ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

METHOD TO CHECK PERFORMANCE OF LASER SCANNERS USING TRIDIMENSIONAL ARTIFACT

Laura Daniela Ordiérez Zúniga
Antonio Piratelli-Filho
Universidade de Brasilia (UnB), Faculdade de Tecnologia, Depto. Eng. Mecânica, 70910-900, Brasília, DF, Brazil
e-mails: lordierez@unb.br, pirateli@unb.br

Abstract. *Tridimensional laser scanner is nowadays used in several applications of reverse engineering since it admits acquisition of geometric information at reduced measurement time and cost. Comparing with instruments as Coordinate Measuring Machines (CMM), it has reduced accuracy and greater uncertainty. The performance verification of laser scanners is under study and currently there is no standard to address this issue. This paper proposes a method to verify the performance of 3D laser scanners. The experimental approach was implemented using 3D laser scanner manufactured by NextEngine. A tridimensional gauge was designed and manufactured in aluminum with specific geometrical features like circles, cylinders, planes and spheres. The measured geometric characteristics were radius, angles and heights. These characteristics were measured with the Rapidworks software. The gauge was calibrated and its features and dimensions were determined and compared with the scanner measured values. The method was suitable to evaluate the instrument performance as estimates of the accuracy and the repeatability were obtained.*

Key-words: *laser scanner 3D, non-contact measurement, performance tests*

1. INTRODUCTION

Reverse engineering has had a deep diffusion in many different application fields such as industry, medicine, art conservation and heritage. The goal of these techniques is to obtain information about physical objects for the design and manufacturing of new products in less time and improved quality.

In respect to data acquisition for part modeling, there are different possibilities. The most known is using Coordinate Measuring Machines (CMM) equipped with contact probes, taking data points one each a time. This machine is useful in measuring parts with simple shapes and well defined. Data acquisition is time consuming and requires manual registration of a small number of points on each surface. Besides, the use of contact stylus is not recommended to measure pieces in soft materials like rubber. Nevertheless, the accuracy and repeatability are high enough to result in good Computer Aided Design (CAD) models, as demanded in Computer Aided Manufacturing (CAM) techniques.

On the other hand, other option is using contactless data acquisition devices as *laser scanners*, based on laser triangulation technology. This method allows determining how deep are the points on a given surface, by interpreting the generated images obtained with a reflected laser beam. Nowadays, *laser scanner* systems are the most used tools in reverse engineering applications, thanks to its acquisition speed and high density of data points.

These measurement instruments introduce errors when determining the coordinates of the points. The point cloud obtained has imprecision from scanner hardware, part geometry, laboratory conditions and software selected options of scanning. These error sources can be controlled to optimize data collected, but performance evaluation must be applied to characterize the instrument.

Literature presented some efforts to performance evaluation of contactless measuring instruments. Crescenzio and Fantini (2011) evaluated scanners with different types of lenses during the scanning a reference plane, characterizing the precision and the accuracy of the scanner. The physical effects, such as surface penetration of the laser beam, range of artifacts created, the shift in the centroid of the laser spot due to a depth discontinuities and the colored variation affecting the accuracy and uncertainty of an active sensor of scanner were studied by Guidi and Remondino (2011). Guidi *et al.* (2010) investigated six different types of scanners in respect to the accuracy and resolution.

Barbero and Ureta (2011) presented a study of the performance of five digitization techniques, measuring three different calibrated parts, a sphere, a cylinder and a gauge block. The authors compared the cloud of points in respect to the accuracy and the meshes obtained with the software in respect to the meshing quality. They observed that filtering cloud of points result in improvement in mesh generated.

This paper proposes a method to verify the performance of tridimensional laser scanners. The experimental approach was implemented using 3D laser scanner manufactured by NextEngine. A three dimensional gauge was designed and manufactured in aluminum with specific geometrical features like circles, cylinders, planes and spheres. The measured geometric characteristics were radius, angles, lengths and heights. The analysis was carried out comparing the results with the calibrated ones and the accuracy and repeatability was established as a performance metrics.

ISSN 2176-5480

2. EXPERIMENTAL

The applied methodology was based on the comparison of the dimensions of a developed gauge manufactured in aluminum, which contains simple geometric features. The feature calibrated dimensions were compared with ones captured by *laser scanner*.

2.1 Measurement instruments

Two instruments were used to take the measurements, a Cantilever CMM and a tridimensional *laser scanner*. These instruments are shown in Fig. 1.

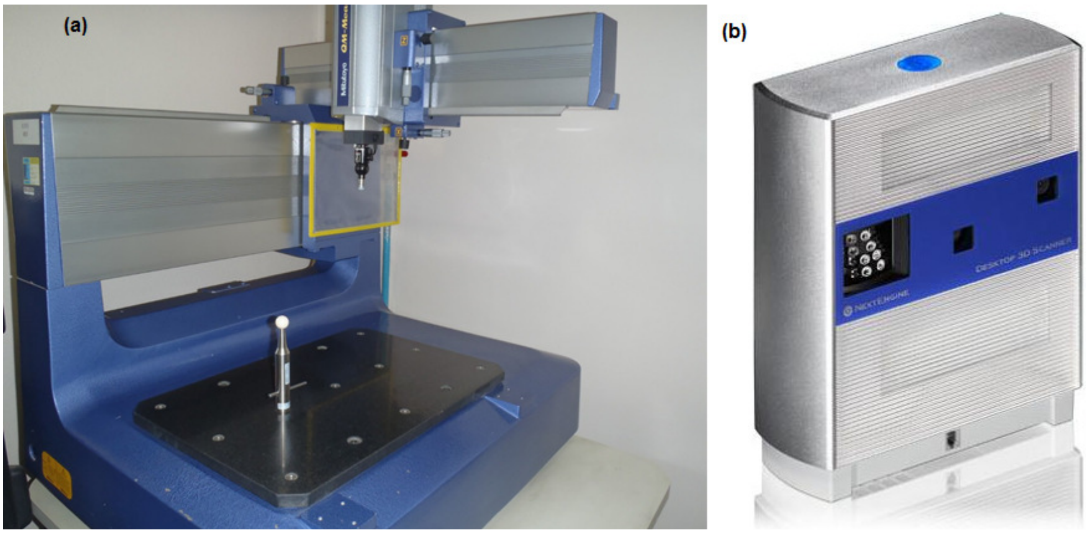

Figure1. Instruments used in the experiment. (a) Cantilever CMM, (b) *Laser Scanner*.

