Proceedings of the ASME 2021
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC-CIE2021
August 17-19, 2021, Virtual, Online

DETC2021-71724

TOWARDS A BUILDING TECHNIQUES OF A BREP MODEL STARTING FROM A MESHED SURFACE

Nessrine ELLOUMI
SETIT, University of Sfax, 3000 Sfax, Tunisia

Aicha BEN MAKHLOUF
LATIS, ENISo, University of Sousse, 4023 Sousse, Tunisia

Borhen LOUHICHI
LMS, ENISo, University of Sousse, 4023 Sousse, Tunisia

Dominique DENEUX
CNRS, UMR 8201-LAMIH, Univ. Polytechnique Hauts-de-France, F-59313 Valenciennes, France

ABSTRACT

For several years, research has been brought to reconstruct a Computer Aided Design (CAD) model from a 3D mesh or point cloud produced by scanning techniques or CAD software. This process, which recreates the geometry of a real part is called Revere Engineering (RE). In the industry, RE enables designers and engineers to virtually simulate, test and validate products before the manufacturing process. Therefore, it is common to use a reconstruction algorithm to rebuild a CAD model of a real object with high quality. This technique solves several problems of exchanging geometric models in engineering, computer vision, computer graphics, 3D animation, medical, mechanic, virtual/ augmented reality, etc. Therefore, CAD model reconstruction promotes the integration of 3D data without recopying or manual transformations and facilitates the visualization and simulation of the deformed model behavior.

The aim of this work is how to rebuild a CAD model starting from a deformed mesh. The complexity of this problem requires to be split into several complementary parts. 3D surface reconstruction is considered as the most difficult step to obtain this geometric model. This paper consists in presenting an original method to reconstruct a CAD model surface (NURBS surface) starting from a triangulation (meshed surface) as a main step of the geometric model reconstruction.

Keywords: Integration, CAD, Analysis, Finite Elements, Triangulation, Surface, NURBS.

1. INTRODUCTION

Computer-Aided-Design (CAD) model reconstruction [1] has an important impact in several different fields (artistic, medical, mechanic, Building Information modeling, etc.). Nowadays, the majority of manufactured objects are designed by CAD (Computer Aided Design) software. In general, these models are defined by geometric information that presents the geometric nature of surfaces and curves (primitives, curves and parametric surfaces and topological information that presents the connectivity, links and orientations of the different entities (faces, wires, edges and vertices).

In the literature, several methods have been developed in order to reconstruct 3D curves [2] and surfaces [3] given point cloud/ 3D mesh. The main objective of these studies is how to reconstruct 3D models with good precision and efficient quality. According to the 3D reconstruction application, an adequate technique should be developed. For example, in manufacturing processes, the continuous representation may be discretized into 3D meshes composed of a finite number of vertices and edges in order to render, exchange and simulate the model. In some situations, the initial model may be lost or unavailable. In other cases, the discrete 3D representation can be modified or deformed, by numerical treatments, and no longer correspond to the initial model. Thus, a reverse engineering method is necessary in order to reconstruct a continuous 3D representation from a discrete representation.

Reverse engineering [4] [5] is used in several fields such as mechanical, electrical, computer vision, medical, etc. The main purpose of RE is to analyze an existing product and produce a copy or an improved version [6]. The aim of this work is to reintegrate the CAD model, which is reconstructed from the finite element results (deformed mesh) into the design tool (CAD) in order to give the designer quantitative means of validation of the designed model.

The remainder of this paper is organized as follows: Section 2 reviews the related works. Section 3 describes the proposed algorithm in details. Section 4 provides the experimental results and a comparison with another method mentioned in the state of the art. Finally, Section 5 concludes the paper.

2. STATE OF THE ART

The 3D reconstruction, refers to the techniques that represents an object or a scene from a cloud of points or a 3D mesh. In the first hand, several algorithms have been developed to generate the CAD model given a set of 3D points. Nina Amenta et al. [7] have developed an approach called Crust algorithm in order to reconstruct 3D surfaces from a point cloud. Their approach is based on Delaunay triangulation and the Voronoi diagram. The Crust algorithm consists of four steps: the first step is the generation of a Delaunay triangulation based on the cloud of points; the second step consists in the calculation of the Voronoi poles. Then, the Delaunay triangulation is constructed based on the points cloud and the Voronoi poles defined in the previous step. Finally, the "Voronoi filtering" step is executed. The advantage of the Crust algorithm consists of fitting closed or open surfaces. However, this approach depends on the number of input points.

