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STUDY OF CONTACT AND NON-CONTACT MEASUREMENT TECHNIQUES APPLIED TO REVERSE ENGINEERING OF COMPLEX FREEFORM PARTS

Antonio Piratelli-Filho, pirateli@unb.br¹

Pedro Henrique Jobim Souza, jobimpedro@gmail.com¹

Rosenda Valdés Arencibia, arvaldes@mecanica.ufu.br²

Nabil Anwer, anwer@lurpa.ens-cachan.fr^{3,4}

¹Universidade de Brasília, Faculdade de Tecnologia, Depto. Engenharia Mecânica, 70910-900, Brasília, DF, Brazil

²Universidade Federal de Uberlândia, Faculdade de Engenharia Mecânica, Uberlândia, Brazil

³Université Paris 13, IUT Saint-Denis, Saint-Denis, France

⁴Ecole Normale Supérieure de Cachan, Laboratoire Universitaire de Recherche en Production Automatisée (LURPA), Cachan, France

Abstract: *This work addresses the problem concerning the reverse engineering of physical parts having complex freeform surfaces, starting from the shape measurement, data processing and part machining. The study was carried out with a small model of a sports car in scale 1:18. The model was measured using a Coordinate Measuring Arm (CMA) with contact probe and a three-dimensional laser scanner. Data was processed using a Computer-Aided Design (CAD) software and Non-Uniform Rational B-Splines (NURBS) curves and surfaces were fitted. The generated CAD model was adopted as reference to create a Computer-Aided Manufacturing (CAM) program for the reconstruction of a prototype of the original part. Aluminum and wood were used as materials to produce the prototypes in a numerically controlled (NC) machining center. The produced part was measured following the same methodology initially applied with original model and a comparison of produced and original model was carried out. The prototypes obtained by different techniques of measurement, non-contact (laser scanner) and contact (CMA), were also compared to determine the most efficient method concerning the accuracy, repeatability and costs. It was found that both measurement techniques are complementary and fusion of data obtained would be desirable in order to increase the accuracy and reduce the cost.*

Keywords: *freeform surfaces, CAD/ CAM, reverse engineering, coordinate metrology*

1. INTRODUCTION

Reverse engineering is the process of obtaining a geometric model from a real manufactured part acquired by 3D measurement techniques. The development begins with the point acquisition, followed by point processing (filtering, denoising, meshing, topology construction, registration) and by application of specific geometric model (model reconstruction, inspection, direct copying for machining or printing) [1].

Manufacturing technology is allowing the growing use of freeform surfaces in many applications. Some examples are related to the aerodynamic profiles of automobile bodyworks and aircraft wings and special types of lenses having aspherical profile. One specific market for these developments is the replication of models or prototypes of automobiles for production of molds and parts with fiberglass composites. The processing involves the measurement of the prototype to acquire surface information and fitting a Computer-Aided Design (CAD) model to data points. A Computer-Aided Manufacturing (CAM) process is used to produce the molds and to manufacture the parts starting from CAD model.

The precision of manufactured parts is a key issue and the reverse engineering process must provide suitable accuracy and repeatability. There are several sources of error in all steps of measurement and processing. The measurement of freeform surfaces presents a series of additional complications when comparing to simple or regular shapes. The manufacturing of parts presents deviations in respect to the reference CAD model used to implement the programming code in CNC machine tool. All these sources of errors must be considered when planning the process.

Savio *et al.* [2] presented an overview of the recent trends in measurement and inspection of freeform surfaces, classifying these efforts in direct and indirect comparison. The direct comparison is related to the verification of the surface against a master template, while the indirect comparison concerns the verification of the surface against a computerized CAD model. In both cases, the selection of the measurement instrument is performed according to the required accuracy and part dimensions.

According to the characteristics of the part under measurement, it is recommended the use of laser tracking interferometry, photogrammetry systems and laser radar to measure large parts. The use of Coordinate Measuring Machines (CMMs) is recommended when flexibility and accuracy are the key points. The application of Photogrammetry systems and interferometric techniques are recommended to inspect high precision optical parts. Other interferometric techniques as computer generated holograms (CGH), sub-aperture interferometry and curvature sensors are applied for quick measurement with sub-nanometer resolution. The technique of profilometry admits measurement with nanometric resolution. There are systems suitable for micro and nanoscale metrology, such as miniaturized probing systems, scanning

force microscopy and atomic force microscope. Besides, X-ray tomography and ultrasonic sensors complete the measurement options [2]. Some of these techniques were compared in respect to the accuracy during digitization [3].

A largely applied technique to measure freeform parts involves the use of CMMs. It requires the definition of a sampling strategy and the specification of the number and the location of the points over part surface. These points are used to fit the freeform curve or surface with CAD software. These CAD programs usually have algorithms that describe the surfaces by parametric representations as B-Splines and Non-Uniform Rational B-Splines (NURBS) [4]. Some applications require registration of different views of a given object that were measured with particular setups [5]. Separation of form from other geometries and elimination of outliers are carried out by filtering with linear, morphological, robust and segmentation methods. When alignment operations are required, a two-steps sequence involving coarse and fine alignment is recommended [2].

