MEASUREMENT OF A SMALL DENTAL PROSTHESIS USING COORDINATE MEASURING ARMS

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Abstract. *Many cases in restorative dental practice may require the substitution of the original tooth by prosthesis fabricated with metal alloys or ceramic materials. A characteristic of tooth surface is that it has a form not defined by a simple mathematical equation and then it is classified as a free form surface. The small dimension of this part is an adverse characteristic that difficult the measurement process involved in recovering its form to perform quality control and reverse engineering processes. Digitization procedures as laser scanning are usually reported as suitable to carry out this task and it results in large samples of points on the surface that are adjusted to create Computer Aided Design (CAD) models. However, these procedures are expensive as demanding high cost equipment. This work investigates the measurement of small free form surface using a coordinate measuring arm with contact probe. The free form surface of a tooth prosthesis was used to the development of the measurement strategy. The prosthesis was measured on a Coordinate Measuring Arm (CMA) using a needle type stylus and a rigid type probe. Two strategies were performed: determining small amount of points along selected paths and determining large samples of points using automatic measurement on CMA. The samples of points exported in IGES format file were used to build the tooth model using CAD software. Error analysis of CAD models was carried out and it was observed that small samples resulted in a suitable CAD model of the small free form surface investigated.*
Key-words: *quality control, free form surfaces, dental prosthesis measurement*

1. INTRODUCTION

Many cases in restorative dental practice may require the substitution of the original tooth by prosthesis fabricated with metal alloys or ceramic materials. Nowadays, there are processes using Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) technologies to design and produce these prosthesis and the process begins with the measurement of a sample prosthesis[(1)]. Different CAD/CAM processes are used to produce crowns and dentures and they differ in production speed, accuracy, materials used, esthetics and implementation[(1)].

The implementation of these CAD/CAM processes may be carried out by reverse engineering techniques. Reverse engineering is considered as a discipline that begins with measurement of the part to be manufactured and requires the development of a CAD model, the development of a CAM program and the manufacturing of a new piece to finally submit to the measurement process[2]. This technology has successfully been applied to create a three-dimensional model of dental prosthesis[1].

A dental prosthesis may be characterized as having a surface not defined by a simple mathematical equation and it is classified as a free form surface. Its small dimension is another characteristic that makes difficult the recovering of the tooth form trough a measurement process and CAD/CAM fabrication. Feng and Pandey[3] carried out a experimental study using design of experiments on a Coordinate Measuring Machine (CMM) and found that the dimension of the measured part significantly affects the digitization uncertainty. The form tolerance of this free form surface is reduced and the selection of the measurement instrument is carried out considering the accuracy, data acquisition process and CAD processing characteristics.

The measurement of small free form surfaces may be performed using CMMs with contact or non-contact probe. The use of non-contact probe on a CMM was reported by Zou et al[4] to control the form quality of a molar tooth surface. Digitization procedures are employed to carry out this task and laser scanning is reported as a suitable technique that generates large samples of points (point cloud) of the surface. The use of contact probes restrict the amount of data generated and increases the time spent in measurement, but it has the advantages of been more accurate and repeatable[2].

The CAD models are created using the measured data and a software using non-uniform rational B-splines (NURBS) has been recommended to generate free-form surfaces[5]. Two different approaches are referred in literature to address the creation of CAD models: curve-net-based method and polygon-based method. Curve-net-based method requires the determination of groups of points that are adjusted to generate the CAD surface. Polygon-based method involves the determination of large samples of points (point cloud) that are manipulated and adjusted to generate surfaces. Both approaches are finalized after the creation of a NURBS surface. According to Zhongwei[6], polygon-based methods are fast and efficient but curve-net-based approach results in more accurate CAD models that can still be modified after conclusion.