The Ball-Pivoting algorithm (BPA) [8] is a robust method which calculates a triangular mesh interpolating a given point cloud. The principle of this method is very simple: three points form a triangle if a ball of a radius specified by the user touches them without containing any other point. Starting from an initial triangle, the ball rotates around an edge while keeping contact with the ends of the edge until it touches another point, forming another triangle. The process continues until all accessible edges are tried, then starts from another triangle, until all points are considered. This method is used to find a triangle of the mesh by interpolating the set of points. This algorithm has been applied to data sets containing millions of points that represent 3D scans of real complex objects.

The Poisson method [9] reconstruct a 3D model given a set of unorganized points by calculating an indicator function χ which has the value 1 at the points inside the model and 0 at the external points. The reconstructed surface is obtained by extracting an appropriate isosurface. The main idea of this method is that there is an integral relationship between the oriented points sampled from a surface of a model and the indicator function of the model. Specifically, the gradient of the indicator function is a vector equal to zero almost everywhere except at points close to the surface, where it is equal to the normal of the interior surface. The Poisson method is robust and it is able to recover fine details from 3D scans. However, to use this method, oriented points are needed. Otherwise, it is necessary to calculate the normals of the points by specific method or software.

Aurélien BEY et al [10], have addressed the problem of rebuilding CAD models from point clouds acquired in the industrial environment. They focused on CAD models described as assemblies of simple geometric primitives such as planes, cones, cylinders and tori. Each of these primitives is a geometrical object entirely characterized by a position and an orientation, as well as a number of geometrical parameters. Moreover, Huang and Menq [11] proposed an original method to reconstruct a CAD model given a set of points basing on a novel scheme which is composed mainly of three steps. In the first step, multiple point clouds are integrated into a watertight triangle mesh in order to recover the shape of the scanned object incrementally. In the second step, the segmentation of the mesh is applied in order to extract and obtain the individual geometric features. In the final step, the connectivity information between the geometric surfaces is extracted and a mathematical description corresponding to each geometric feature is calculated.

In addition, authors in [12] introduced a new method to reconstruct an arbitrary topological surface given a set of unorganized points. This surface had three representations, namely, quadrilateral mesh, Catmull-Clark subdivision surface and the B-spline surface as presented in Figure 1.

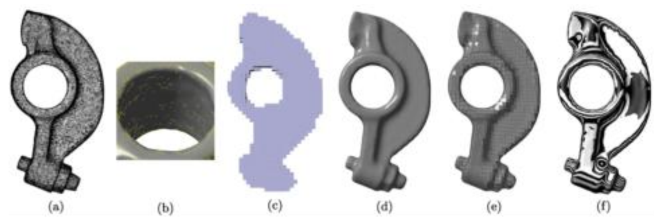

FIGURE 1: RECONSTRUCTION OF THE ROCKER ARM MODEL: (A) SET OF 3D POINTS. (B) SPARSE REGION. (C) VOXEL MODEL (D) CATMULL-CLARK LIMIT SURFACE. (E) QUADRILATERAL MESH. (F) B-SPLINE SURFACE [12]

In the other hand, reconstruction of the CAD model given a 3D mesh, different researches have been developed. In 2012, Wang et al., [13] proposed a method to reconstruct 3D models given 3D meshes (Figure 2). This method is composed of four main steps: First of all, the input mesh must be examined in order to eliminate noise. Second, the mesh is segmented to obtain individual geometric entities. Then, two methods are integrated: a method based on solid entities and a method based on surface entities, to reconstruct primitive entities from the geometric entities segmented in the previous step. Finally, modeling operations, such as surface cutting operations, are performed to combine the primitive entities in order to obtain the final model.