A Cantilever type CMM manufactured by Mitutoyo was used to calibrate the gauge. This machine has scale resolution of 0.001 mm and a work volume of 300 mm x 500 mm x 300 mm. The standard measurement uncertainty was obtained in the CMM calibration certificate and it is 0.003 mm. The operation and measurements were performed using the software MCOSMOS.

A tridimensional *laser scanner* manufactured by NextEngine was used to perform gauge measurements in performance test. This *scanner* is based on the Multistripe Laser Triangulation (MLT) technology and may be characterized as a portable and low cost instrument. This instrument is equipped with a twin array of 4 solid state lasers (class 1M, 10 mW) with wavelength λ = 650 nm and with two 3 Megapixel CMOS RGB array sensors. There are two different scanning modes, wide and macro, and the ideal position for wide mode requires the object to be 45 cm far from the front of the scanner, while macro mode requires the object to be 16 cm far away. The accuracy in *wide* mode is reported by manufacturer as 0.381 mm and in *macro* mode is reported as 0.147 mm. Instrument operation is performed with the SCANSTUDIO software and data points are captured and stored as cloud of points. Other software, RAPIDWORKS, was used to convert cloud of points in a mesh and after fitting a surface and take measurements of the geometric characteristics and dimensions.

2.2 Developed gauge and calibration

A gauge having different geometrical features was developed and Fig. 2 shows its designed features. The gauge was manufactured in aluminum, having eight geometric elements that were machined separately and assembled in a rectangular aluminum plate of dimensions 142 mm x 83 mm x 10 mm. The features that were measured are presented in Table 2. In his table, *h* represents the height, *d* indicates the diameters, *L* means the lengths, *l* indicates the widths and finally the symbol α represents the angles. These features were measured using the Cantilever model CMM.

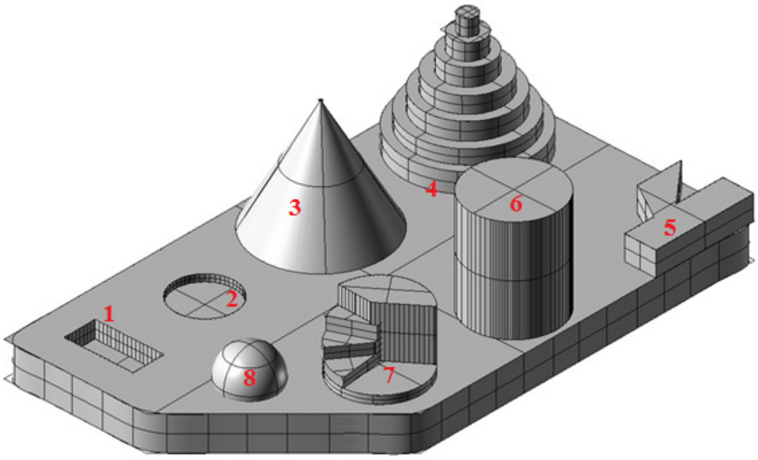

Figure 2. Gauge and features developed.

Table 2. Gauge parameters.

1	**Rectangle (hole)**	*L1, l1, h1*
2	**Circle(hole)**	*d2, h2*
3	**Cone**	*d3, h3*
4	**Circular stairs**	*d41, d42, d43, d44, d45, d46, d47,h41, h42, h43, h44, h45, h46, h47*
5	**Angular shape**	*h5,L5,α51, α52*
6	**Cylinder**	*h6,d6*
7	**Irregular stairs**	*d7,h71, h72, h73, h74, h75*
8	**Sphere**	*d8*

The standard measurement uncertainty u_c and the expanded measurement uncertainty U were determined to all parameters. Equation (1) presents the combined standard uncertainty as a function of the standard uncertainties associated to the CMM, to repeatability and to room temperature.

$$u^2{}_c = u^2{}_{RPT} + u^2{}_{AP} + u^2{}_{CMM} + u^2{}_{\Delta T20} + u^2{}_{TDIF} + u^2{}_{Res} \quad (1)$$

The symbol u_{RPT} is the standard uncertainty associated with the repeatability of the 10 measurements done with the CMM. The standard deviation of the mean is $S/\sqrt{n}$ (Piratelli-Filho *et al.*, 2012). The symbol u_{AP} is the standard uncertainty associated to CMM probe and it was obtained a value of 3.2 µm, extracted from CMM calibration certificate. The symbol u_{CMM} is the standard uncertainty associated to the measurement of distances and angles on CMM. This value was determined by the machine calibration certificate, trough expanded uncertainty of U = 1.2 + L/600 µm. The symbol $u_{\Delta T20}$is the contribution of the temperature change with respect to the reference temperature (20 °C) and the symbol u_{TDIF} is the contribution of the temperature difference between the CMM and the part. The symbol u_{Res} is the contribution of the CMM resolution and had a value of 0.204 µm, considering a triangular probability distribution and CMM scales resolution of 1 µm.

The standard measurement uncertainties related to the temperature changes in respect to the reference 20 ◦C ($u_{\Delta T20}$) and to the difference between the gauge and CMM (u_{TDIF}) were determined by equations 2 and 3, respectively (µm). In these expressions, L is the measured length (mm), Δα is the difference between the thermal linear expansion coefficient of the CMM and the gauge, assumed as $15\ x10^{-6}$ °C^{-1}. The temperature difference ΔT_1 is the difference between room temperature and 20 ◦C and the value u_T is the standard measurement uncertainty of the thermometer used, stated as 0.1 ºC by the calibration certificate. The value $u_\propto$ is the standard measurement uncertainty associated to the thermal expansion coefficient and considered as 10% and the temperature difference ΔT_2 is the difference between temperature of the CMM and the gauge.

$$u^2{}_{\Delta T20} = \left(\frac{1000.L.\Delta\propto.\Delta T_1}{2.\sqrt{3}}\right)^2 + (1000.L.\Delta\propto.u_T)^2 + (1000.L.\Delta T_1.u_\propto)^2 \quad (2)$$

$$u^2{}_{TDIF} = \left(\frac{1000.L.\Delta\propto.\Delta T_2}{2.\sqrt{3}}\right)^2 + (1000.L.\Delta\propto.u_T)^2 + (1000.L.\Delta T_2.u_\propto)^2 \quad (3)$$

2.3 Performance test

Performance was determined by comparing the measured and calibrated gauge dimensions, to characterize the accuracy and repeatability of the 3D scanner. The statistical analysis and the graphs were developed in MatLab software and the analysis was carried out with the measurement results of all gauge features.