There are many sources of errors in CAD modeling process, as calibration of CMM probe, CMM accuracy, accessibility of the surface, part fixture and surface finish, noise, measurement strategy, CAD surface adjustment, among others[2]. Feng and Pandey[3] presented a study to investigate the impact of CMM parameters on digitization uncertainty using design of experiments. Huang, Gu and Zernicke[7] presented an approach to compare two free-form surfaces based on a reference surface model. A direct verification of the CAD model may be carried out using commercial software and it is performed by graph comparison of the measured points with the adjusted model, e.g., determining the deviations of the CAD surface generated.

A review of free form surface inspection was recently carried out and presents contact and non-contact measurement methods and geometric processing steps[8]. According to Li and Gu[8], future research on free form surface will focus on the increase of accuracy and efficiency and the reduction of the cost of inspection. To address the last issue, new methods may be developed to recover the original surface using instruments having small cost and high flexibility.

This work investigates the measurement of small free form surfaces using a CMM with contact probe. The free form surface of a plaster made tooth prosthesis was used to the development of a measurement strategy. The prosthesis was measured on a CMM type articulated arm (Coordinate Measuring Arm – CMA) using a needle type stylus and a rigid probe. Two approaches were implemented: i) determining small amount of points along selected paths on surface; ii) determining large amount of points using automatic measurement on CMA. The samples containing the determined points were exported in IGES (Initial Graphics Exchange Specification) format file and used to reconstruct the tooth geometry using CAD software. Analysis of CAD model adjustment errors was carried out to compare these different measurement approaches.

2. MEASUREMENT OF SMALL FREE FORM SURFACES USING CMA

The experimental work was carried out on a Coordinate Measuring Machine type articulated arm (Coordinate Measuring Arm - CMA) fabricated by Romer, model ARM 100. This CMA has a volumetric reach of 2.5 m and an accuracy of 0.07 mm. A rigid probe with a needle type stylus was connected and G-Pad software was used to acquire the coordinates of points on the part surface. Figure 1 shows the experimental setup.

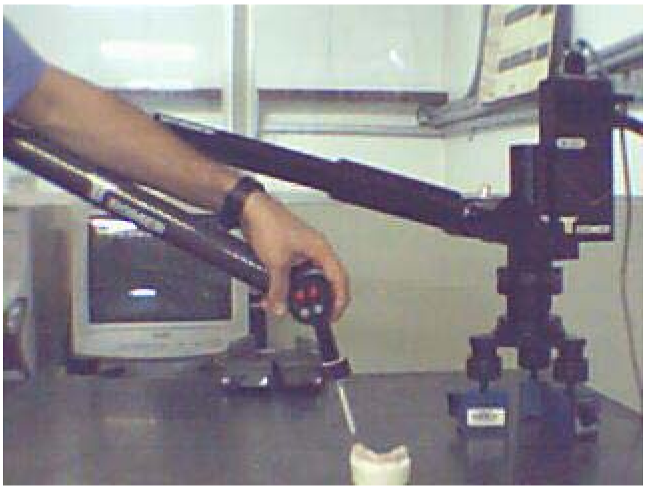

Figure 1 – CMA positioned to measure dental prosthesis.

The measurements were performed on a plaster made dental prosthesis with dimensions about 10 x 7 x 8 mm, fixed on the surface of a nylon plate and clamped on a cast iron measuring table, as shown in figure 2. Two different measurement strategies were applied at which the CMA stylus had touched the prosthesis surface at an angle of 90^o, both strategies using contact measurement.

Figure 2 – CMA stylus touching a sample of dental prosthesis

The first measurement approach was applied drawing a grid of lines on the surface of the prosthesis. The grid was designed tracing parallel lines on the surface, in two perpendicular directions. It was observed that the regions with accentuated curvature required finely divided grid to increase the accuracy of the model developed. Groups of points were determined guided by CMA G-Pad software and according to an adopted direction of measurement. It was determined 12 groups of points with 23 points each and 3 groups of points with 22 points each, resulting in 342 measured points. Each group of points was adjusted as a polyline curve by the CMA software.