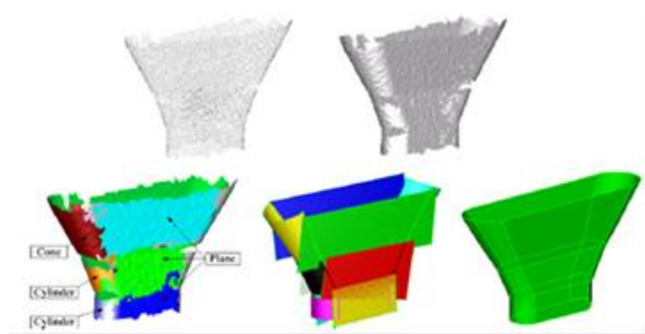

FIGURE 2: VALIDATION OF CAD A MODEL RECONSTRUCTION [13]

In 2013, Beniere [14] proposed a method to reconstruct the CAD model given a 3D mesh. The algorithm is divided into three steps (as illustrated in figure 3). The first step consists of the extraction of geometric primitives and the reconstruction of the corresponding surfaces (planes, cylinders, spheres and cones). In this step, curvature is used to identify the shape around each vertex. Then, the vertices belonging to each entity are detected and grouped together and the surface parameters are calculated for each point zone.

In the second step, the topology of the B-Rep model is constructed by extracting the neighborhood relationships between surfaces. The wire of each surface is then computed from the intersections between adjacent primitives. Finally, in the third step, the information extracted or reconstructed during the two previous steps is combined to rebuild a coherent B-Rep model. The drawback of this method is that the studied geometric primitives are limited to planes, spheres, cones and cylinders.

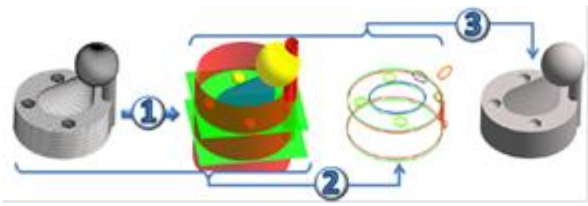

FIGURE 3: OVERVIEW OF THE RECONSTRUCTION METHOD PROPOSED BY BENIERE [14]

Later, Louhichi et al [15] have proposed a method to reconstruct a geometric model from a deformed mesh based on the approximation of the parameters (control points) of a B-Spline surface. The algorithm has as inputs an initial CAD model, an initial mesh and a deformed mesh. To reconstruct the different deformed surfaces, a method based on weighted displacement estimation is proposed. The aim of their proposed work is to solve the problem of unorganized points of the deformed meshed surface. The founding hypothesis of the method is that the topology of the model must be preserved after deformation. Thus, the number of faces and edges of the reconstructed deformed CAD model must be the same as the number of faces and edges of the initial model before deformation. Only the geometrical information of the B-Rep model must be updated to obtain the deformed CAD model.

In the same context, Ben Makhlouf et al. [16] proposed an original method to reconstruct a geometrical model given a deformed mesh. This method is mainly based on the optimization of surface control points using the iterative algorithm of Levenberg Marquardt. Given a set of unorganized points extracted from the deformed mesh the algorithm calculates in each step the distance between the interpolation points and the reconstructed surface. The calculated distance is minimized until the optimized parameters approximating the point cloud are obtained. This method is optimal and robust since it converges after few iterations even if the initial parameters are far from the result. Another approach based on the Thin Plate Spline method (TPS) [17] is then proposed to solve the problem the unorganized set of points. This method calculates the regular lattice of points in order to approximate the B-Spline surface parameters. The advantage of this method is that it approximates the 3D surface even if the input points are non-regular. The evaluation of the error between the interpolation points and the reconstructed surfaces demonstrates the performance of the proposed approach to reconstruct deformed CAD models.

3. PROPOSED APPROACH TO REBUILD A CAD MODEL GIVEN A DEFORMED MESH

The reconstruction of a CAD model from the 3D mesh [18] [19] has become more and more important in integrated design, notably by the simulation in real time of the design process and/or the manufacturing of 3D products. The simulation of 3D models produces visible deformations, which degrade the generated 3D mesh quality and sometimes makes it invalid (Figure 4). To resolve the above problem, 3D mesh should be reconstructed in the simulation process. Around the permanent deformations, not only the mesh must be recalculated but the boundary conditions must also be repositioned on the new form of the model. Within a context of integrated design, the boundary conditions are captured on the CAD model That's why, the deformations of the finite element model must be transmitted to the CAD model in order to take into account the new boundary conditions.

