EFFECT OF DIGITIZATION PARAMETERS ON FREEFORM RUNNER MEASUREMENT APPLYING FACTORIAL DESIGN

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Abstract. *This work proposes an approach to optimize the selection of the digitization parameters of a freeform jet ski aluminium runner. The experimental approach involved the selection of variables and levels based on software ScanStudioHD, used to carry out measurements with the laser scanner 3D NextEngine. Firstly, the part was coated with special powder to take measurements with an Articulated Arm Coordinate Measuring Machine (AACMM) and the determined data points were fitted to a Non-Uniform Rational B-Spline (NURBS) using Rhinoceros software. The resultant Computer-Aided Design (CAD) model was considered as reference. Secondly, the same coated part was digitized with the NextEngine scanner to capture the cloud of points at each experimental condition and to compare with the reference CAD model with Rhinoceros software, determining the deviations. The variables selected to investigate were the scan type (A), the number of points (B) and the target (C), adopted with number of levels 3, 3 and 2, respectively. A Factorial design was built and the number of experimental runs was 18. The runs were performed in random order, with the part positioned at a fixed distance from the laser source (Wide). The mean (M), the standard deviation (SD) and the scanning time (ST) were determined in each run (response variables) and the Analysis of variance (ANOVA) was applied to find the statistically significant variables with levels to minimize the response. The use of factorial design proved suitable to reduce the variability of the deviations and scanning time in the digitization process.*

Keywords: *jet ski runner, analysis of deviations, design of experiments.*

1. INTRODUCTION

Laser scanners 3D has been used to perform measurement tasks along reverse engineering processes in industry. This instrument makes possible to capture a cloud of three-dimensional points of the part surface in short time and the reconstruction of Computer-Aided Model (CAD) can be easily performed. Reverse engineering packages creates surfaces from the cloud of points obtained with scanners and are a useful tool in design community. These instruments emit laser beams on the part surface, which are reflected and returns to the camera receiver. The point coordinates are determined by triangulation and are presented on the computer screen. Nevertheless, there are several variables that introduces errors in coordinates of the points, related to hardware, software, part dimensions, surface finishing, room temperature and air humidity (Sansoni *et al.*, 2009).

Barbero and Ureta (2011) compared five digitization techniques: computerized tomography (CT), laser probe with CMM, laser scanner Handyscan Exascan, laser scanner with Krypton camera and fringe projection with Atos. The authors analyzed the preparation of the point cloud, the elimination of noise, the reduction of the number of points, the softening of the triangular meshes, the repair of the mesh and the hole filling. Gestel *et al.* (2009) presented a performance test for laser line scanners probes used in CMMs. The test involved the use of a planar artifact as a gauge reference and other objects like spheres, steps and edges can still be used. The authors carried out a quick verification, a scan depth, an angle and a thermal stability tests. Low accuracy applications can be carried out with the Kinectc sensor that works by emission of an infrared laser and triangulation. González-Jorge *et al.* (2013) presented an evaluation of Microsoft Kinect and Asus Xtion sensing systems, with a built gauge having five spheres and seven cubes fixed on a rectangular section tube. Khoshelham and Elberink (2012) investigated the accuracy and resolution of Kinectc sensor and recommends its use at distances ranging from 1 to 3 m from objects.

Guidi *et al.* (2007) presented an study of performance of low cost active sensors for cultural heritage documentation comparing the NextEngine 3D scanner with the Minolta Vivid 910 camera and ShapeGrabber SG100 camera, in respect to accuracy and repeatability. The authors used a reference plane and archeological objects to determine the deviations of the point cloud in relation to the surface and the mean, the standard deviation and the range were adopted as performance parameters. Guidi *et al.* (2010) investigated the resolution, accuracy and uncertainty of different range sensors like NextEngine 3D scanner and others, measuring objects having regular geometries as gauges. Polo and Felicisimo (2012) performed an evaluation of the uncertainty and repeatability of a NextEngine 3D scanner using a wood birdhouse as a reference object. Piratelli-Filho *et al.* (2014) present an approach to carry out the repeateatability and reproducibility (R&R) test of a NextEngine 3D scanner, using a gauge with regular geometries as circle, planes, cones, etc. The tests were planned by a hyerarquical 2-stages design having the parameters geometry and dimension as variables and analyzing the deviations in respect to the calibrated values with the Analysis of Variance (ANOVA).