The second measurement approach was carried out without pre-established sequence of measurement. Automatic measurement option of CMA software was used to capture groups of 200 points at random sequence on prosthesis surface. The beginning and the end of the measurement process was activated pushing the gray button at CMA probe and careful positioning of the needle on the surface was fundamental to the success of these procedure. It was determined a group with 1000 points and other with 2000 points of the prosthesis surface.

Point-to-point and automatic measurements required a precise control of the probe stylus to reach contact during all the measurement process. In both methods, the determined points were stored in files as IGES format. Two adjustment methods were used to create CAD models, according to the measurement methods adopted: curve-net-based method and polygon-based method.

Curve-net-based method was applied in conjunction with point-to-point measurement procedure, determining groups of points for each line traced on the prosthesis surface. These groups of points were adjusted as splines and exported as IGES format. In this approach, Rhinoceros software was used to generate CAD models, as it is a curve-net-based software that works with NURBS (non-uniform-rational B-splines). Starting from splines or polylines, adjusted with the measured groups of points, the software builds NURBS curves and surfaces to create a CAD model. The pre-processing of measured data was investigated in this approach, adjusting the lines imported to NURBS curves using rebuild and refit-to-tolerance options.

Polygon-based method was carried with data obtained using automatic measurement option at G-Pad software. The determined point clouds were transformed in polygonal surfaces that were adjusted and improved to finally generate a NURBS model at Rhinoceros software.

An error analysis was performed to verify the created CAD models, comparing the measured points with the respective CAD model generated. A tolerance of 0.5 mm was considered as reference to inspect the adjusted surfaces.

3. RESULTS

The dental prosthesis was measured to adjust curve-net-based and polygon-based CAD approaches. These approaches are presented and compared using respective CAD model and error analysis. As all points used to construct the models and to carry out analysis were determined at the same coordinate reference system, it was not necessary to perform localization step as explained by Li and Gu(8). It must be observed that the CMA uncertainty estimation was 0.07 mm, performed by Romer manufacturer performance test. These uncertainty value is attributed to point uncertainty in work space. In literature, there is an application of standard ANSI/ASME B89 that can be used to carry out CMA performance verification(9).

3.1. Point-to-point measurement and curve-net based approach CAD models

After measurement, groups of points were obtained and exported as IGES files. These IGES files were imported by Rhinoceros and Figure 3 shows the curves and points on CAD software screen. These curves may or not be pre-processed before generate CAD models. Pre-processing involved the adjustment of these polylines using Rhinoceros commands *rebuild* and *refit-to-tolerance*. The *Rebuild* command converts the previous curves (polylines) in NURBS curves, developing a 3rd degree polynomial with 10 control points. *Refit-to-tolerance* command converts original curves in NURBS curves, adjusting these curves with a tolerance of 0.01 mm. The *loft* command was used to build a NURBS surface that is represented by the net showed in figure 4, in which the *loose* option and a grid with 25 points were selected.