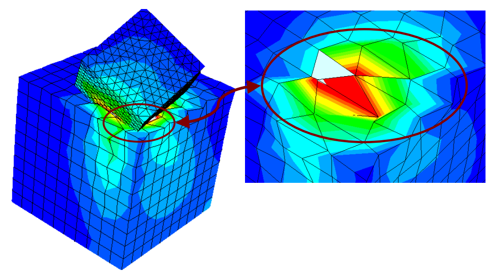

FIGURE 4: INVALID MESH

Nowadays, 3D model study which is based on numerical simulation is proceeded while considering the original model. The reconstruction of the CAD models from the analysis results tends to raise this limitation and makes it possible to visualize and simulate the behavior of 3D models in their deformed configuration (normal operating state) and to detect possible interference effects, which are undetectable in the non-deformed state.

3.1 General algorithm to reconstruct the CAD model

The general algorithm described by Louhichi et al. [20] represents the different steps in order to reconstruct a CAD model from a deformed mesh (Figure 5). The main steps of this algorithm are the following:

- Identification of the triangulation associated with each face of the model.
- Reconstruction of the bearing surfaces corresponding the faces.
- Reconstruction of the wires, edges and vertices for each intersection of the reconstructed faces.

This paper presents an original approach to reconstruct a CAD model from a network of points extracted from a 3D mesh. The proposed approach is validated on different 3D models (section 4).

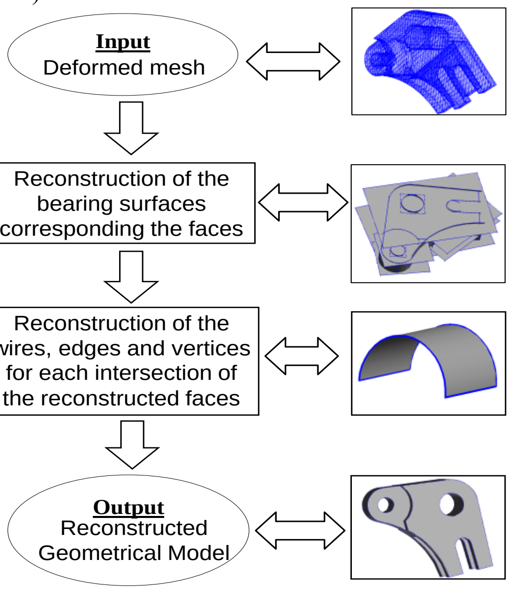

FIGURE 5: GENERAL RECONSTRUCTION ALGORITHM

3.2 Proposed algorithm to reconstruct a CAD face from triangulated surface

The proposed approach consists of the following steps: Extracting geometric points from the nodes of the meshed face, building a regular network of points using the coordinates of the extracted points, and then applying NURBS model to fit these regular points into a mathematical surface which interpolate the deformed CAD surface [21] [22] (Figure 6.). The main problem of this approach is the construction of the regular points.

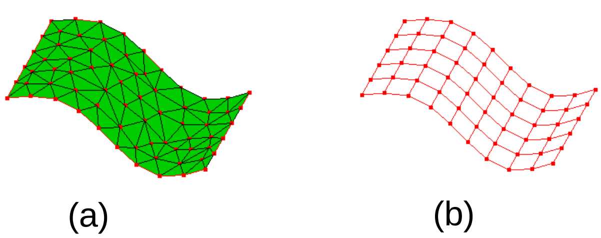

FIGURE 6: (A) TRIANGULATION, (B) REGULAR BASE OF POINTS

The developed algorithm (Figure 7) is based on the parameterization of the surface before and after deformation (displacement of the nodes) [18] [19].

The steps of the algorithm are:

- Construction of a regular network of points on the non-deformed face in its parametric space (u, v).
- Determination of this network in real space (x, y, z) to obtain the base grid of points on the non-deformed mesh in 3D space.
- Calculation of the network of points by interpolation of the deformed real surface using the Walton's algorithm (as detailed in section 3.2.2).
- Determination of the control points of the NURBS (deformed surface) from the points calculated in the previous step [24].