The literature presents investigations of 3D scanners with no mention about parameters selected with the software used to digitization. It was generally considered that the software parameter selection was at the best option to the particular task but this condition depends on operator ability and training. Besides, the gauges are generally composed of regular geometries like planes and circles but the scanned objects are many times composed of freeform ones. Intending to contribute to this research area, this work proposes an approach to optimize the selection of the digitization parameters of a freeform jet ski aluminium runner. The experimental approach involved the selection of variables and levels based on software ScanStudioHD, used to carry out measurements with the laser scanner 3D NextEngine.

2. EXPERIMENTAL

The experimental work was carried out using a laser scanner 3D, manufactured by NextEngine. The scanner has an accuracy of 0.127 mm (Macro mode) and 0.381 mm (Wide mode), stated by the manufacturer. The scanner was controlled by the software ScanStudio HD PRO and the digitizing parameters were selected on computer screen, showed in Fig. (1). The Range must be settled as a function of the part dimension, being MACRO, WIDE or EXTENDED. The Positioning is related to the number of views adopted to capture the points, being SINGLE, BRACKET or 360. The option BRACKET takes three different views and the option 360 can be used with divisions varying between 4 and 16. The selection of number of points by squared inch (points/in^2) is related to the required density of the cloud of points and for this software (WIDE range) it changes from 80 to 220 points/in^2 (QUICK), 280 to 1,100 points/in^2 (small definition, SD) and from 2,000 to 17,000 points/in^2 (high definition, HD). The target is related to the illumination of the part surface and may be used as LIGHT, NEUTRAL or DARK. The Start and Tilt are options used to change the inclination of the part in relation to horizontal or vertical direction (NextEngine, 2009).

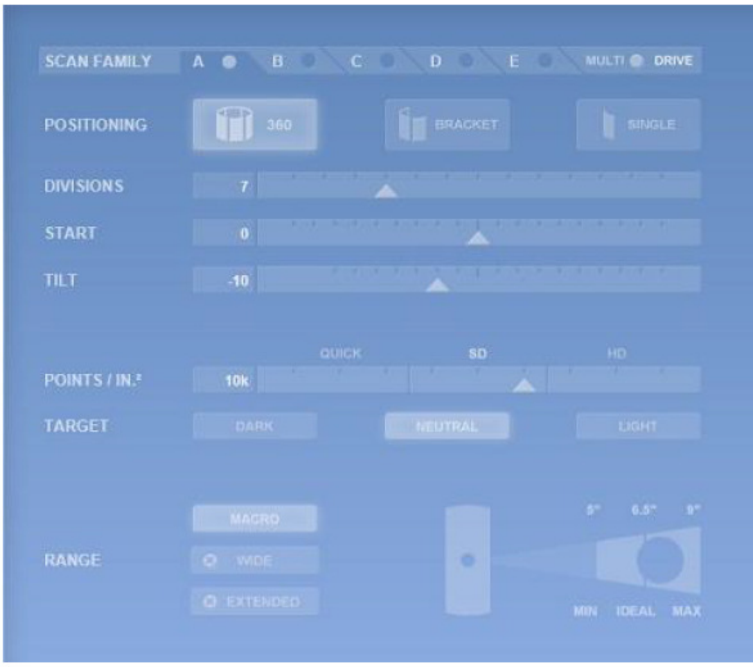

Figure 1. ScanStudio HD screen of digitization (NextEngine, 2009).

The freeform part used in this research was a jet ski rotor with three runners, showed in Fig. (2) during scanning. The rotor was firstly measured with an Articulated Arm Coordinate Measuring Machine (AACMM) from Romer manufacturer to create a reference Computer-Aided Design (CAD) model. The AACMM has an arm reach of 2.5 m and an expanded uncertainty (95%) of 0.06 mm, with a GPad software to capture points on the part surface. A rigid probe was used to capture the points with a needle stylus touching the surface, according to a strategy defined by lines traced on the runners surface. The points were adjusted at each line to Non-Uniform Rational B-Spline (NURBS) curves and surface using the software Rhinoceros (Piratelli *et al.*, 2014).