The accuracy of each feature was estimated by comparing the dimensions of each parameter (calibrated) with the results obtained from scanner (bias=measured-calibrated). The angle determination accuracy was verified by evaluating the angle α between the two planes intercepted. Figure 3 presents the comparisons of the measured (scanned) values with the calibrated ones (CMM) of angles, circle diameter, height of conic feature and height of the stairs.

The repeatability was considered as the variability observed in data samples (cloud of points) and the variability observed when measurement was repeated in the same conditions. Thus, the standard deviations of the features determined were evaluated to all gauge geometries.

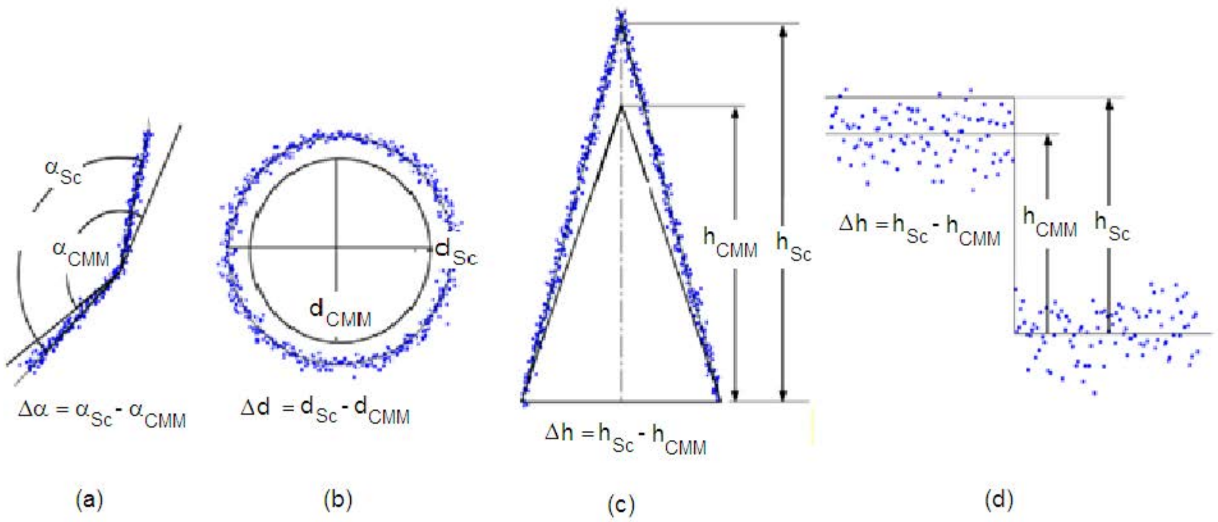

Figure 3. Deviations of angle between planes, diameter of the cylinder, height of the cone and height of the stairs.

3. RESULTS AND DISCUSSION

3.1 Gauge calibration

Table 3 presents the values of the calibrated gauge parameters. The mean and standard deviation were determined and it was observed that some parameters presented standard deviations very large compared to others, like d_3, h_{43}, h_{45}, h_{46} and h_5. This variability was associated to the calculation method and to the variability of some points defining the geometric elements involved.

The uncertainties of all gauge parameters were determined and Table 4 shows the calculation results to the height *h1*. The sources of uncertainty and its contributions are presented, as type A and type B ones, as well its probability density functions admitted and its contributions. The uncertainty of the CMM, the uncertainty of the resolution and the uncertainty of the probe stylus were obtained from the calibration certificate CMM for a coverage probability of 95%. The contributions of the temperature were determined considering that the room laboratory temperature was at 20.2 °C, the temperature of the CMM was 20.5 ºC and piece temperature was 21.2 °C.

The expanded measurement uncertainty for a probability of 95% of all gauge parameters described was calculated considering the effective number of degrees of freedom (ν_{eff}) following the formula the Welch-Satterthwaite and a probability of 95% to determine the coverage factor k using the student t probability distribution. Table 5 shows the expanded uncertainty $U_{95\%}$ (coverage probability of 95%) for all gauge parameters. It was observed the greatest expanded measurement uncertainties were influenced by the type A standard uncertainties like measurement standard deviations.

ISSN 2176-5480

Table 3. Calibrated parameters of the gauge.

Parameter	***Mean (mm)***	***Standard deviation (mm)***	***Parameter***	***Mean(mm)***	***Standard deviation(mm)***
h1	4.940	0.001	***d42***	31.745	0.004
L1	25.017	0.010	***d43***	25.911	0.006
l1	15.685	0.011	***d44***	20.558	0.006
h2	2.030	0.003	***d45***	14.002	0.003
d2	17.261	0.016	***d46***	9.474	0.004
h3	32.455	0.007	***d47***	4.998	0.003
d3	34.950	0.413	***h41***	4.766	0.300
d41	36.845	0.003	***h42***	4.616	0.340
h43	5.023	0.339	***h6***	29.029	0.028
h44	4.724	0.089	***d6***	24.922	0.006
h45	4.799	0.349	***d7***	23.985	0.014
h46	4.250	0.400	***h71***	1.993	0.044
h47	5.660	0.005	***h72***	4.659	0.042
h5	7.200	0.298	***h73***	7.700	0.043
L5	29.901	0.009	***h74***	11.451	0.043
α51	120.383	0.149	***h75***	16.532	0.040
α52	39.904	0.118	***d8***	16.072	0.008

Table 4. Measurement uncertainty determination of parameter ***h1***.