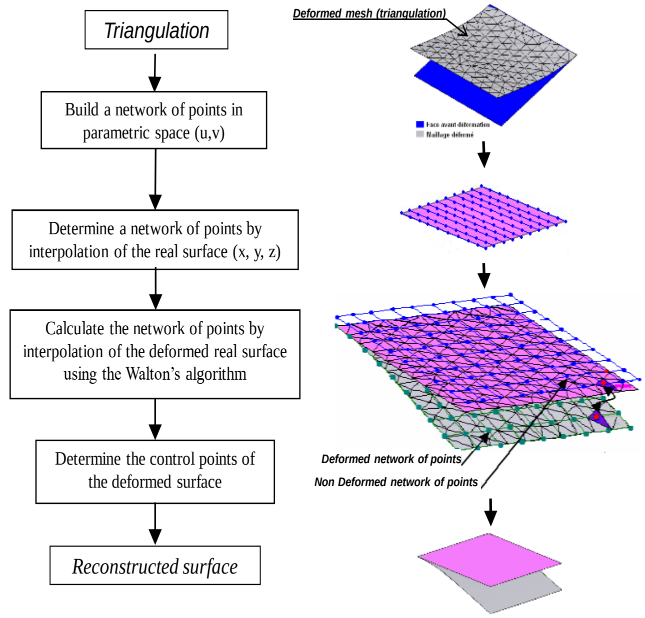

FIGURE 7: ALGORITHM FOR RECONSTRUCTION OF A SURFACE BY TRIANGULATION

The third step of the algorithm is based on Walton's algorithm [24] presented is the next section.

3.2.1 Walton's algorithm

Walton [24] developed an algorithm for evaluating a Bézier surface from a triangle in the corresponding mesh. Steven [25] subsequently improved this algorithm.

The algorithm consists of two steps:

1. Calculating for each nodes of the triangulation, a vector which represents the normal in this node at the reconstructed surface (Figure 8).

The normal at a meshed surface in a node P is defined as follows:

$$N_p = \sum_{i=1}^{n} N_i * w_i \quad (1)$$

Where :

n : is the number of triangles belonging to the surface which has as its vertex the node P.

N_i : are the normal vectors at the triangles that have as a vertex the node P.

w_i : are the weighting coefficients associated with the normal vectors N_i, defined as follows:

$$w_i = \frac{\alpha_i}{\sum_{i=1}^{n} \alpha_i} \quad (2)$$

α_i are the angles at point P of the triangles that have as their vertex the point P.

2. Given a triangle defined by three points P0, P1 et P2 and three vectors N0, N1 et N2, the portion of the surface that will be reconstructed corresponding to the selected triangle is evaluated using the following equation:

$$S(u,v,w) = \sum_{i+j+k=4} P_{i,j,k} \frac{4!}{i!\,j!\,k!} u^i v^j w^k, \quad (3)$$
$$u,v,w \geq 0; \quad u+v+w=1; \quad i,j,k \geq 0$$

Where u, v and w : are the coordinates of a point in the triangle (Figure 16).

$P_{i,j,k}$: are the control points (Figure 9) of a surface portion (Bezier surface calculated from a triangle), depending on P0, P1, P2, N0, N1 and N2.

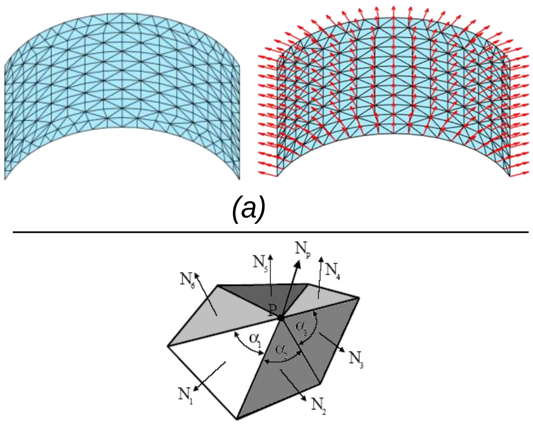

Figure 8: THE NORMAL VECTORS CONSTRUCTION

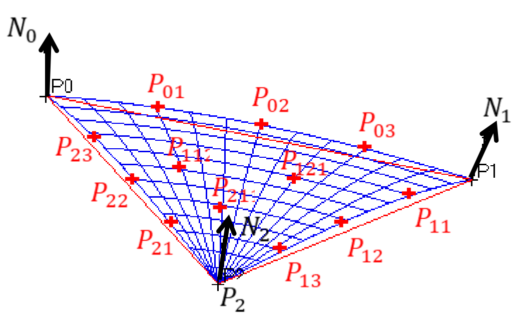

Figure 9: CONTROL POINTS OF A BEZIERS TRIANGLE

3.2.2 Adaptation of the Walton's algorithm

Walton's algorithm evaluates the surface locally for each triangle of the mesh. The third step of the proposed algorithm repeats the following steps for each the interpolation point:

1. Calculate the local coordinates of the point (non-deformed base) projected in the triangle (non-deformed mesh) ***u***, ***v*** and ***w***.
2. Insert a point, which has as its coordinates ***u***, ***v*** and ***w*** in the same triangle of deformed mesh by projecting the point of the non-deformed mesh on the deformed mesh.
3. From the inserted point, determine the base interpolation point (u,v,w) on the reconstructed surface by Walton's algorithm [24].