Errors or deviations between CAD model and data points are usually carried out by 3D colored maps. In addition, specific parameters may be determined and curvature evaluation may be presented in graphics using commercial CAD software. The uncertainty evaluation of freeform requires the knowledge of the error sources involved in measurement. These sources are composed by those present when measuring regular geometries with the consideration of probe tip radius compensation, errors associated to optical system measurement as local curvature and light scattering from surface, deformation effects and software errors originated from registration and filtering [2].

Manufacturing of freeform and complex parts is mostly carried out on 3-axis and 5-axis CNC machine tools. The 5-axis CNC machines have similarities in respect to 3-axis, as the three linear translation movements of 3-axis CNC machine tools, but additionally there are two rotation movements. The literature presents a comparison of these two types of machine tools and it was observed that 5-axis machines are capable of produce high precision freeform surfaces despite of 3-axis shows improved stiffness and lower cost [6]. The high-speed machining of complex surfaces were also addressed [7].

The machining operations involves the programming of the cutting tool path, the definition of the tool size and shape, the tool orientation, the spindle speed and the travelling velocity of the tool tip. The tool path planning is selected as a function of the surface quality and the time spent in manufacturing. The tool orientation is defined to reduce the time of operation and to avoid gouging. The tool geometry depends on which cutting operation was selected and the type and the size are established to reduce the tool switch and the total machining cost. The machining operations may be classified as rough, semi-finish, finish, clean-up, final polishing and treatment. These operations are planned to avoid the presence of gouges that occurs with undesired contact between the tool and the part. The gouge sources were investigated and classified as local, rear or global, according to the function of the tool section that is causing the defect [6]. Zou *et al.* [8] presented an approach to optimize the tool path planning in CAM Processing of freeform surfaces.

There are some examples in literature of CAD/CAM processing and reverse engineering. A comparison of three commercial CAD/CAM systems applied to manufacture titanium dental restorations was carried out by Witkowski *et al.* [9]. A denture framework was manufactured by CAD/CAM rapid prototyping process [10]. The approach to design a dental prosthesis was presented by Song *et al.* [11]. The investigation of a dental freeform surface manufacturing was presented by Rudolph *et al.* [12] where the quality of digital data, surface type and teeth shape were established. The performance of measurements carried out with an AACMM to CAD modeling of a dental prosthesis was studied by Piratelli-Filho and Motta [13]. A study of turbine runner reverse engineering was performed with an AACMM [14]. Topics related to the measurements, CAD model fitting and CAM processing are under investigation by authors [3, 6].

This work addresses the problem of the reverse engineering of models having complex freeform surfaces, starting from the measurement, the data processing, the CAD modeling and the fabrication of replicates by CAM techniques. The error sources of the different processing steps were investigated and a comparison of the results from two different measuring systems, contact and non-contact, was performed.

The paper is organized as follows: Section 2 describes the experimental procedure detailing the measurement and processing steps. Section 3 presents CAD/CAM processing results, e.g., the CAD models and the generated surfaces. Section 4 presents the analysis and discussion of the deviations between CAD and machined surfaces. Section 5 gives conclusions.

2. EXPERIMENTAL PROCEDURE

A small prototype having freeform surfaces was used to carry out experimental tasks. A model of a sports car in scale 1:18 was used as prototype. The car bodywork was made with rigid plastic and had dimensions nearly 300 x 150 mm. The white color on the bodywork prevailed and some details in blue and black were also found. This information is important when dealing with non-contact measurements like laser scanner. The measurement was conducted using two methods, contact and non-contact.

Contact measurement was carried out with an Articulated Arm Coordinate Measuring Machine (AACMM), Romer model Arm 100, with a spherical work volume with 2.5 m in diameter. The machine performance was established by the expanded measurement uncertainty (95%) of 0.060 mm in length and the probe repeatability uncertainty (95%) of 0.016 mm. A needle stylus rigid probe was coupled to the arm extremity to capture the point coordinates on the surfaces. The AACMM was operated by the software G-Pad and information about data points and calculus was stored as IGS format file. Special attention was given to variables related to the part stiffness, elastic deflection during fixation over AACMM base and probe contact during force. Fixation was done by three treaded bolts under the car model joining with a steel support.

The strategy involved the scratching a series of lines in a transversal direction of the car body and demarking the point locations where coordinate information would be acquired. Forty four transversal lines were scratched on the surface with variation in the distance depending on the curvature of the surface. The lines referred to the curvatures of the profiles were also determined. Only half of the surface was measured to build the other part by mirroring. The groups of points obtained were saved and exported in IGS data format. Figure (1) shows the car bodywork with the measurement strategy scratched over the surface.