Source of uncertainty	Uncertainty type	Probability density function	DF	Stand.uncert. $u(i)$ (μm)	$c(i)$	Contribution $u(i)xc(i)$ (μm)
u_{RPT}	A	Normal	10	0.400	1	0.400
u_{AP}	B	Rectangular	∞	3.200	1	3.200
u_{Res}	B	Triangular	∞	0.204	1	0.204
u_{CMM}	B	Normal	∞	1.208	1	1.208
$u_{\Delta T20}$	B	Rectangular	∞	0.035	1	0.035
$u^2{}_{TDIF}$	B	Rectangular	∞	0.010	1	0.010

Combined standard uncertainty $u_c = 3.5\ \mu m$
Effective degrees of freedom $v_{eff} = 49808$
Coverage factor $k = 1.96$
Expanded uncertainty $U_{95\%} = 6.8\ \mu m$

ISSN 2176-5480

Table 5. Expanded measurement uncertainty ($U_{95\%}$) for all gauge parameters.

Geometry	***Parameter***	***$U_{95\%}$ (µm)***	***Geometry***	***Parameter***	***$U_{95\%}$ (µm)***
Rectangle hole	*h1*	6.4	Circular stairs	*d41*	6.7
	L1	9.1		*d42*	6.9
	l1	9.8		*d43*	7.4
Circular hole	*h2*	6.7		*d44*	7.5
	d2	12.9		*d45*	6.8
Cone	*h3*	7.9		*d46*	6.9
	d3	295.5		*d47*	6.6
Angular shape	*h5*	213.3		*h42*	214.7
Cylinder	*h6*	21.1		*h45*	64.0
	d6	7.6		*h46*	249.4
Sphere	*d8*	8.0		*h47*	286.1
Irregular stairs	*d7*	11.9		*h48*	7.1
	h71	31.9	***Geometry***	***Parameter***	***$U_{95\%}$ (º)***
	h72	30.2			
	h73	30.9	Angular shape	*α51*	107.2
	h74	31.4		*α52*	84.6
	h75	29.2			

3.2 Scanner performance test.

Before measurement on scanner 3D, the gauge was painted in white to make the surface suitable to scanning, avoiding reflections of the incident laser beam. Figure 4 shows the measured gauge, with the geometric elements as holes, planes, sphere, cone, cylinder, angular stairs and circular stairs. The qualitative first evaluation of the CAD model obtained showed good definitions of the built geometric elements, with visible and well defined edges and vertices and regular aspect of surfaces and tridimensional characteristic.

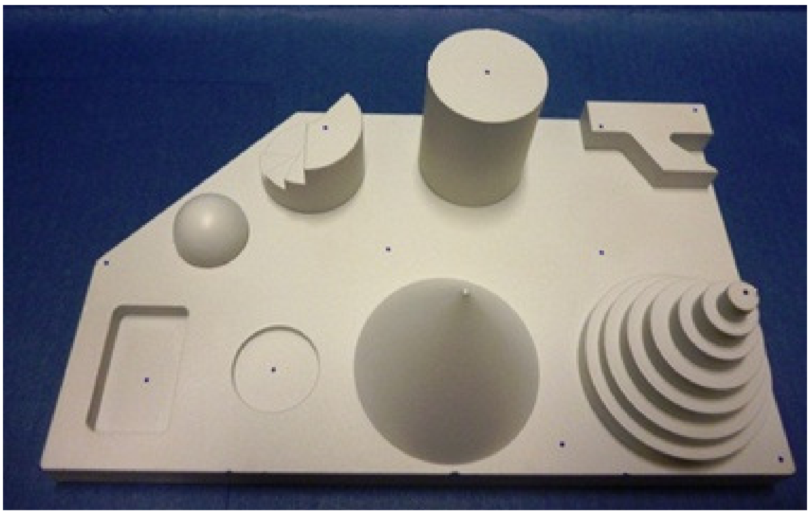

Figure 4. CAD model of the scanned gauge.

The accuracy and repeatability analysis were based on graphs comparing the systematic errors of the measured gauge parameters (red points) with the respective expanded uncertainties (95%) obtained in calibration (dashed blue lines). Additionally, it was presented the limits established by the 3D scanner manufacturer to the instrument accuracy (green lines), correspondent a maximum of 0.381 mm as *wide* mode was used in the measurements.

Figure 5 shows the geometric dimensions of the rectangle hole, as h_1, L_1 and l_1. It was observed that the accuracy was reduced as increasing the length of the figure (negative errors), as well as the repeatability, denoted by the standard deviation. The length l_1 presented values outside the limits stated at manufacturer manual and the biggest standard deviation.

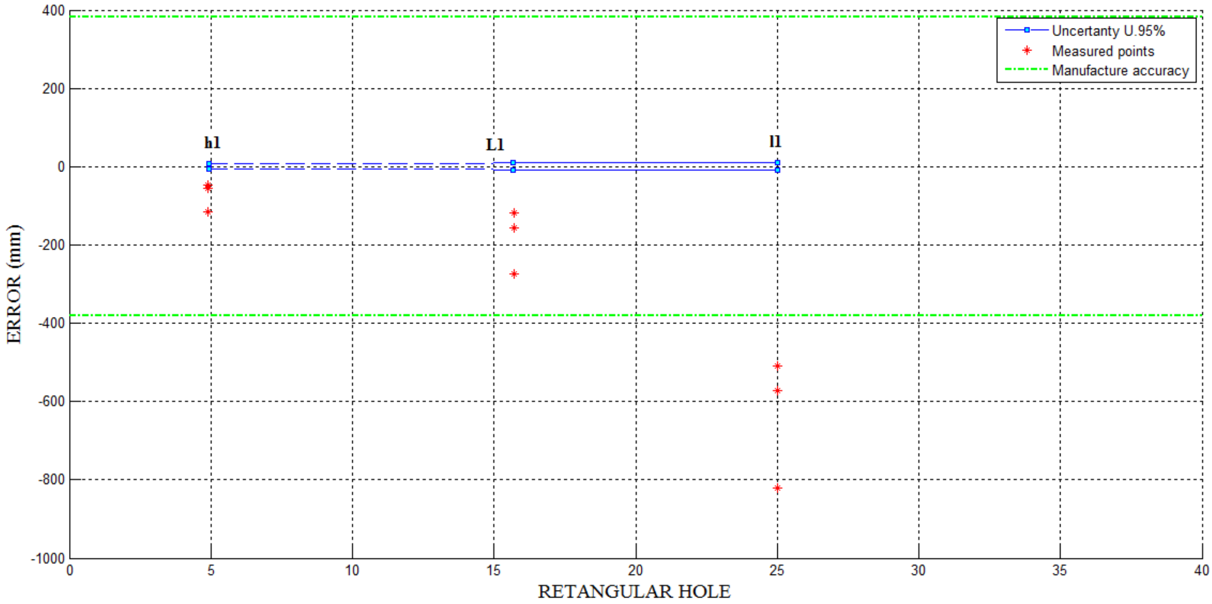

Figure 5. Results of performance with scanner, errors in rectangular hole.