4. EXPERIMENTS

4.1 Surface reconstruction validation

To validate the proposed approach, a planar face (Figure 10) is reconstructed. The dimension of the face is around 10^5 mm, the displacements of the nodes are around 10^4 mm. The errors of the meshed nodes with respect to the reconstructed surface are presented in Array 1:

Array 1: ERRORS IN THE MESHED NODES WITH RESPECT TO THE RECONSTRUCTED SURFACE

Number of nodes	Number of interpolation points	Max Error	Min Error	Average of the errors	Deviation Type
139	*121*	*0.11 mm*	*3.9 10^{-6} mm*	*1.4 10^{-2} mm*	*2.2 10^{-2}*

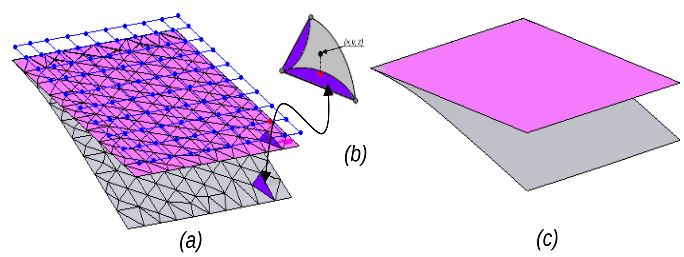

Figure 10: PROCEDURE FOR EVALUATION AND RECONSTRUCTION OF A SURFACE.
(A) DEFORMED AND NON-DEFORMED MESH, (B) SURFACE EVALUATED FROM A TRIANGLE, (C) RECONSTRUCTED SURFACE

In the above example, the errors are acceptable with respect to the dimensions of the surface.

The second example presents a cylindrical face (Figure 11) reconstruction. Given that the dimension sizes of the face and displacement are around 10^5 mm, the errors are acceptable since they are around 100 mm (Array. 2).

Array 2: ERRORS IN THE MESHED NODES WITH RESPECT TO THE RECONSTRUCTED SURFACE

Number of nodes	Number of interpolation points	Max Error	Min Error	Average of errors	Deviation Type
135	*121*	*1.5 mm*	*2.7 10^{-3} mm*	*0.4 mm*	*0.3*

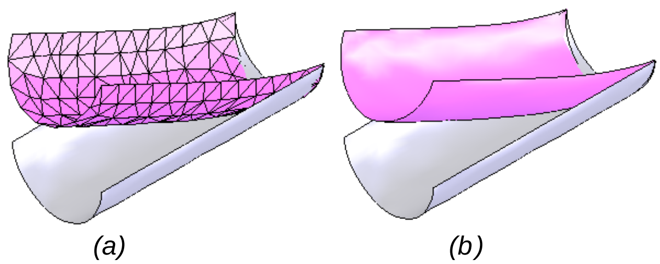

Figure 11: (A) MESH OF A DEFORMED CYLINDRICAL FACE, (B) DEFORMED CYLINDRICAL FACE

4.2 CAD model reconstruction validation

In the first example (Figure 12), the model represents a prismatic part of simple topology. The part is constrained to a flexion strain. During the reconstruction, the faces are identified and reconstructed one by one, and then the edges and loops are found by the intersection of the different faces. The faces of the initial CAD model are planar surfaces, the identification of their corresponding triangulation's is done directly (without investigating the topology), because the topology is not changed. All the reconstructed faces are of the NURBS type, except for the embedded face, which is planar.

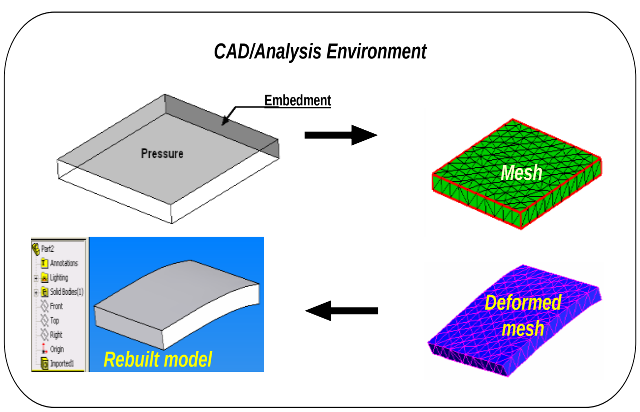

Figure 12: VALIDATION EXAMPLE: PRISMATIC PART IN FLEXION

In the second example (Figure 13), the part chosen contains cylindrical faces and it is also constrained to a flexion strain.