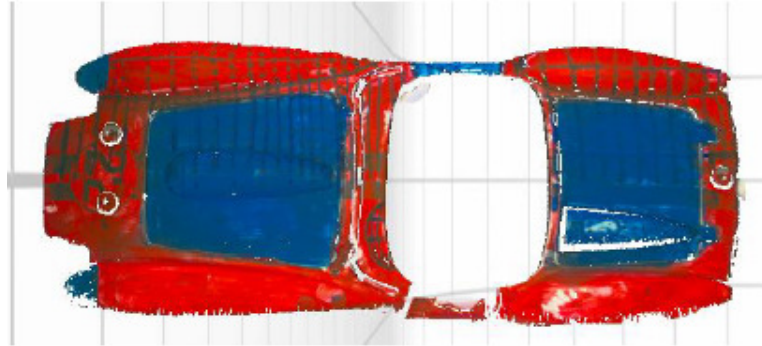


Figure 1. Prototype with designed strategy to carry out measurement with AACMM.

Data was imported by Rhinoceros Software and an initial verification of outliers was carried out observing the control points and respective curves. When there are two curves for the same region, the command *Mean curve* was used to obtain one single curve, deleting the originals. The command *snap* was applied to join the curves that are in sequence but were measured separately. The commands *Loft*, *Sweep two rails* and *Patch* were used to build the surfaces. A plane was determined with mean reference points to obtain the other side of the car bodywork and to apply mirroring by *mirror* command. The resulting CAD model was exported in *parasolid* format.

Non-contact measurement was performed with a laser scanner, NextEngine 3D Desktop HD, model 2020i. This scanner has four sources of laser with 10 mW each and a wavelength of 0.650 μm . The determination of the coordinates is performed by laser triangulation. Two modes of operation were available, Macro and Wide, and the density of points during measurement is 248 points/ mm^2 (Macro) and 35 points/ mm^2 (Wide). The scanning speed is 50,000 processed points per second, with a precision stated by manufacturer (standard uncertainty) of 0.127 mm (Macro) and 0.381 mm (Wide).

The first step in measuring was to observe the surface color and visual aspect and evaluate the need for painting. Dark surfaces, as well as reflexive or transparent ones, in general, do not produce good results and there is a need of painting the surface to improve the quality of the results of scanning. In this case, neutral and light colors as white or gray are very desirable to be applied to recover the surface but it depends on availability and price. The prototype used in this work was recovered with low cost gouache paint in colors red along scanning desired regions and dark blue on others. The prototype was positioned in vertical direction over the scanner rotating base at 400 mm from the scanner unit, as showed in Fig. (2.a), configuring the mode Wide in measurement.

Data points were obtained with the software ScanStudio HD, selecting the mode 360 to measure the part in all angles and the number of divisions was stated equals to 8. The scanning area was selected on computer screen and then the measuring process had started. The cloud of points obtained was then converted in a mesh that was reprocessed with the ScanStudio to eliminate the undesirable parts like fixation and scanner base and align and fuse the different meshes obtained (admitted tolerance equals to the uncertainty in Wide mode, 0.381 mm). The fused mesh was exported by ScanStudio and imported by other software, RapidWorks, to refine and create the NURBS surface. The command *decimate* was applied to simplify and standardize the mesh, followed by *Healing Wizard* used to fill voids and correct defects. The command *Smooth* was applied to remove irregularities of the mesh and finally *Auto surfacing* was used to create the NURBS surface (CAD model) that was exported in *IGES* format.

The part was produced using a numerically controlled three-axis CNC Machining Center, from Feeler model Fv-1000 with Mitsubishi M6 command, showed in Fig. (2.b). The machine work volume was 1000 x 500 x 505 mm, with the tool displacement in axis x, y and z, respectively. Parts of a maximum 500 kg in weight are admitted over its 475 mm x 1150 mm base. The CNC machine spindle speed may be controlled between 50 and 8000 rpm and the feed rate may be adjusted at a maximum of 10000 mm/min. The CAM processing admits the specification of until 22 different tools, automatically changed during processing. The average time spent in changing the machining tools was stated by manufacturer as nearly 11 seconds.

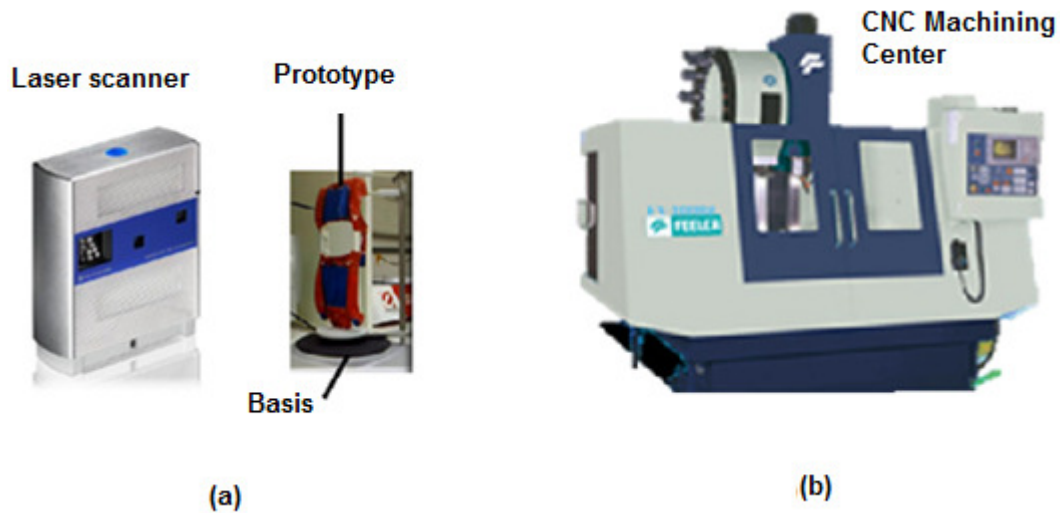


Figure 2. Laser scanner 3D and prototype positioned to carry out measurement (a) and CNC Machining Center (b).