Figure 6 shows the errors associated to the geometry of the circular hole. It was observed that the diameter present the biggest errors than the height of the hole. The standard deviation of the diameter was biggest than the standard deviation of the heights, with one value outside the border stated by the manufacturer.

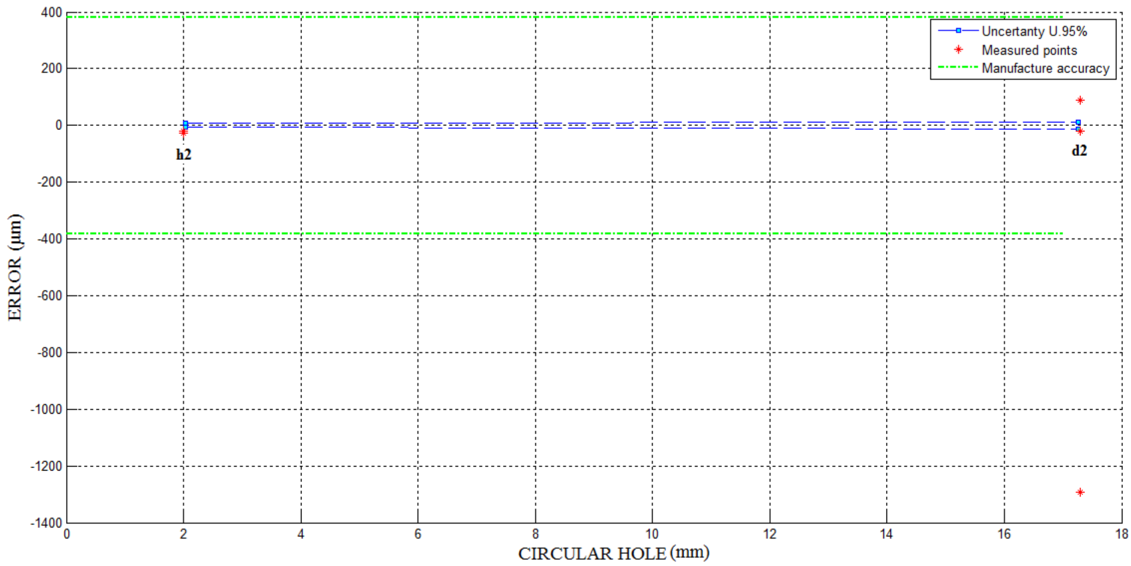

Figure 6. Results of performance with scanner, errors in circular hole.

Figure 7 presents the results associated to the cone. It was observed that the uncertainty of the diameter was biggest than the CMM machine uncertainty, but as the errors are enclosed by the uncertainty limits, it not possible to conclude about accuracy. For height, all error are biggest than CMM uncertainty limits and are outside manufacturer limits,

ISSN 2176-5480

presenting a negative bias. Figure 8 shows errors in height and diameter of the cylinder. Diameter errors are outside the manufacturer limits, but height ones are not outside. Standard deviations are almost the same in both cases. Figure 9 presents the errors in diameter of the sphere, and it was observed negative errors (bias) between manufacturer borders and a standard deviation close to the cylinder d6 diameter.

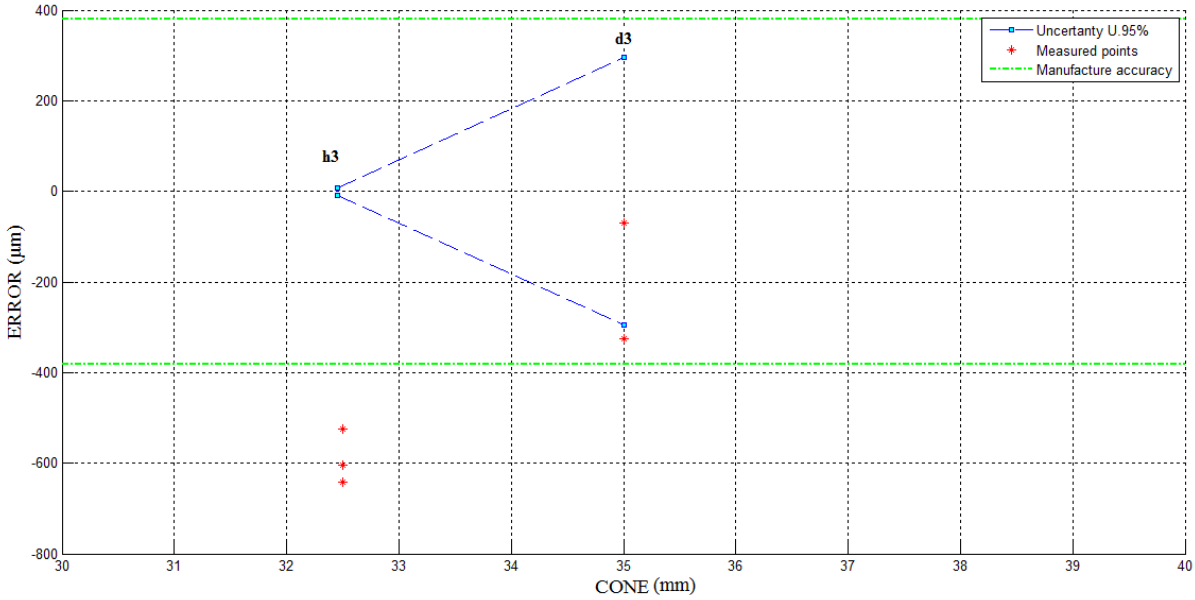

Figure 7. Results of performance with scanner, errors in circular cone.