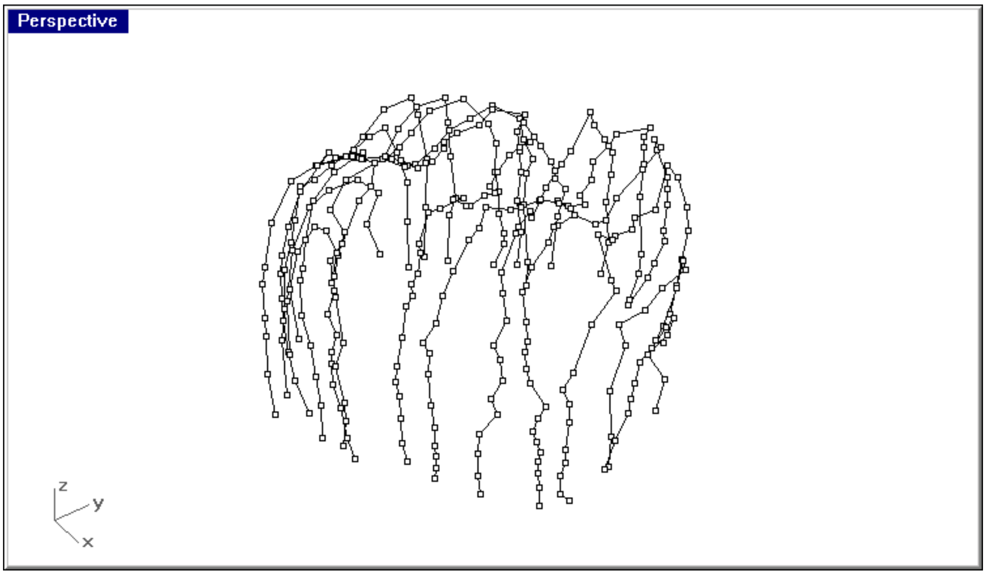

Figure 3 – Points with adjusted polylines.

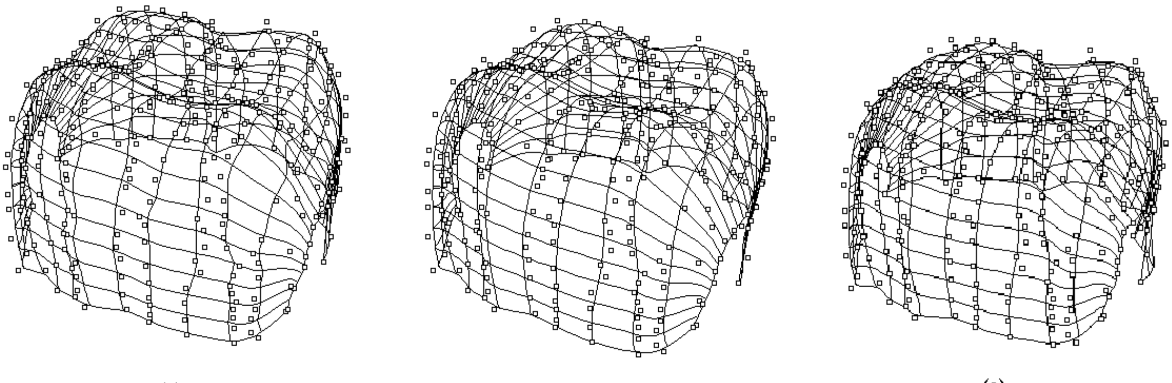

Figure 4 - NURBS surface developed using: a) lofted polyline curves; b) rebuilt polylines and lofted to surface; c) refitted to tolerance polylines and lofted to surface.

Figure 5 shows the shaded NURBS surfaces created. As shown, there are small differences among these CAD models, evidenced at vertices of the dental crown. Quantitative error analysis was performed and it is shown in figures 6, 7 and 8. As observed, the CAD models contains the great majority of measured points having errors smaller than 0.5 mm, as 334, 334 and 335 of 343 points (97.7%, 97.7% and 98.0 % respectively) appeared within adopted tolerance. A small portion of these points was not considered (2.3%, 2.3% and 2%). It is shown that average distances and standard deviations were 0.07 and 0.06 mm to the first adjusted model (lofted polyline curves), 0.08 and 0.08 mm to rebuilt polyline curves and lofted to surface, and 0.08 and 0.08 mm to refitted-to-tolerance polyline curves and lofted to surface.

Observing these figures it can be seen that models with pre-processed data (rebuilt and refitted-to-tolerance polylines) presented small amount of deviations of magnitude between 0.2 and 0.4 mm (denoted by colors green and orange) and between 0.4 and 0.5 mm (red), proved by the standard deviations. These small deviations may be related to the smoothing of surfaces during adjustment of curves and it is nearly the same as the first lofted polyline curves (without pre-processing). It must be still observed that these standard deviations were of the same magnitude of the CMA uncertainty, stated by the manufacturer.