The control and implementation of processing CNC program was carried out using software SURFCAM. The variables like the tool type, the tool path, the number of steps and the machine spindle rotation were controlled by lines written in the software language. A simulation of the processing may be carried out by software before machining the surface. The first step was the conversion of the data file *parasolid* format by using *open* command, showing the CAD model on the computer screen. The required volume of the material was defined by the command *create/line/rectangle* that presented a region with dimensions of the material block used to machine the surface. The control of machine tool parameters was performed by the *operation manager* window, according to the following description.

The first step was selecting the rectangle created by using the menu *setup one*, with the command *edit setupinformation>stock* and selecting the *geometry Bounding Box*. The machining operations with respective tools are presented in Tab. (1). First, a rough machining operation was implemented with command *NC>3 axis>Z roght*, where the tool type, rotation, cutting speed and others were defined and the tool path was automatically created and showed on computer screen. The commands *Z finish*, *Planar* and *Contour 2D* were selected to define the pre-finishing and finishing operations. The G-code was then created with menu *Operation Manager*, selecting *ArcFltr* and *Post* in sequence, following the steps demanded by the software to define *Fanuc01* language and coordinate system *54*. The code was automatically generated and showed on screen by a pop-up window, after that it was saved and sent to the CNC machine tool to begin the machining.

Table 1. Machining operations and tools used.

Operation Number	Tool Number	Tool Comments
1	15	Coromill 16
2	5	6 mm – 4 flute – HSS Ballmill
3	5	6 mm – 4 flute – HSS Ballmill
4	17	Topo 27.6

The surface was fabricated using blocks of aluminum and wood that were attached rigidly to the machine tool table. The CNC Machining Center was turned on and reset by pressing the *zrn* button. The longitudinal block dimension of the aluminum and wood blocks were aligned to the machine tool *x* axis using a dial gauge and the origin of the coordinate system was transferred to the block. The machining program was loaded into the memory card of the CNC Machining Center and the production began.

The analysis of the part produced was performed determining the deviations in respect to CAD freeform surfaces. The first analysis was applied to investigate the deviations between the measured points and the fitted CAD model. The second analysis was applied to investigate the deviations between the points measured on manufactured CAM surface and the CAD model. The deviations between CAD model and data points were carried out with Rhinoceros software (data from AACMM and laser scanner).

In respect to AACMM data, the fitted curves were selected on the computer screen and the points were extracted by the command *Extract points* in the *Curves* software menu. In respect to laser scanner, data file was imported and points were presented on screen. The deviations in both cases were determined comparing the points with the CAD model using the command *Point set deviation*. Analysis was presented by plotting deviation intervals with different colors over the CAD model of the propeller and pointing the deviations with respective locations over the CAD surface. Statistical parameters as mean, median and standard deviation were determined to comparison.

3. CAD/CAM PROCESSING RESULTS

The points determined with AACMM were fitted to NURBS curves as showed in Fig. (3.a). The surfaces generated as description are presented in Fig. (3.b). The grid lines show the mesh obtained with Rhinoceros to represent the freeform surface as a NURBS model. The NURBS surface showed uniformity with a few distortions in mesh caused mainly by the designed measurement strategy. The NURBS curves generation was carried out manually and the deviations may be reduced by a careful adjustment. Figure (4) presents the CAD model obtained with data from laser scanner.

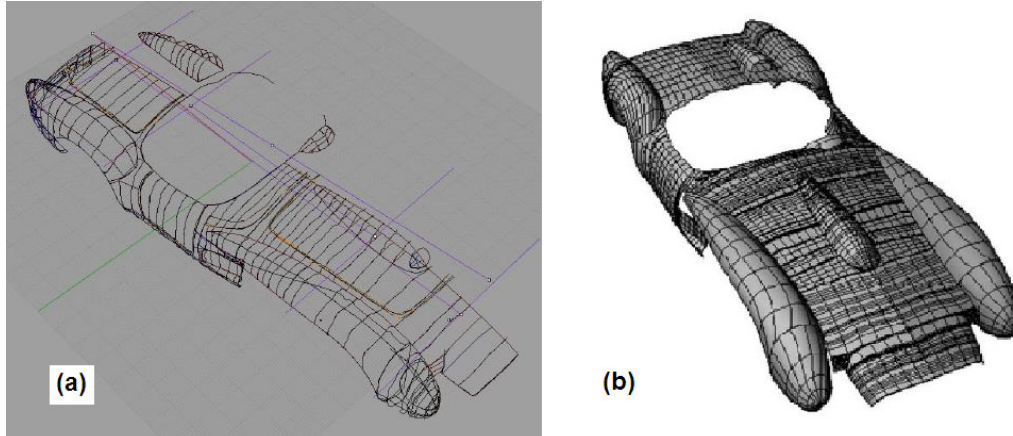


Figure 3. Raw data from AACMM measurement (a) and fitted CAD model (b).