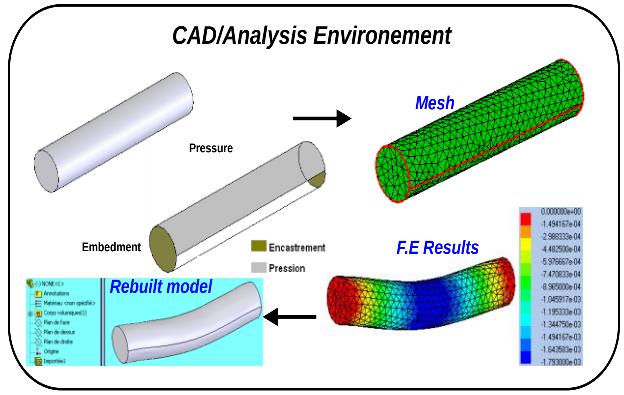

Figure 13: VALIDATION EXAMPLE: CYLINDRICAL PART IN FLEXION

4.3. Comparison

This section presents a comparison with an existing method mentioned in the state of the art: the Thin Plate Spline (TPS) method [17] using a more general example containing 15 faces.

The selected surface in Figure 14 is more complex than the above reconstructed surfaces. The obtained reconstruction error proves that the proposed approach is more efficient giving a good quality of reconstruction (Array 3).

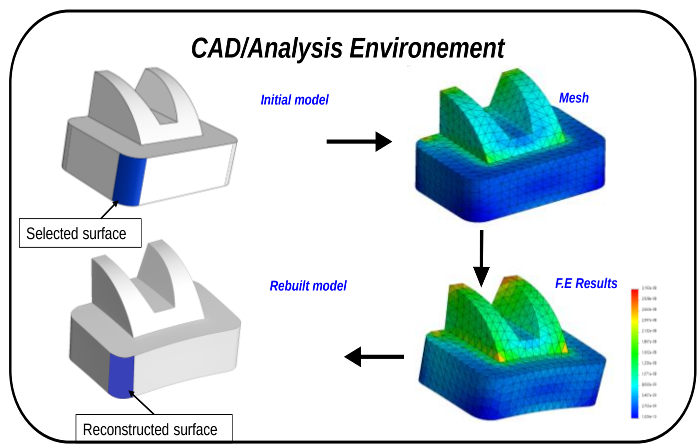

Figure 14: VALIDATION EXAMPLE OF A GENERAL MODEL

Array 3: RECONSTRUCTION ERROR OF THE SELECTED SURFACE

	Proposed Approach	TPS
Average error of the selected surface	2.72 *10^{-4} mm*	3.23 *10^{-4} mm*

The results shown in (Array 3) demonstrate that the error of the surface reconstruction using the proposed approach given the deformed mesh of the selected surface is lower than the error reconstruction of the same surface using the TPS method. As result, the proposed approach improves the reconstruction quality and guarantees more precision of the reconstructed surfaces.

5. CONCLUSION

This paper presents an original approach to rebuild the CAD model (BREP) using the results of a Finite Element analysis. In this work, a new reconstruction algorithm for a regular base grid of points derived from a triangulation has been developed. The approach is based on the Walton's algorithm to find a regular grid of points in order to construct the NURBS surface corresponding to the 3D deformed meshed surface. Given different case studies, the algorithm is validated by calculation of the minimum, maximum and average error. The obtained results prove that the proposed approach is precise and efficient giving a good quality of reconstruction.

REFERENCES

[1] Tarsitano, Achille, et al. "Accuracy of CAD/CAM mandibular reconstruction: a three-dimensional, fully virtual outcome evaluation method." Journal of Cranio-Maxillofacial Surgery 46.7 (2018): 1121-1125.

[2] Inga-Ortega, Juan, et al. "Electrical load curve reconstruction required for demand response using compressed sensing techniques." 2017 IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America). IEEE, 2017.