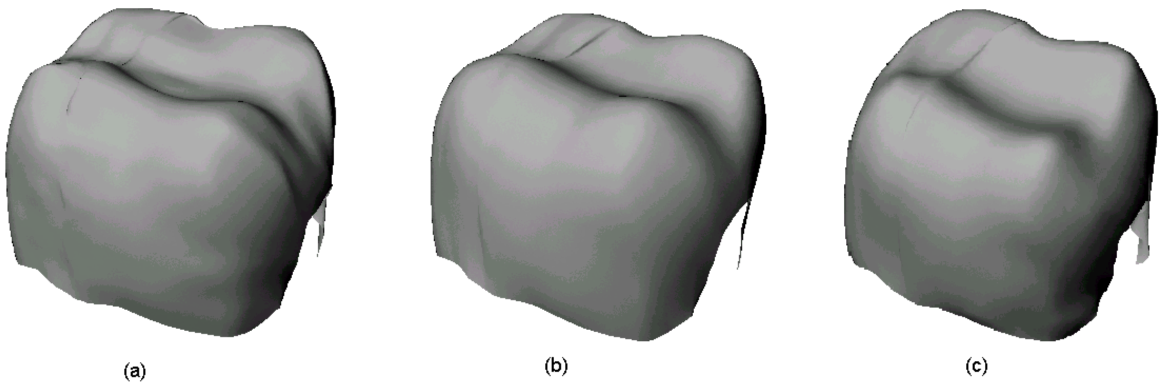

Figure 5 – Shaded NURBS surfaces of: a) polyline curves lofted; b) rebuilt polylines and lofted; c) refitted to tolerance polylines and lofted.

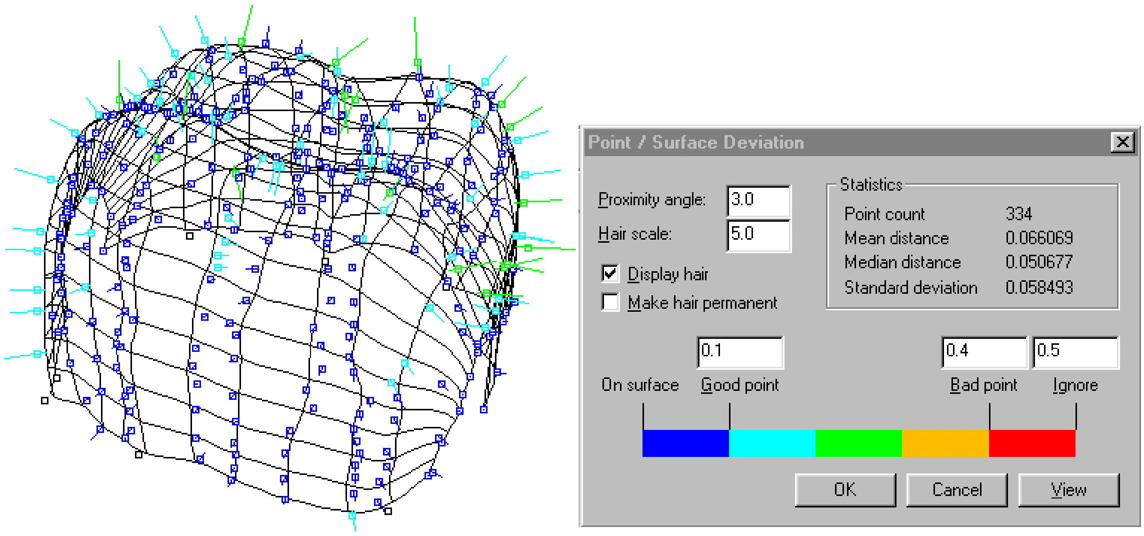

Figure 6 – Error analysis of NURBS surface without pre-processing (polyline lofted).