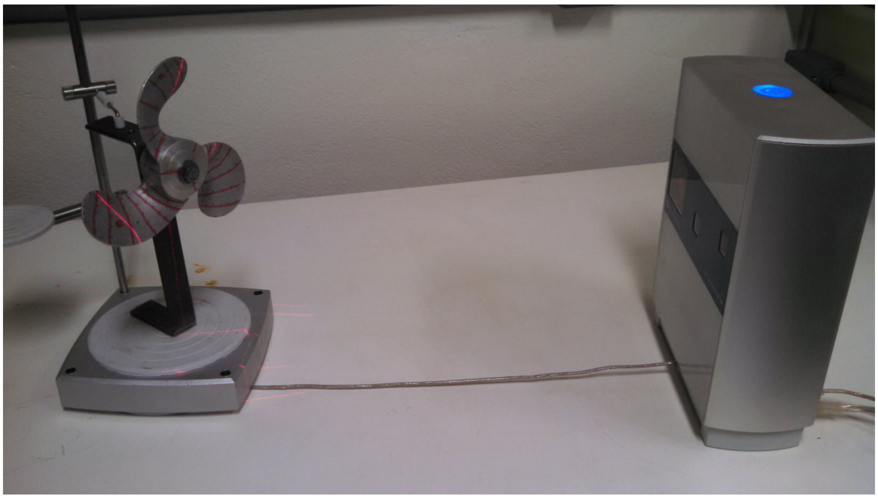

Figure 2. Jet ski rotor under measurement with 3D laser scanner.

The investigation of the optimal selection of digitization parameters was carried out through a factorial design with three variables with mixed number of levels. Taking in account the options of the ScanStudio HD PRO, the adopted variables were the *Positioning* of the part, the *density* of cloud of points (Points by squared inch) and the *Target* (target). The number of levels was defined as 3, 3 and 2, respectively. A third level to Target (Dark) was not possible to apply because of the large reflection of light in aluminium surfaces. Other variables like inclination and range were constant during all experimentation, being the range settled at WIDE. Table 1 presents these variables and the levels adopted and Table 2 shows the runs of the factorial design with the combination of the parameter levels at each line.

Table 1. Factors and levels adopted in experimentation.

Factors	**Number of levels**	**Levels Values**
Positioning	3	Single (1), 360-4 div (2), 360-16 div (3)
Density	3	80, 500, 17000 (points/in^2)
Target	2	Light (1), Neutral (2)

Table 2. Factorial design.

Run	**Positioning**	**Density**	**Target**
1	1	80	1
2	2	80	1
3	3	80	1
4	1	500	1
5	2	500	1
6	3	500	1
7	1	17000	1
8	2	17000	1
9	3	17000	1
10	1	80	2
11	2	80	2
12	3	80	2
13	1	500	2
14	2	500	2
15	3	500	2
16	1	17000	2
17	2	17000	2
18	3	17000	2

The part was digitized in random run order, each run according to the combination of the levels of the three variables. For example, the run number one was prepared fitting the runner on scanner basis and selecting the variables Positioning at level 1 (SINGLE), Density at 80 points/in^2 and Target at level 1 (LIGHT). The captured cloud of points was saved in a file to analysis. The deviations between the scanned points and the CAD model were calculated with the Rhinoceros software (option *POINT SET DEVIATION*) to each experimental run of the factorial design and the graphics were registered. The statistics mean, median and standard deviation were determined for each run and the time spent in digitization was also considered. A Rhinoscript algorithm was built to determine and save the deviations point-surface.

The analysis was carried out with the values of time, mean, median and standard deviation at each run, applying the statistical Analysis of Variance (ANOVA) technique. The F test was conducted to verify the null hypothesis that all levels of each variable produced the same mean deviation (H_0: $\mu_1=\mu_2=\mu_3$). When F was greater than the expected in F distribution (99%), the null hypothesis was rejected and an alternative hypothesis (H_1: $\mu_1 \neq \mu_2 \neq \mu_3$) was accepted. An algorithm was implemented in MatLab software to perform calculations and graphics.

3. RESULTS AND DISCUSSION

The analysis was carried out by comparing the digitized points of the freeform runner with the fitted CAD model. Figure (3) presents the analysis of deviations determined with run 15. This graphic shows the deviations by color category and it must be observed that the class between 0-0.6 contain most of the deviations (blue), but there are many deviations in other categories, 0.6-1.2 (cyan), 1.2-1.8 (green), 1.8-2.4 (orange) and 2.4-3.0 (red). Information as the number of digitized points, the mean, the median and the standard deviation were presented in the analysis. As observed, the mean was 1.079 mm, the median was 1.083 and the standard deviation was 0.7013 mm.