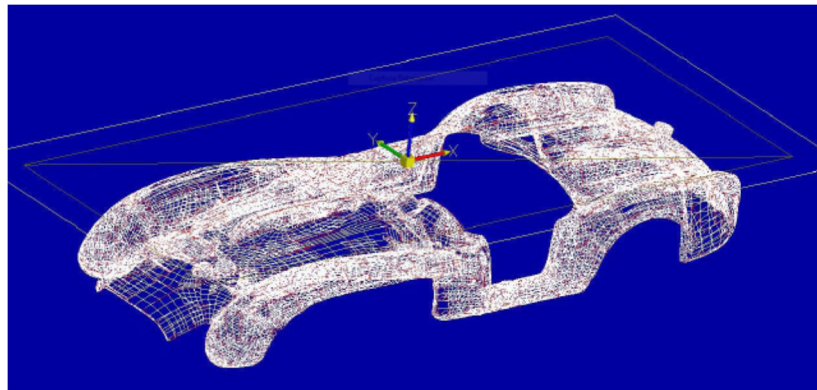


Figure 4. CAD model from laser scanner measurement.

Figure (5) shows the tool path generated by SURFCAM software. The red lines represent the paths along with the tool was moved during machining operations. The shaded portion in blue color represents the block and the light green indicates the car bodywork under machining.

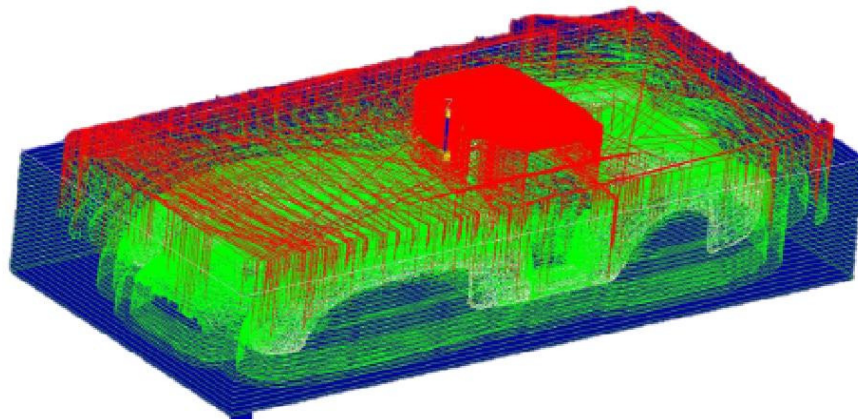


Figure 5. Path followed by machining tool (red) during CAM manufacturing.

The Computer-Aided Machining (CAM) processing was performed in four steps, the rough, finish, planar and contour operations, as showed in Tab. (2). The processing variables as plunge rate, feed rate and spindle speed were established to reduce time spent in machining and the adopted values at each operation is showed in this table. The minimum and maximum coordinates in the x, y and z axis of the machine tool shows the moving range during the steps of processing. The saved G-code program having this parameters configuration had 197,466 lines and the implementation CNC machine tool resulted in 72 minutes and 19 seconds to manufacture the car bodywork, disregarding the time between tool changes. This time between tool changes was about 10 seconds and the CNC machine executed the changes automatically. It was observed that rough operation was the most time consuming than the others.

Table 2. Machining steps during fabrication of the surface.

Tool	Operation	Plunge Rate (mm/min)	Feed Rate (mm/min)	Spindle Speed (rpm)	Min X	Min Y	Min Z	MaxX	MaxY	Max Z	CycleTime (min:s)
15	3 Axis Z Rough	3000.000	3700.00	6000	-124.101	-67.587	-25.000	136.671	66.353	8.000	27:36
5	3 Axis Z Finish	2500.000	2500.00	6000	-116.100	-49.987	-45.000	119.079	48.755	33.000	18:52
5	3 Axis Planar	2000.00	4000.00	6000	-116.150	-49.949	-35.000	119.128	48.550	13.000	20:31
17	2 Axis Contour2D	1211.000	3433.00	4500	-132.200	-64.200	-45.000	132.200	64.200	25.000	5:19
Overall					-132.200	-67.587	-45.000	136.671	66.353	33.000	72:19

The sculpted surfaces are presented in Fig. (6), in wood (a) and aluminum (b). It may be observed small irregularities in the details of the machined surface that may be explained by the limitations of the machine and the geometry of the used tool. The secondary surfaces applied to join together two primary ones showed good aspect in a visual analysis and an additional quantitative verification is demanded.



Figure 6. Wood (a) and aluminum (b) replicates obtained by CAM manufacturing.