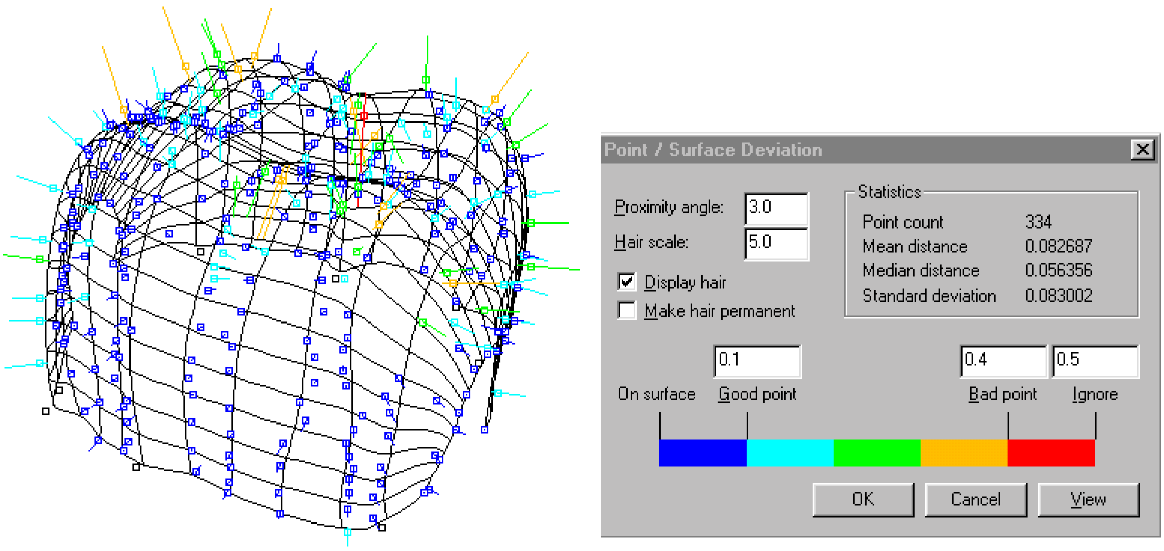

Figure 7 – Error analysis of NURBS surface with pre-processing (rebuilt option)

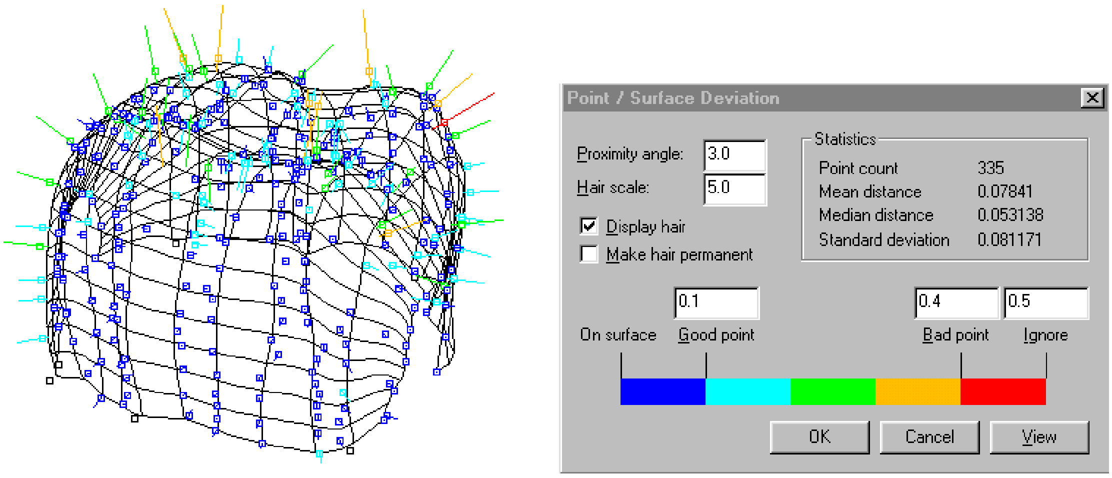

Figure 8 – Error analysis of NURBS surface with pre-processing (refitted-to-tolerance option)

The comparison of pre-processing methods applied showed small differences as the CAD model deviations presented nearly the same standard deviation, but it must be pointed out that models without pre-processing may have outstanding defects.