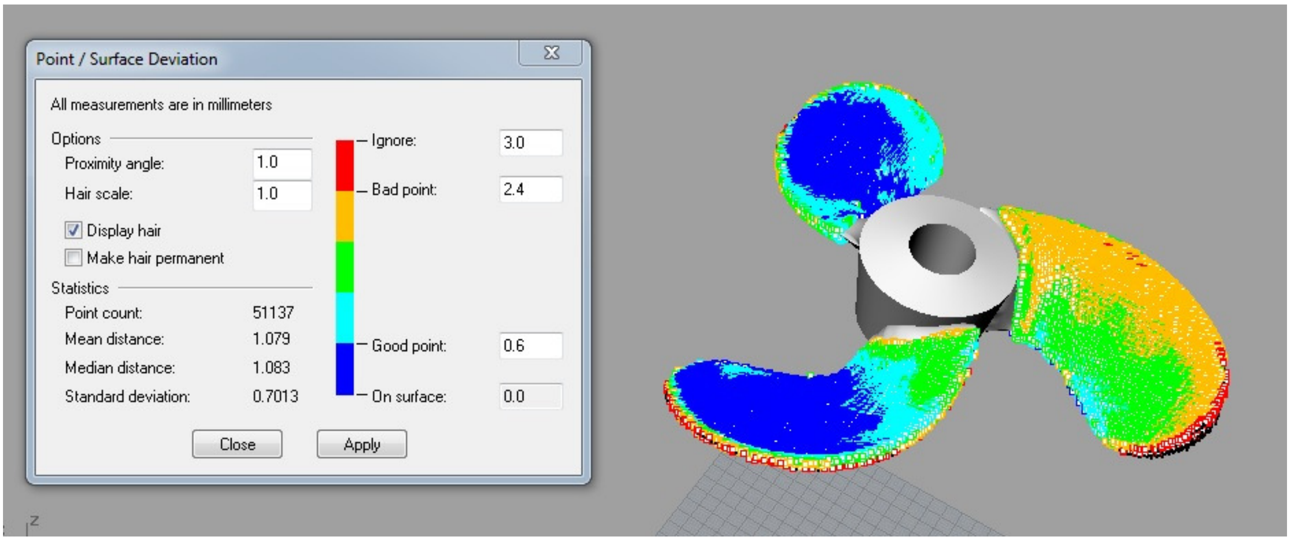

Figure 3. Deviations point-CAD model to run number 15.

The analysis was improved by the development of an algorithm using Rhinoscript to extract the deviations after an analysis with POINT SET DEVIATION command in Rhinoceros. This algorithm saved the deviations in files txt for ease analysis. Figure (4) presents the normal probability plot (a) and the histogram (b) of the deviations for run number 15, built with Matlab. These graphs show that normal probability distribution of the deviations of this run could not be accepted. The same behavior was observed in graphics of the other runs. A possible reason is the noise in the scanner results and filtering these data can be applied but with increased processing time.

The statistics mean, median, standard deviation and time spent in execution were determined and are presented in Table 3. The time spent in scanning was smaller in runs 1, 4, 10 and 13, equals to 1 minute. Among these, the run 10 produced the smallest mean, median and standard deviation, of 0.2347 mm, 0.1882 mm and 0.1881 mm, respectively. The parameters Positioning, density and target were set at 1 (single), 80 (points/in^2) and 2 (neutral) levels. A comparative view is presented in Fig. (5) where these differences can be better observed. Run 13 produced very similar results and doubt about the best scanner factors choice remains as 500 points/in^2 produced almost the same response (factor density).