4. DEVIATION ANALYSIS AND DISCUSSION

Figures (7) and (8) present the deviations of the measured data points (AACMM and laser scanner) in relation to the created CAD model (complete surface). In both cases, it was observed a large amount of points remaining in the interval between 0 and 0.1 mm (blue). There are some points located at the edges, details and secondary surfaces that presented deviations bigger than 0.5 mm (red), mainly on surface determined by the AACMM. As a consequence, the standard deviation of AACMM CAD model was 0.170 mm and of laser scanner CAD model was 0.282 mm. This may be related to the accuracy of the measuring instrument and to the adjustment of CAD models to NURBS surfaces. The difficulty observed when positioning the AACMM probe stylus on curved surfaces during measurement of secondary surfaces and details of model has influence on deviations, as well as the reduced number of points acquired in relation to laser scanner that limited the precision of the curves fitted in the CAD model. The CAD model from AACMM measurements was selected to carry out the CAM processing and it was the reference to the analysis of CAM model.

Figures (9) and (10) show the deviations between the adopted CAD model and the data points determined over the CAM manufactured surfaces (complete surface). As observed, the deviations of CAM surface manufactured in aluminum present better uniformity, with most deviations lying between 0 and 0.1 mm and small amount above 0.4 mm. By the contrary, the CAM surface manufactured in wood presented a large variability, with deviations distributed in all intervals (colors). This is reflected in standard deviation determined, and the aluminum part showed a standard deviation of 0.101 mm and the wood part was equal to 0.254 mm.

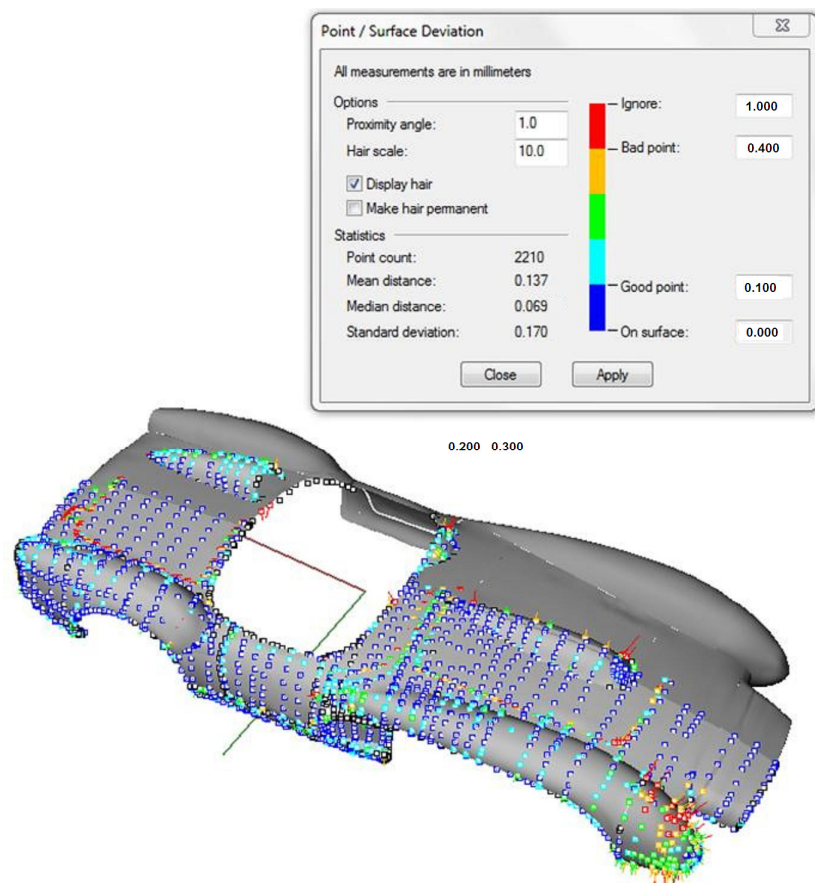


Figure 7. Deviations of AACMM measured points from fitted CAD model.