3.2 – Automatic measurement and polygon-based approach CAD models

Measurement with automatic option on CMA was used to collect large samples of data points. Two point clouds were obtained having 1000 and 2000 points and they were saved as IGES format files. These files were opened in CAD software and the steps of *wrap, polygon mesh, grids* and NURBS generation were performed in this sequence. The *wrap* command was applied to create polygons with data points. Polygon model was relaxed and spikes were eliminated to construct patches and grids. NURBS surfaces were fitted with 6 control points and tension 0.25. The CAD models generated were saved in IGES format file. The adjustment errors of these surfaces were verified using Rhinoceros software and figures 9 and 10 show error analysis of 1000 and 2000 points NURBS surfaces.

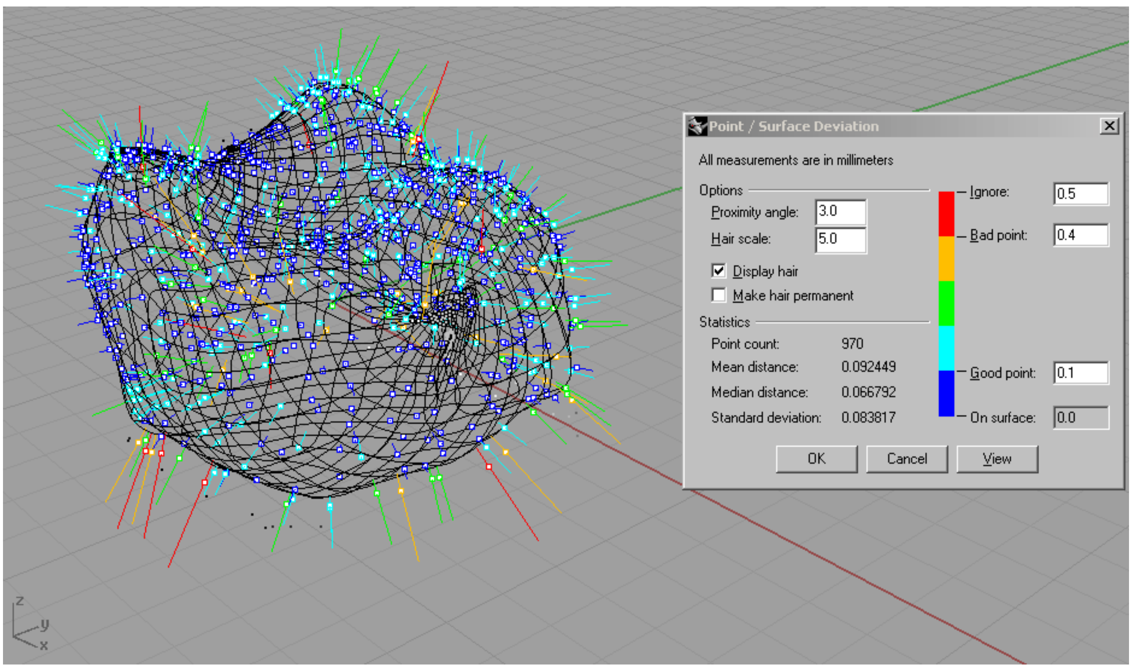

Figure 9 – Error analysis of NURBS surface with 1000 points

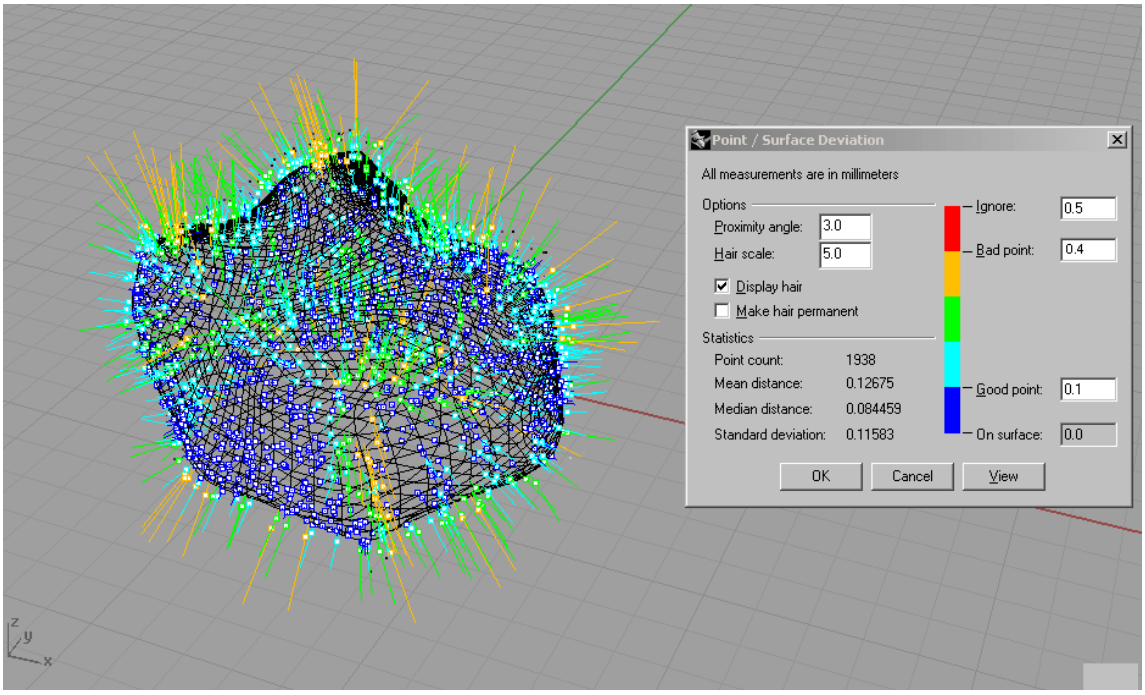

Figure 10 – Error analysis of NURBS surface with 2000 points

As observed, these models display the great majority of measured points having errors smaller than 0.5 mm, as 970 of 1000 and 1938 of 2000 points (97.0% and 96.9 % respectively) lies into adopted tolerance. A small portion of points was discarded (3.0% and 3.1%). It is shown that average distances and standard deviations were 0.09 and 0.08 mm to the first adjusted model (1000 points) and 0.13 mm and 0.12 (2000 points). Observing these figures it can be seen that the model with 2000 points presented the same average and standard deviation as the 1000 points model.