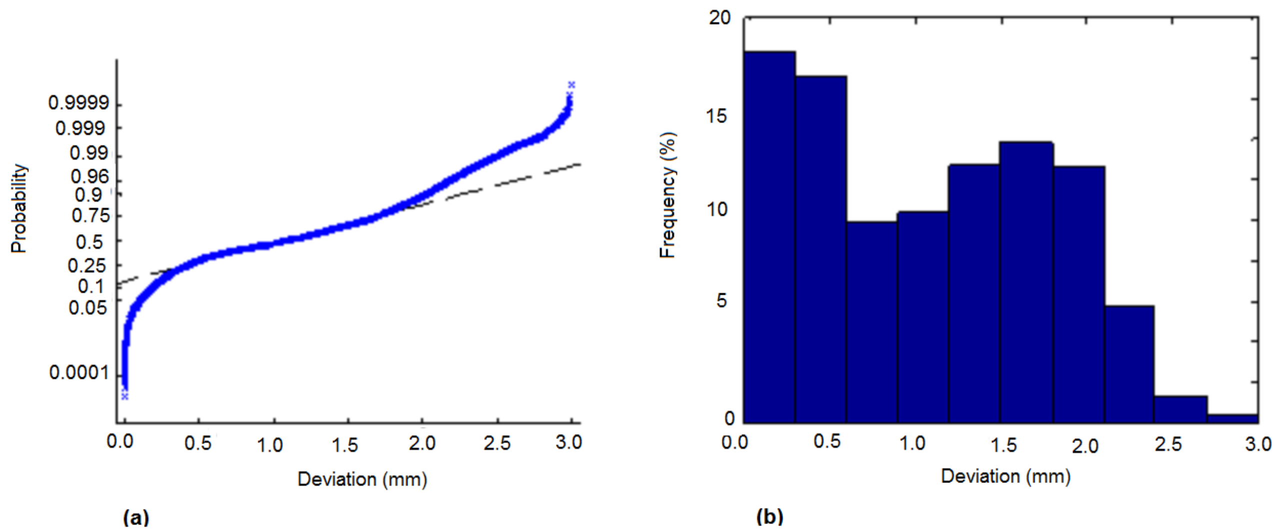

Figure 4. (a) Normal probability plot and (b) histogram of the deviations points-CAD model, for run number 15.

Table 3. Results of scan time, mean, median and standard deviation of deviations points-freeform surface.

Run	Time (min)	Mean (mm)	Median (mm)	Standard Deviation (mm)
1	1	0.3266	0.2869	0.2323
2	4	0.5479	0.5108	0.3672
3	15	0.5285	0.4277	0.4181
4	1	0.3182	0.2581	0.2757
5	7	0.5484	0.3715	0.3715
6	23	0.4916	0.4271	0.3247
7	2.5	0.3015	0.2542	0.2407
8	15	0.6164	0.5947	0.4071
9	70	0.4475	0.3291	0.3984
10	1	0.2347	0.1882	0.1891
11	4	0.3984	0.3765	0.2462
12	15	0.6718	0.5610	0.5563
13	1	0.2572	0.2032	0.2057
14	7	0.4503	0.4292	0.2574
15	23	1.0790	1.0830	0.7013
16	2.5	0.3343	0.2802	0.2648
17	15	0.5421	0.4362	0.4342
18	70	0.4717	0.3694	0.4033

The analysis by ANOVA was carried out with the run statistics and with the time spent and the results are presented in Tables 4 to 7. The most important parameters of scanning of the freeform part were the Positioning for mean, median and standard deviation, at 95% probability. It means that the smallest values of these statistics are determined when scanning in SINGLE mode, no matter which target or density of points are adopted. For the time spent in scanning, it was observed that Positioning, Density and the interaction of these two factors were important at 99% probability.

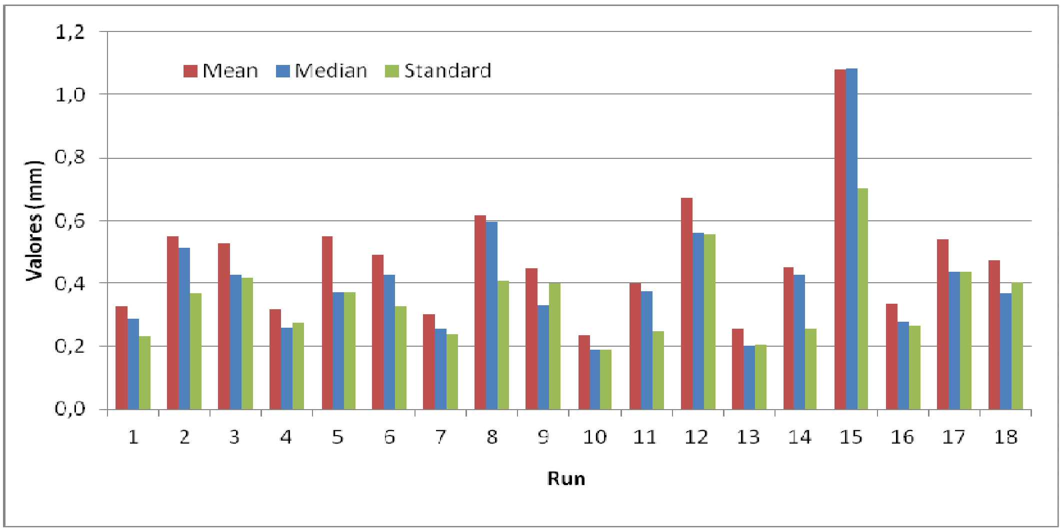

Figure 5. Comparison of the mean deviations, median and standard deviation in runs number 1 to 18.