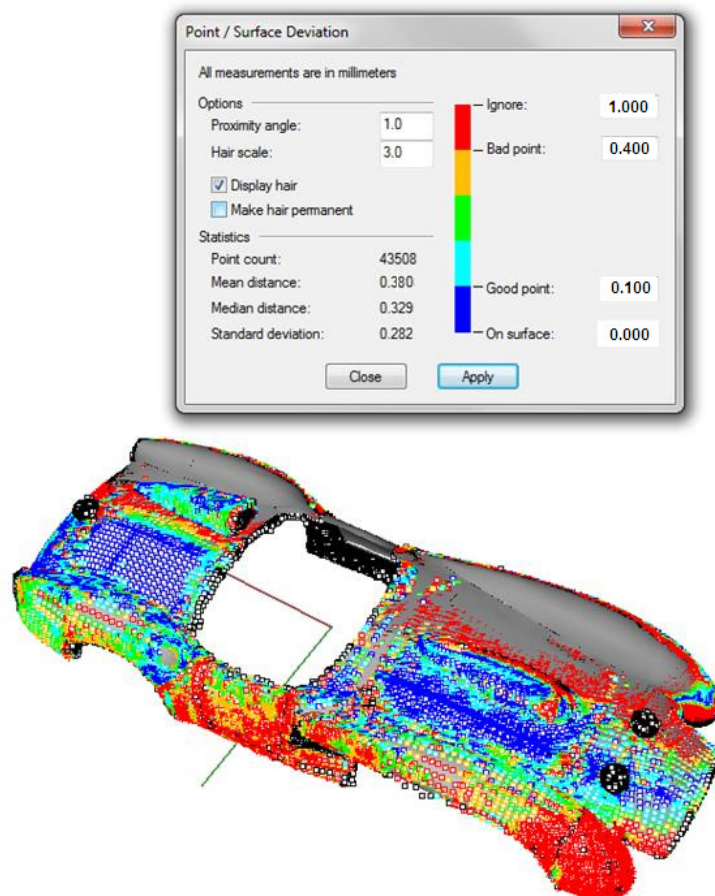


Figure 8. Deviations of laser scanner measured points from fitted CAD model.

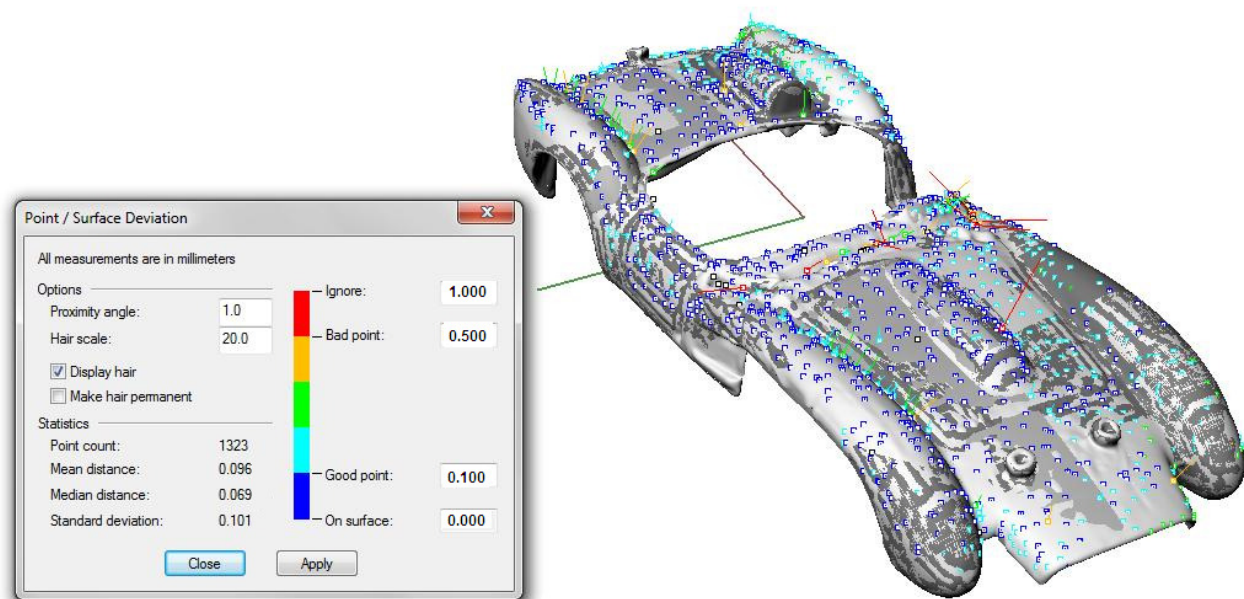


Figure 9. Deviations of CAM manufactured surface in aluminum.

