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## REMODELING OF COMPLEX SURFACE PATCHES BY USING THE METHOD OF CHARACTERISTIC FEATURES – THE SKI SHOE HEEL LIP EXAMPLE

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**Abstract.** *Reverse engineering is an important part of the industry because it enables a more profound understanding of product properties such as shape, geometry, material, and functionality. If there is a requirement to acquire information about an object shape or geometry, then two activities are generally conducted, scanning and remodeling. Scanning presumes using a 3D scanning device to obtain product geometrical data, while remodeling produces a part geometrical model. Various methods are used for obtaining a geometrically accurate and topologically correct geometrical model of the scanned part, and in this paper, a novel method based on Characteristic Product Features (CPF) is presented. CPF is focused on defining product Features of Interest (FsOI) and using them to fulfill reengineering requirements of a specific industrial product. FsOI represent particular sections of the part that are geometrically defined and can be used for further processing, such as creating specific 3D models. The CPF method application was demonstrated by making a ski shoe heel lip 3D geometrical and physical model using 3D printing. The resulting models completely satisfied initial geometrical, functional, and mechanical requirements.*

**Key words:** *Reverse Engineering, Reverse Modeling, Feature-Based Design, CAD*

### 1. INTRODUCTION

Reverse engineering is a common process applied in the industry, and it enables a more profound understanding of various product properties such as shape, geometry, material, color, functionality, and manufacturing technology [1, 2]. If there is a requirement for information about an object shape or geometry, then two activities must be conducted, scanning and remodeling. Scanning presumes using a 3D scanning device to acquire geometrical data about the product by applying a different scanning technology (non-contact or contact scanning devices). The output from the process is a point cloud

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consisting of many points from the product outer surface or interior. The point cloud is used in the remodeling process for 3D geometrical model creation. Various methods are used for remodeling (NURBS patches, SubD surfaces, etc.), but they are mainly based on a strict geometrical, mathematical, or numerical representation of the resulting model surface (or surface part) [2-7]. This paper presents a new approach for remodeling the outer surface of a product based on Characteristic Product Features (CPFs). CPFs are important geometrical or functional entities specific to a particular part, e.g., holes, fillets, ribs, or user-defined, and they are used to define model geometry as more product-oriented. Each feature will be geometrically defined, i.e., an adequate 3D model will be created, representing a basis for adding additional properties, called feature descriptors. These descriptors refer to adding selected product characteristics to pure mathematical (geometrical) product descriptions, such as adding functionality, manufacturing technology, or material definition. The complete feature definition can consist of more than one feature descriptor, which refers to one for geometric description (point cloud, STL, IGS, STEP), other for material definition and/or technology definition, etc. Using this set of descriptors, every product Feature of Interest (FOI) can be completely defined and used individually or as a product assembly, but feature geometrical descriptors are mandatory. Therefore, the method(s) for their creation is the focus of this paper. The presented product description by using feature descriptors adds a lot of benefits to the 3D model creation, such as faster remodeling, better geometrical accuracy, and topological and functional correctness.

## 2. STATE OF THE ART

Part remodeling is a standard part of the reverse engineering process. Through the application of this process, a geometrically accurate and topologically correct 3D model is created [2-5]. Different procedures and methods are applied in the remodeling process, and they can be divided based on the quantity and quality of the scanned data [5]. Thus, remodeling can be done by using complete data, or it can be conducted using insufficient data about part geometry. In the second case, the cause for lack of data (or lack of valuable data) can be hardware (e.g., scanner), software (e.g., scanner software), or the original part with incomplete geometry [5, 6]. For all cases, the geometrical accuracy of the model and topological correctness are influenced by the specific requirements. Therefore, the construction of a particular part 3D model can be more or less complex [7, 8], and it can consist of the following steps [7]: Importing the point cloud; Filtering the point cloud; Initial mesh creation; Mesh adaptation; Surface or Solid model creation. Usually, each stage has additional processes which must be performed to form a required model.

Importing the point cloud presumes inserting the scanned data in the form of a set of points into the CAD software, which is a straightforward activity.

The second step is filtering the point cloud data, which includes several processes: point cloud analysis, cloud separation into individual sections, and removing or adding points [9]. Point data analysis refers to the study of the cloud geometry and shape, and as a result, the remodeling procedure is defined [7, 9]. This procedure always includes some processing of the point cloud, such as the aforementioned section definition and point insertion and removal [10]. Developing 3D models of complex objects can be a demanding task in terms of the needed computer resources and design time. Therefore, a division into

sections with a smaller number of points and with simpler geometry can speed up the process, but on the other hand, it can sometimes be complicated to merge individual clouds or meshes [9, 11]. To conclude, the point cloud analysis is an essential process and should be done by an experienced designer. The point removing process almost always includes the elimination of noise (irregular scanned data) or unnecessary data (e.g., excess points from flat surfaces).

The initial mesh creation step is a process that develops a polygon mesh with a defined edge length and number of vertices. The mesh validity is expressed through the manifold property, isolated triangles, and uniform facets normals, and it is generally hard to achieve it for complex part surfaces. Usually, after the initial mesh creation, an adaptation of its geometry is required to correct those errors [7, 12]. Mesh adaptation does not correct only errors but can include adding extra polygons or mesh smoothing to improve the model geometry and topology [13].