Table 4. ANOVA results for scanning time.

Source	SS	DF	MS	Fc	Prob > F
Positioning	3977.444444	2	1988.722222	3.5×10^{15}	<.0001
Density	1748.777778	2	874.388889	1.54×10^{15}	<.0001
Target	0.000000	1	0.000000	0.00	1.0000
Positioning x Density	1915.555556	4	478.888889	8.42×10^{14}	<.0001
Positioning x Target	0.000000	2	0.000000	0.00	1.0000
Density x Target	0.000000	2	0.000000	0.00	1.0000
Residual	0.000000	4	0.000000		
Total	7641.777778	17			

Table 5. ANOVA results for mean.

Source	SS	DF	MS	Fc	Prob > F
Positioning	0.32182502	2	0.16091251	9.61	0.0297
Density	0.02093106	2	0.01046553	0.62	0.5806
Target	0.00543925	1	0.00543925	0.32	0.5993
Positioning x Density	0.09959713	4	0.02489928	1.49	0.3552
Positioning x Target	0.10921369	2	0.05460685	3.26	0.1446
Density x Target	0.02678805	2	0.01339403	0.80	0.5104
Residual	0.06700705	4	0.01675176		
Total	0.65080125	17			

Table 6. ANOVA results for median.

Source	SS	DF	MS	Fc	Prob > F
Positioning	0.26485680	2	0.13242840	8.17	0.0387
Density	0.02462395	2	0.01231198	0.76	0.5254
Target	0.01210568	1	0.01210568	0.75	0.4363
Positioning x Density	0.15953132	4	0.03988283	2.46	0.2024
Positioning x Target	0.11449832	2	0.05724916	3.53	0.1308
Density x Target	0.06328209	2	0.03164105	1.95	0.2562
Residual	0.06487267	4	0.01621817		
Total	0.70377084	17			

Table 7. ANOVA results for standard deviation.

Source	SS	DF	MS	Fc	Prob > F
Positioning	0.16194171	2	0.08097085	7.95	0.0404
Density	0.00198376	2	0.00099188	0.10	0.9093
Target	0.00275282	1	0.00275282	0.27	0.6306
Positioning x Density	0.02990697	4	0.00747674	0.73	0.6141
Positioning x Target	0.05079566	2	0.02539783	2.49	0.1981
Density x Target	0.00406042	2	0.00203021	0.20	0.8269
Residual	0.04073713	4	0.01018428		
Total	0.29217848	17			

The analysis of the results for variable Positioning is presented in Fig. (6), for mean, median and standard deviation. It was observed that the smallest results for mean, median and standard deviation were obtained using Positioning 1, e.g., with scanning in SINGLE positioning option at ScanStudio HD PRO. Positioning with options 360 - 4 divisions and 360 – 16 divisions were applied to the runner and the time spent in digitization was increased in respect to SINGLE, changing from maximum values of 2.5 min (SINGLE) to 15 min (360 – 4 divisions) and 70 min (360 – 16 divisions).