[3] Hao, Long, Xiang Huang, and ShuangGao Li. "Surface reconstruction based on CAD model driven priori templates." Review of Scientific Instruments 90.12 (2019): 125116. [4] Xia, Zhiliang. "Application of reverse engineering based on computer in product design." International Journal of Multimedia and Ubiquitous Engineering 9.5 (2014): 343-354.

[5] Kumar, Atul, Pramod Kumar Jain, and Pushparaj Mani Pathak. "Reverse engineering in product manufacturing: an overview." DAAAM international scientific book 39 (2013): 665-678.

[6] Gameros, A., et al. "A reverse engineering methodology for nickel alloy turbine blades with internal features." CIRP Journal of Manufacturing Science and Technology 9 (2015): 116-124.

[7] Bhattarai, Suyesh, et al. "Adapted Delaunay triangulation method for free-form surface generation from random point clouds for stochastic optimization applications." Structural and Multidisciplinary Optimization 61.2 (2020): 649-660.

[8] Lu, Wuyue, and Ligang Liu. "Surface reconstruction via cooperative evolutions." Computer Aided Geometric Design 77 (2020): 101831.

[9] Qin, Xu-Jia, et al. "Surface reconstruction from unorganized point clouds based on edge growing." Advances in Manufacturing 7.3 (2019): 343-352.

Bey, Aurélien, et al. "Reconstruction d'un nuage de points 3D étant donné un modèle CAO a priori." RFIA 2012 (Reconnaissance des Formes et Intelligence Artificielle). 2012.

[11] Xu, Mingliang, et al. "Interactive mechanism modeling from multi-view images." ACM Transactions on Graphics (TOG) 35.6 (2016): 1-13.

[12] Yoshihara, Hiroki, et al. "Topologically robust B-spline surface reconstruction from point clouds using level set methods and iterative geometric fitting algorithms." Computer aided geometric design 29.7 (2012): 422-434.

[13] Wang, Jun, et al. "A framework for 3D model reconstruction in reverse engineering." Computers & Industrial Engineering 63.4 (2012): 1189-1200.

[14] Bénière, Roseline, et al. "A comprehensive process of reverse engineering from 3D meshes to CAD models." Computer-Aided Design 45.11 (2013): 1382-1393.

[15] Louhichi, Borhen, Gad N. Abenhaim, and Antoine S. Tahan. "CAD/CAE integration: updating the CAD model after a FEM analysis." The International Journal of Advanced Manufacturing Technology 76.1-4 (2015): 391-400.

[16] Ben Makhlouf, Aicha, et al. "Reconstruction of a CAD model from the deformed mesh using B-spline surfaces." International Journal of Computer Integrated Manufacturing 32.7 (2019): 669-681.

[17] Ben Makhlouf, Aicha, et al. "Reconstruction of the CAD Model using TPS Surface." 2019 23rd International Conference Information Visualisation (IV). IEEE, 2019.

[18] Dhatt, Gouri, and Gilbert Touzot. Une présentation de la méthode des éléments finis. Presses Université Laval, 1981.

[19] Batoz, Jean-Louis, and Gouri Dhatt. Modélisation des structures par éléments finis: Solides élastiques. Presses Université Laval, 1990.

[20] Louhichi, B., Aifaoui, N., Hamdi, M., BenAmara, A., & Francois, V. (2010). An optimization-based computational method for surface fitting to update the geometric information of an existing B-Rep CAD model. International Journal of CAD/CAM, 9(1), 17-24.

[21] Piegl, L., and W. Tiller. "The NURBS Book, Springer-Verlag, New York." (1997).

[22] Suriano, Saumuy, et al. "Progressive measurement and monitoring for multi-resolution data in surface manufacturing considering spatial and cross correlations." IIE Transactions 47.10 (2015): 1033-1052.

[23] Wang, Xinlong, et al. "Research on trajectory planning of complex curved surface parts by laser cladding remanufacturing." The International Journal of Advanced Manufacturing Technology 96.5 (2018): 2397-2406.

[24] Walton, Desmond J., and Dereck S. Meek. "A triangular G1 patch from boundary curves." Computer-Aided Design 28.2 (1996): 113-123.

[25] Owen, S. J., & White, D. R. (2003). Mesh-based geometry. International Journal for Numerical Methods in Engineering, 58(2), 375-395.