Comparing curve-net-based approach and polygon-mesh approach, similar results were obtained to an established tolerance of 0.5 mm. The models showed good agreement and both approaches applied are recommended to build CAD models of small dental prosthesis. Error analysis showed a small amount of points lying out of 0.5 mm tolerance. Nevertheless, the point-to-point method required less time to perform CAD reconstruction and it was less error prone in the measurement step.

4. CONCLUSION

Measurement of small free form surfaces had presented some difficulties when using contact measurement. Accessibility of the surface by CMA stylus is restricted in small dimension part and the operator skill is an important variable to achieve representative samples of points. Even so, the methodology was suitable to the development of representative CAD models.

Two measurement strategies were implemented to carry out measurement of small free-form surfaces like a dental prosthesis using a CMA and rigid probe, point-to-point measurement with curve-net-based approach and automatic measurement with polygon-based approach. It was observed that the increase in amount of points determined by contact measurement increased the dispersion in relation to the CAD model. An advantage of contact method over non-contact ones that must be pointed out is the reduced cost of the CMAs. It was observed that point-to-point measurement was the most suitable method to create a CAD model of the small free form surface as it requires nearly the same time of measurement and less time of CAD processing, having adjustment errors of the same magnitude as automatic measurement.

The sequence of this work is been directed to investigate the development of CAM programs to prototype manufacturing. Besides, the analysis of the uncertainty associated to the CMA and to CAD models is an interesting research topic.

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