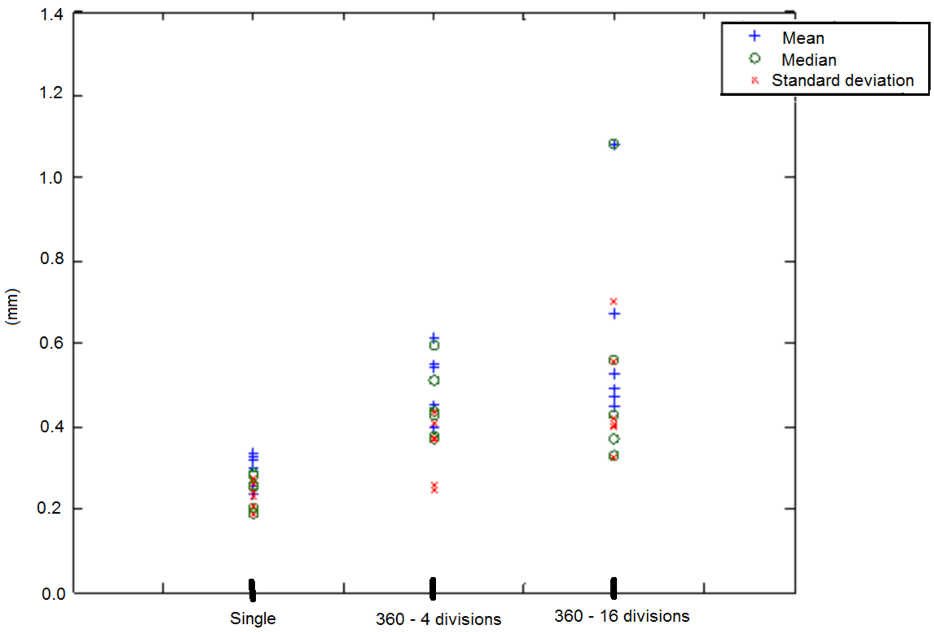

Figure 6. Comparison of mean, median and standard deviation for POSITIONING at levels SINGLE (1), 360 – 4 DIVISIONS (2) and 360 – 16 DIVISIONS (3).

4. CONCLUSIONS

An experimental approach was developed in search of the best scan condition of freeform jet ski runner. The deviations between the scanned points and the respective CAD model were determined to different conditions stablished by a factorial design of experiments with mixed number of levels. The analysis of the scanning variables was performed using ANOVA and the best scan condition in respect to the mean, median and standard deviation of the deviations and time spent in scanning was determined.

The first evaluation was carried out with the deviation points-CAD model and it was observed a non-normal probability distribution. This behavior was associated to the noise present in scan results and can be avoided by filtering the data obtained.

The ANOVA results points to the most significant factors, with 95% or 99% probability. For time spent in scanning, the positioning, the density of points and the interaction positioning x density had significant influence, at 99% probability. For mean, median and standard deviation, the variable Positioning was significant at 95% probability. In resume, the positioning at the single option produced the best results (smallest time, mean, median and standard deviation of the deviations points-CAD surface). This result could be associated to the alignment required when taking more than one view.

Future research may be carried out to investigate noise filtering and better alignment methods.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Barbero, B.R. and Ureta, E.S., 2011. “Compartive study of different digitization techniques and their accuracy”. *Computer-Aided Design*, **43**, 188-206.

Gestel, N.V., Cuypers, S., Bleys, P. and Kruth, J.P., 2009. “A performance evaluation test for laser line scanners on CMMs”. *Optics and Lasers in Engineering*, **47**, 336-342.

González-Jorge, H., Riveiro, B., Vazquez-Fernandez, E., Martínez-Sánchez, J. and Arias, P., 2013. “Metrological evaluation of Microsoft Kinect and Asus Xtion sensors”. *Measurement*, **46**, 1800–1806.

Guidi, G., Remondino, F., Morlando, G., Del Mastio, A., Uccheddu, F. and Pelagotti, A., 2007. *Performances Evaluation of a Low Cost Active Sensor for Cultural Heritage Documentation*. ETH: Zurich, Swizterlands.

Guidi, G., Russo, M., Magrassi, G. and Bordegoni, M., 2010. "Performance Evaluation of Triangulation Based Range Sensors". *Sensors*, **10**, 7192-7215.

Khoshelham, K. and Elberink, S.O., 2012. “Accuracy and Resolution of Kinect Depth Data for Indoor Mapping applications”. *Sensors*, **12,** 1437-1454.

NextEngine, *User’s guide*. November 25, 2009.

Piratelli-Filho, A., Zúñiga, L.D.O. and Arencibia, R.V., 2014. “Application of repeatability and reproducibility (R&R) tests for laser scanner 3D performance tests”. In *Proc. of the Congresso Nacional de Matemática Aplicada à Indústria, CNMAI.* Caldas Novas, GO, Brazil. (in portuguese)

Polo. M.E. and Felicisimo, A.M., 2012. “Analysis of Uncertainty and Repeatability of a Low-Cost 3D laser scanner”. *Sensors*, **12**, 9046-9054.

Sansoni, G., Trebeschi, M. and Docchio, F., 2009. “State-of-The-Art and Applications of 3D Imaging Sensors in Industry, Cultural Heritage, Medicine, and Criminal Investigation”. *Sensors,* **9**, 568-601.

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