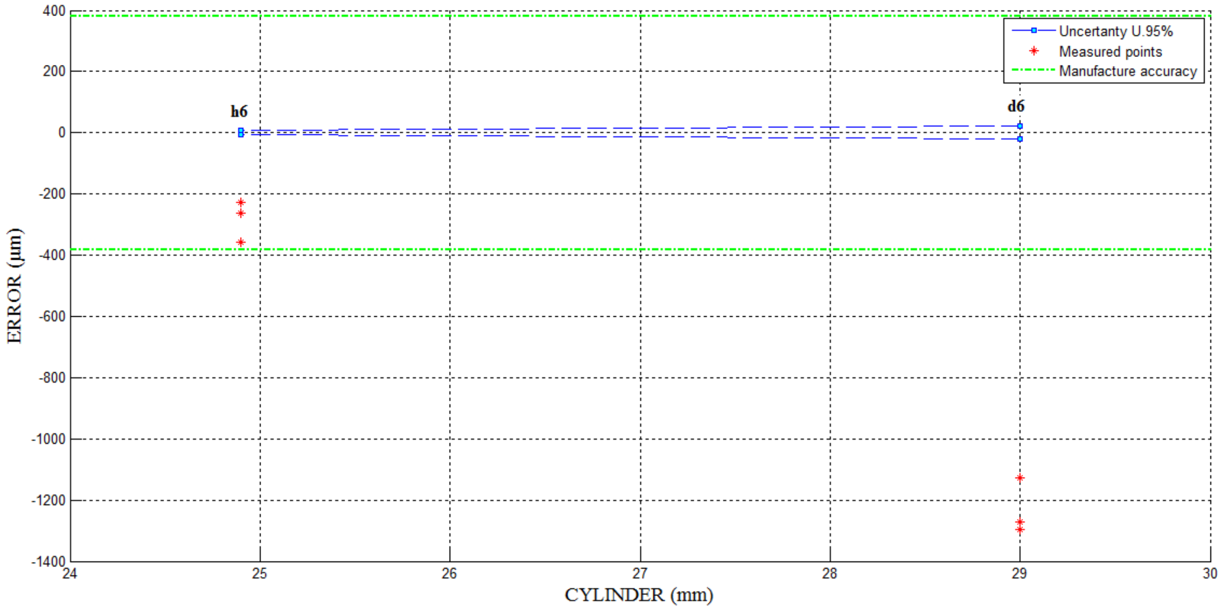

Figure 8. Results of performance with scanner, errors in cylinder

.

ISSN 2176-5480

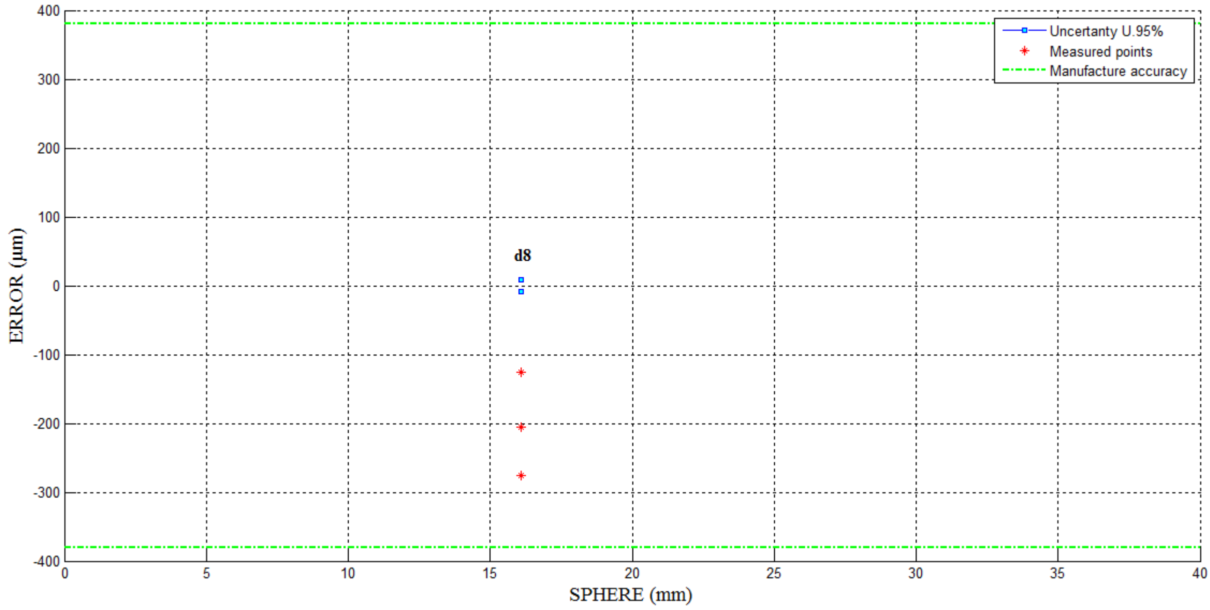

Figure 9. Results of performance with scanner, errors in sphere.

Figures 10 and 11 present the errors in heights and diameters of the circular stairs. It was observed that most of the errors are enclosed by CMM expanded uncertainty limits (95%), for dimensions lesser than 6 mm, except the parameters h41, d47 and h47, but all enclosed by the manufacturer accuracy limits. The standard deviations were nearly constant. For dimensions greater than 6 mm, there were determined diameters and it was observed an increase in standard deviations and the errors were greater than before. For dimensions greater than 20 mm, there are errors out of the manufacturer limits. The uncertainty of heights was bigger than that of the diameters.