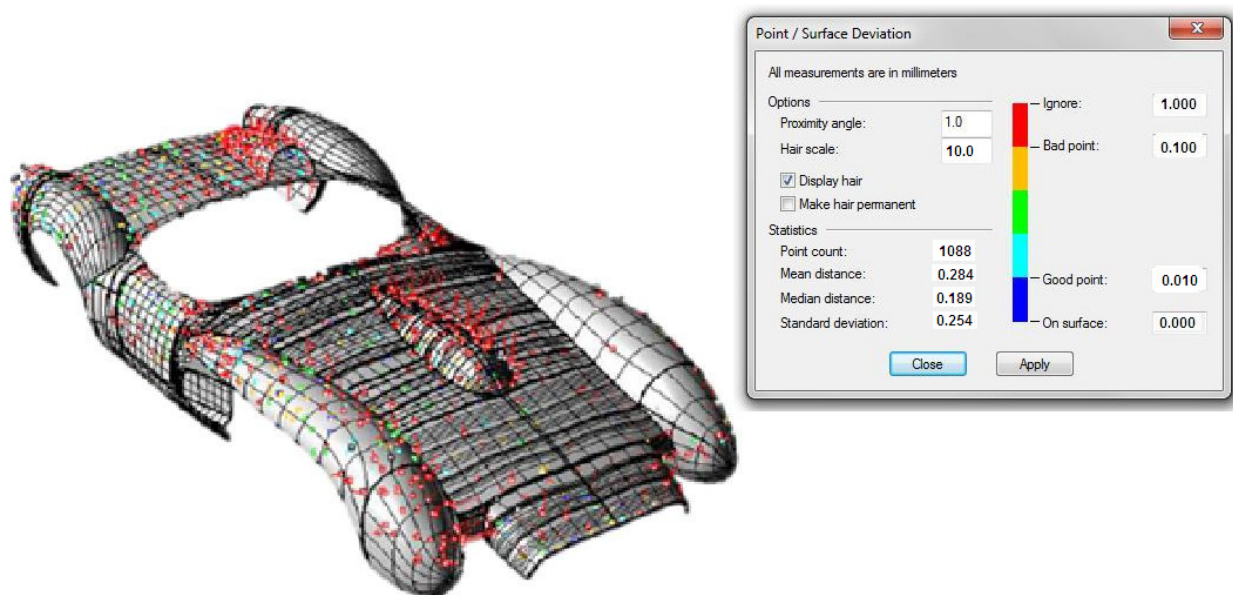


Figure 10. Deviations of CAM manufactured surface in wood.

5. CONCLUSIONS

Reverse engineering techniques were applied to produce models with freeform surfaces through CAD/CAM processing of a sports car prototype. The CAD and the CAM processing were evaluated by determining the deviations between the measured points on part surface and CAD fitted model (CAD analysis) and between the measured points on CAM machined surface and CAD fitted model (CAM analysis). The standard deviation was adopted as measure of quality of these steps.

The CAD model fitted from AACMM data points presented a standard deviation smaller than the respective from laser scanner cloud of points, as it were 0.170 mm and 0.282 mm, respectively. Thus, the measurement with the AACMM contact probe is most suitable when accuracy and precision are key issues. The standard deviations of CAM manufactured surfaces in aluminum and wood presented values as 0.101 mm and 0.254 mm, respectively. These differences were associated mainly to the stiffness of the material, as the Elastic modulus of aluminum is bigger than the wood. The sources of errors that caused this difference were related to the machining forces that deformed elastically the block of the material during fabrication and the forces due to the contact and the fixation during the measurement with AACMM, at the final verification step.

A research topic under investigation that can increase the machined part uniformity and the repeatability of the data points is the data fusion technique. This technology involves mixing the two different types of measurements performed, e.g., mixing data from laser scanner and AACMM before fitting the CAD model. Besides, the increase in quality of the manufactured part may be obtained through using CNC machine tools with 5-axis.

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7. REFERENCES

- [1]. Raja V., Fernandes, K. J. Reverse engineering: an industrial perspective. Springer series in advanced manufacturing, 2008.
- [2]. E. Savio, L. De Chiffre, R. Schmitt, Metrology of freeform shaped parts, *Annals of the CIRP* 56 (2007) 810-835.
- [3]. B.R. Barbero, E.S. Ureta, Comparative study of different digitization techniques and their accuracy, *Computer-aided Design* 43 (2011) 188-206.
- [4]. L.A. Piegl, W. Tiller, *The NURBS Book*, Springer, Berlin, 2nd Edition, 1997.
- [5]. H. Zhao, N. Anwer, P. Bourdet, Curvature-based Registration and Segmentation for Multisensor Coordinate Metrology, *Proceedings of the CIRP* 10 (2013) 112-118.
- [6]. A. Lasemi, D. Xue, P. Gu, Recent development in CNC machining of freeform surfaces; a state-of-the-art review, *Computer-aided Design* 42 (2010) 641-654.
- [7]. L. Tapie, B. Mawussi, B., A. Bernard, Topological model for machining of parts with complex shapes, *Computers in Industry* 63 (2012) 528-541.
- [8]. Q. Zou, J. Zhang, B. Deng, J. Zhao, ISO-level tool path planning for free-form surfaces, *Computer-Aided Design* 53 (2014) 117-125.
- [9]. S. Witkowski, F. Komine, T. Gerds, Marginal accuracy of titanium copings fabricated by casting and CAD/CAM techniques, *The Journal of Prosthetic Dentistry* 96(1) (2006) 47-52.
- [10]. R.J. Williams, R. Bibb, D. Eggbeer, J. Collis, Use of CAD/CAM technology to fabricate a removable partial denture framework, *The Journal of Prosthetic Dentistry* 96(2) (2006) 96-99.
- [11]. Y.L. Song, J. Li, L. Yin, T. Huang, P. Gao, The feature-based posterior crown design in a dental CAD/CAM system, *International Journal of Advanced Manufacturing Technology* 31 (2007) 1058-1065.
- [12]. H. Rudolph, R.G. Luthardt, M.H. Walter, Computer-aided analysis of the influence of digitizing and surfacing on the accuracy in dental CAD/CAM technology, *Computers in Biology and Medicine* 37 (2007) 579-587.
- [13]. A. Piratelli-Filho, J.M.S.T. Motta, Performance of CAD model recovering method based on CMA measurement and NURBS modeling applied to small free form surfaces, *Ciência & Engenharia* 16(1/2) (2007) 67-72.
- [14]. A. Piratelli-Filho, J.A. Araújo, A.C.P. Brasil-Junior, Reverse engineering of hydraulic turbine runners using coordinate measuring arms and NURBS modeling, *Revista Tecnologia* 30(1) (2009) 114-122.