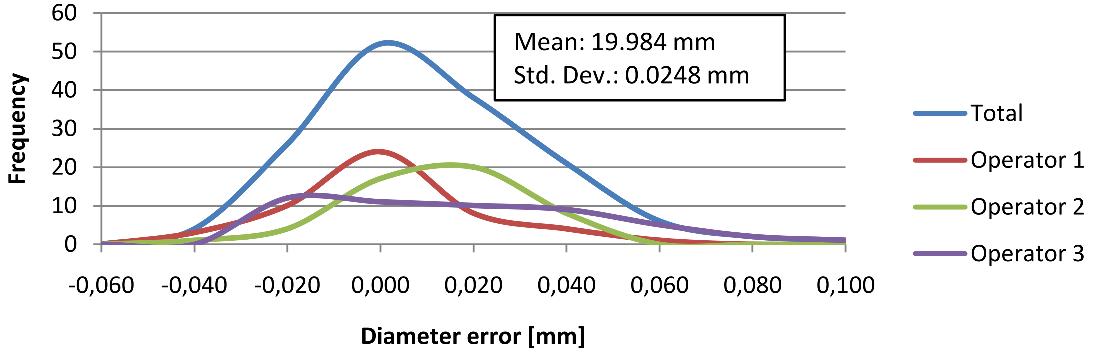

Fig. 2. Operators performance comparison.

Another operator comparison is carried out for each gauge measurement set. Fig. 3 shows the mean value for each gauge measurement set and the standard deviation associated to each operator. The mean diameter of the spheres is in a range of 0.040 mm with a maximum error of 0.021 mm with respect to the mean of the measurements. Regarding dispersion, operators 1 and 2 obtain similar results, about 0.020 mm, and operator 3 reaches up to 0.030 mm.

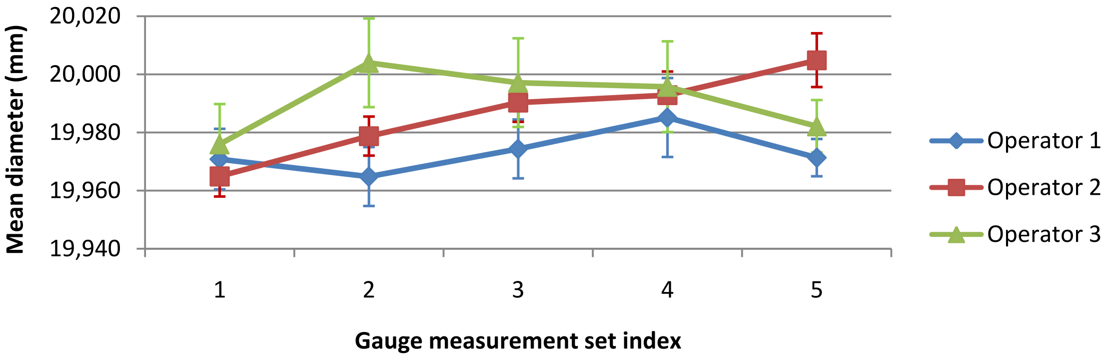

Fig. 3. Mean diameter and standard deviation for the 5 sets of measurements of a sphere.

As an example of the methodology, Table 4 shows the result for sphere diameter tolerance. In this case, both factors, operator and gauge, have a significant impact on the measurement results, although gauge contribution is quite lower than operators'. This fact shows that the operator can lead to measurement error regardless the AACMM qualification. In fact, operators should be evaluated and qualified as an important part of the measurement system as well.

Table 4. Results of the repeatability and reproducibility for sphere diameter.

Main effects	Sum of squares	Degree of freedom	Mean squares	F	p
Operator	0.008403	2	0.004201	8.556152	0.000317
Part	0.007471	4	0.001868	3.803545	0.005803
Interaction	0.009248	8	0.001156	2.354289	0.021104
Error	0.066288	135	0.000491		
Total	0.091409	149	0.000613		

Furthermore, the variance and standard deviation associated to each factor were calculated. Since the sum of each factor variance is the total variance, unlike standard deviation, the contribution for each factor was also calculated as the percentage of variance, Table 5. It was noted that although gauge factor is significant ($p>0.05$), its contribution to the total variance is so low that this gauge is suitable for AACMM evaluation. In addition, the contribution of the operator and the AACMM to the measurement performance is quantified. This way AACMM is evaluated subtracting the influence of operator. The values in bold show the highest influences of each column factor. Note that the sum of the four factor percentages gives 100% although the percentage of interaction factor is not showed.

Table 5. Contribution of operator and gauge for all measured features.

Tolerance	σ^2 % AACMM	σ^2 % Operator	σ^2 % Gauge	σ Total variance
Sphericity	**56.85**	**33.05**	0.00	0.0103
Cylindricity, outer cylinder	34.11	**44.97**	4.61	0.0165
Cylindricity, inner cylinder	**50.79**	16.52	9.06	0.0134
Flatness	**86.80**	12.67	0.53	0.0033
Parallelism between outer cylinders	**55.77**	0.00	0.00	0.0139
Parallelism between inner cylinders	**60.54**	22.44	6.78	0.0189
Parallelism between planes	45.20	**51.40**	3.40	0.0167
Perpendicularity between cylinders	39.50	**38.24**	0.00	0.0433
Perpendicularity between planes	**91.63**	2.83	3.65	0.0121
Diameter, sphere	**76.47**	9.48	3.69	0.0253
Diameter, outer cylinder	22.90	**24.85**	7.17	0.0446
Diameter, inner cylinder	42.46	10.41	0.00	0.0297
Distance between spheres	9.70	12.19	0.00	0.0641
Distance between outer cylinders	3.86	**28.21**	2.00	0.1043
Distance between inner cylinders	3.61	20.34	0.00	0.0996
Distance between planes	2.12	**27.72**	0.00	0.1038
Angularity	29.80	**62.79**	4.55	0.0590

5. Conclusion

Current methodologies for AACMM evaluation are clearly based on previous MMC experience, both gauges and procedures. Usually, only distances between spheres (exceptionally with distances between planes) are measured so it is excluded the evaluation of operator performance, which controls many measurement parameters, measurement technique. In other words, evaluation methodologies do not agree to real measurements carried out in industrial environment. Throughout this paper, we propose a completely different methodology and far more ambitious. On one side, a *features-based gauge* is proposed, manufactured and test it. The use of this gauge allows us to evaluate the capacity of the operator to measuring several geometric features with an AACMM. The corresponding methodology allows for assessing the agreement between AACMM and CMM for different dimensional and geometrical tolerances. In addition, this methodology was repeated with different operators in order to evaluate, by means of ANOVA, which quantity the contribution to total error of the gauge, operator and AACMM.

Results of the evaluation test show that this approach is capable of quantifying the operator contribution to measurement performance as well as the AACMM real contribution without the operator influence. For example, it can be said that, talking about geometric tolerances, AACMM error contribution is an important part of total error, while for dimensional tolerances the same factor is considerably lower. Furthermore, operator has a relevant influence in the error form of spheres and cylinders - both outer and inner. Regarding the *features-based* gauge, the low error contribution indicates that this gauge is suitable for AACMM evaluation. It goes without saying that this *features-based gauge* was not only capable to evaluate the AACMM and the operator's technique for each type of tolerances, but also allows the operator training.

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