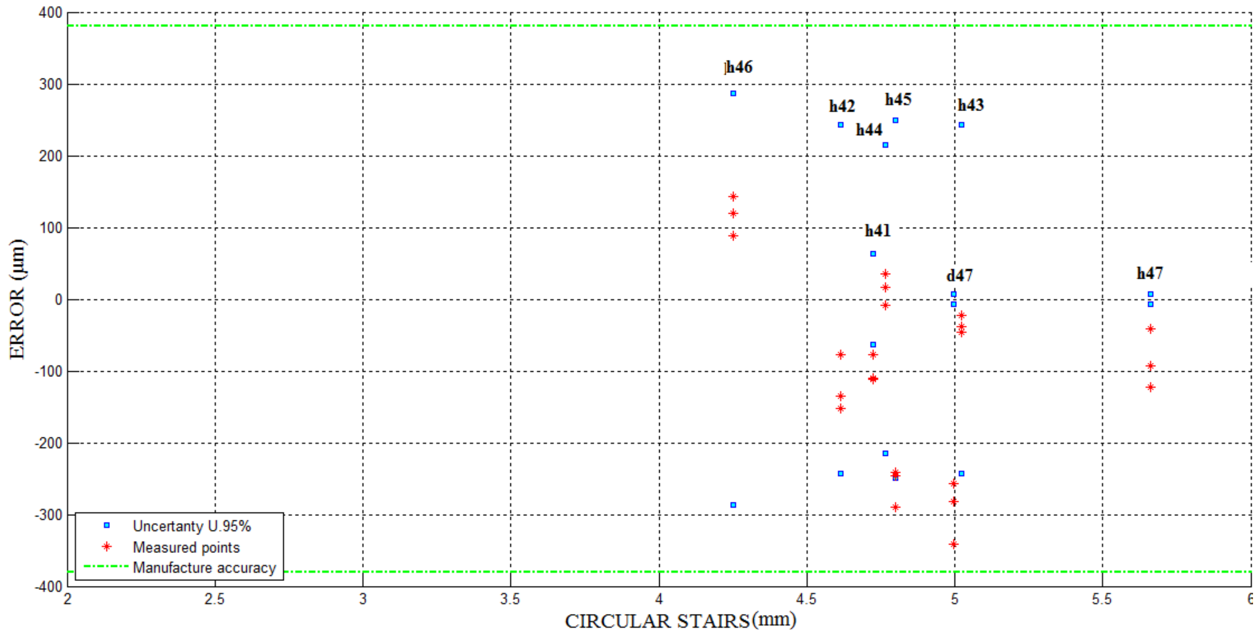

Figure 10. Results of performance with scanner, errors in heights and diameters of the circular stairs.

ISSN 2176-5480

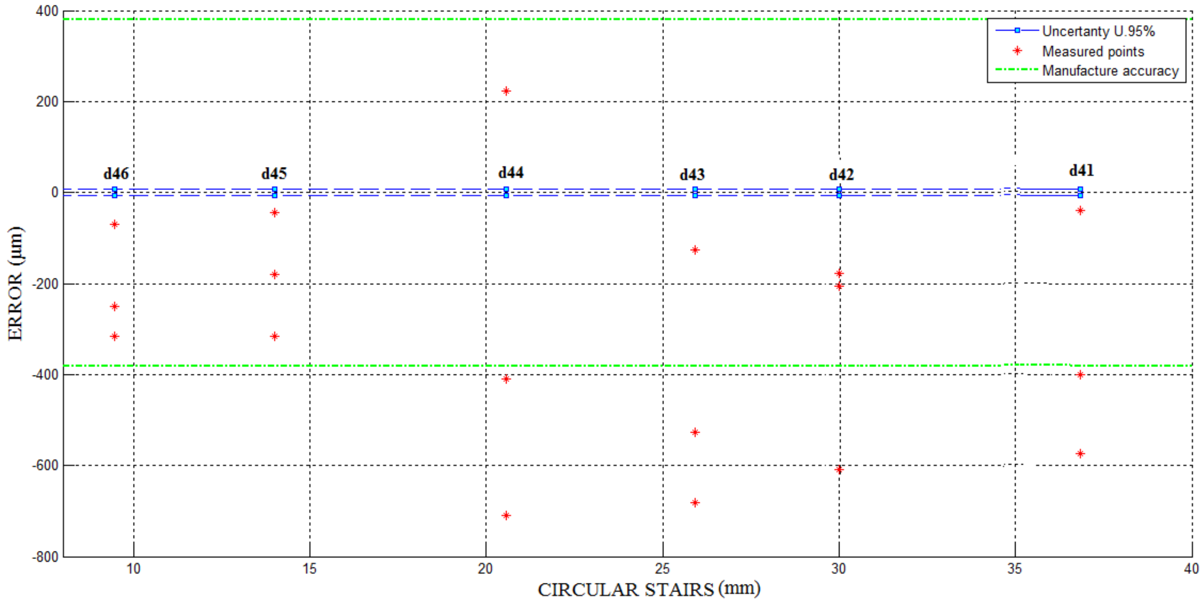

Figure 11. Results of performance with scanner, errors in diameter of the circular stairs.

Figure 12 shows the errors associated to determination of heights and diameter of the irregular stairs. It was observed that almost all errors are outside the limits of stated accuracy limits (manufacturer), but the standard deviation and the uncertainty were approximately constant in the interval. The errors were negative in respect to the calibrated geometries.

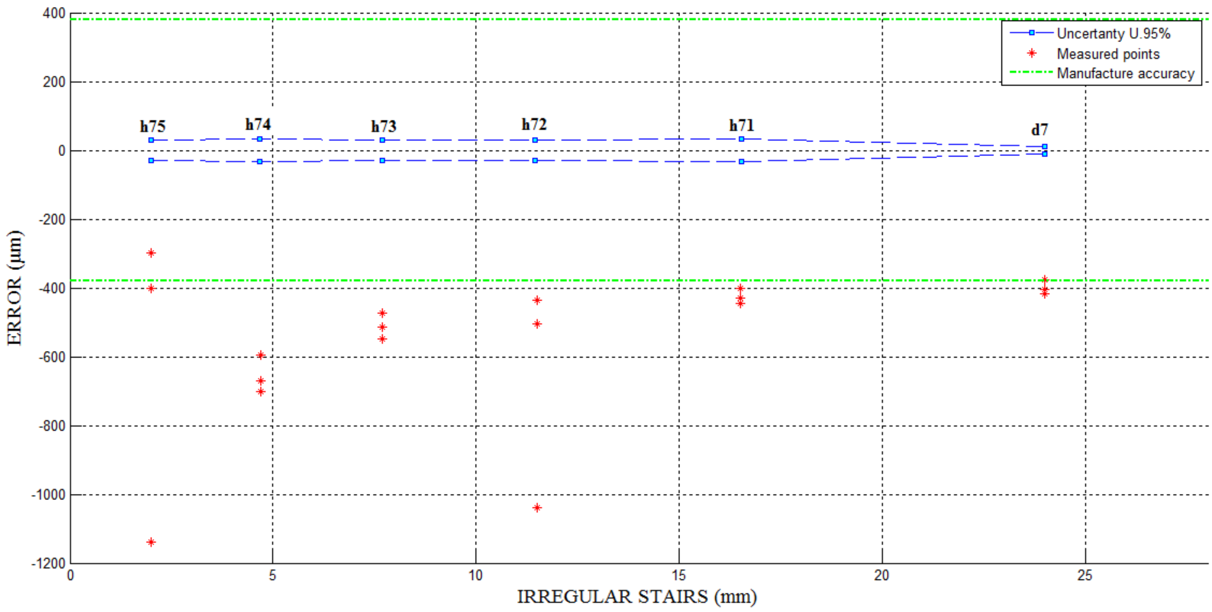

Figure 12. Results of performance with scanner, errors in irregular stairs.

Figure 13 shows errors in the diameter and angles of the angular shape feature. The errors in diameter were negative and the errors in angle measurements were positive. The angle errors were about 1° and this may be associated to the method used to calculate these values, based on determination of two planes with the cloud of points.

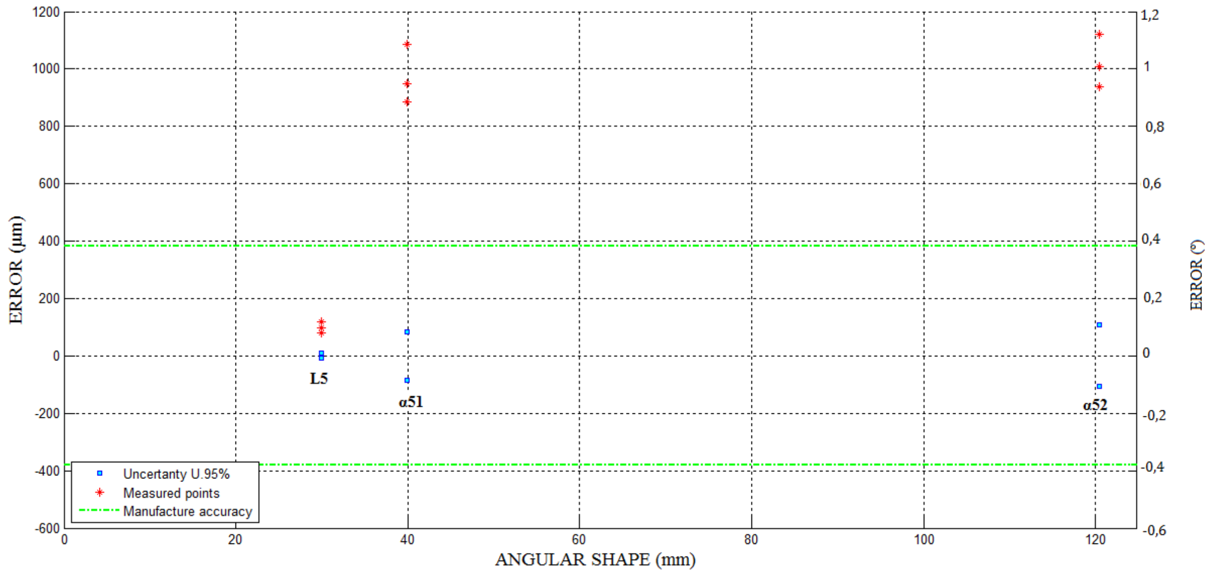

Figure 13. Results of performance with scanner, errors in angular shape.

After the analysis of the results, it was determined the scanner repeatability as the range of the observed errors, for all parameters determined, and it was equal to 1.222 mm. The scanner accuracy was associated to the dimensions of the geometric features, and its value change between 0.010 and 1.232 mm.

4. CONCLUSIONS

The performance test was applied using a gauge developed with different geometric features, to investigate distinct measurement situations. The features admitted the investigation of lengths in three dimensions, as the objects had width, larger and height variations.

The gauge was calibrated to determine the dimensions and the combined standard uncertainties and the expanded uncertainties. The results of uncertainty determination showed large differences in uncertainty values with some geometric features presenting big values, at the same order of manufacturer stated accuracy limits. These differences were attributed to the calculations done to fit geometries like planes used to determine the lengths and heights by software functions. The performance test was time consuming, especially when measuring the feature dimensions with scanner software. The errors were determined and it was observed that accuracy was associated to the geometric features and ranging from 0.010 to 1.232 mm. The scanner repeatability was determined by the range of all errors and it was observed a value of 1.222 mm.

Future works may be carried out to reduce the uncertainties in gauge calibration, trough improving the surface manufacturing quality and the number of different features in the gauge. The method of performance determination may be optimized to simplify the evaluation. Statistical techniques like analysis of variance could be applied to analyze the data.

5. REFERENCES

Barbero B. R., Ureta E. S., "Comparative study of different digitization techniques and their accuracy", *Computer-Aided Design*, Volume 43, Issue 2, February 2011, Pages 188-206.

Crescenzio F., Fantini M., "Experimental analysis for error compensation of laser scanner data" *2011*. In *International conference on Innovative Methods in Product Design,* Venice, Italy.

Guidi G., Remondino F., Morlando G., Del Mastio A., Uccheddu F., Pelagotti A.,"Performances evaluation of a low cost active sensor for cultural heritage documentation", *Structured Light and Laser Scanning*, 2011, Pages 59-69.

Guidi G. , Russo M., Magrassi G., Bordegoni M., "Performance evaluation of triangulation based range sensors", 2010, *Sensors [1424-8220]* vol:10 iss:8 pg:7192 -215

Piratelli-Filho A., Tavares F.H., Arencibia, R.V., "Application of Virtual Spheres Plate for AACMMs evaluation", *Precision Engineering*, Volume 36, Issue 2, April 2012, Pages 349-355.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.