Surface or solid model creation is a process that mainly depends on a model's purpose. For example, if there is a requirement to perform 3D printing, surface milling, or to do some computer animations or rendering, then it is perfectly valid to create a surface model. Still, it is necessary to create a solid model if it is required to perform simulations (e.g., Finite Element Analysis - FEA). In any case, the process starts by using the mesh model to create basic constructive geometry such as curves (e.g., B-splines, NURBS, T-splines), lines, and axes, and then use them to create surface patches or solid (volume) elements [14]. In some cases, basic geometry can be made directly using a filtered point cloud (if the cloud is valid enough) or if a quick reconstruction is needed for presentation purposes [15].

### 3. METHODOLOGY

The methodology consists of several steps, which are represented in Fig. 1. The process starts with importing the point cloud and finishes with a complete definition of the selected product features, and their implementation. The point cloud is initially a set of points acquired from the scanning activity [16], where each point represents a minimal geometric definition of the scanned product. In the next process (P2) each product FOI is described semantically, and a list of features is created. This list can be represented using a plain text file or some other type of representation, e.g. a visual (sketch). Finally, it is necessary to conduct process P3 to provide a complete definition of feature(s) properties, through feature descriptors. This process is the most important activity in the application of this methodology. It consists of several feature definitions and is not limited to those presented in Fig. 1 (geometrical, mathematical, functional, etc.). The methodology is open, and other feature descriptors of the product feature can be added to the list.

This paper will focus on the geometrical definition of the product Features of Interest (FsOI). To define product feature(s) geometrically, it is required to use a filtered product point cloud. Then, each product feature is defined by selecting a group of points that belong to that product feature, i.e., product feature(s) is geometrically represented by a set of points in the point cloud, as presented in Eq. (1).

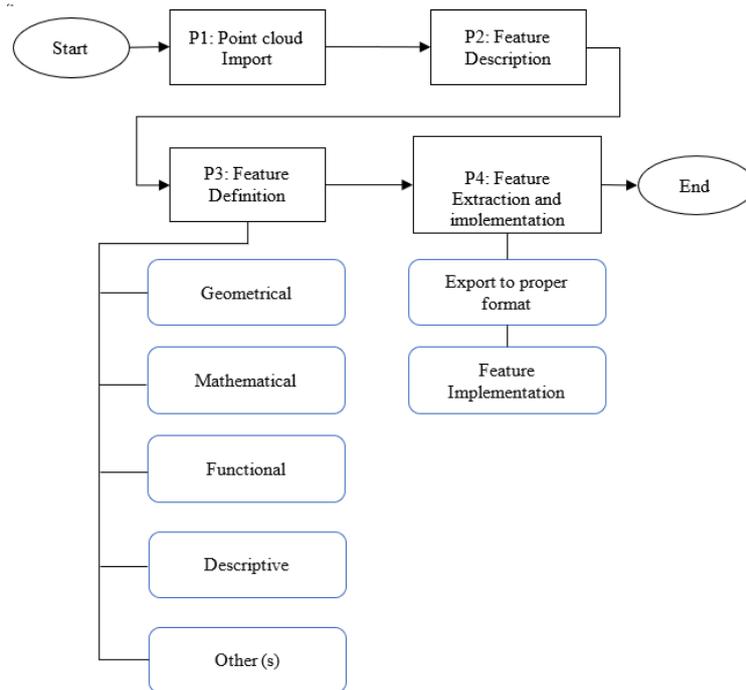
$$PC = \{P_i \mid P_i \text{ is point from scanning device}\}$$

$$P_i^F = \{P_j | P_j \text{ belongs to defined feature set } n_i \leq j \leq m_i\} \quad (1)$$

$P_i^F$  is individual product feature – Feature of Interest (FoI),

$P_j$  – individual points;  $n_i, m_i$  are minimal and maximal points indexes

The definition of the feature and its belonging points is a significant step in the methodology, and it is done in the point cloud analysis step. Still, it is not limited to only that activity; the product feature and its points set can be modified at any time. Finally, the groups of points are defined and exported in a separate file accompanied by the point cloud file.



**Fig 1.** The main components of the methodology

The group of points can be further processed in the remodeling step, e.g. creating mesh(es), forming geometrical elements such as curves, and forming 3D models (surface or solid) at the end. Each following individual step can produce an output and further define product feature(s). For example, the mesh element can be exported to an STL file and then joined to the point cloud file of the product, thus creating a set of files for an individual feature – point cloud (\*.txt) and mesh file (\*.stl). The whole set of product FsOI can contain many files for each component; if required, they can be used individually or assembled into the whole product and used as a part model. The one important capability of a product

feature is the parametrization of its point set, thus creating a parametric point cloud model for a unique feature with the capability to adapt to different parameters [15], not just geometrical, but also functional, technological, and so on.

### 3.1 Methodology application - heel lip tread area example

To demonstrate the methodology, a real-life example is used. The example refers to remodeling the heel lip part of the ski shoe, Fig. 2a. The problem with the original part is the constant breaking of the tread area while walking, so it is important to improve the mechanical properties of this part of the shoe and keep functional properties such as ski mounting intact. The solution is to remodel the feature (FOI), improve mechanical and functional characteristics, and improve walking. The steps conducted in the remodeling process are:

1. Scanning of the model by using a Shining3D EinScan-SE 3D scanner (accuracy  $\leq 0,1$  mm, point distance  $0,17 - 0,2$  mm, white light), Fig. 2b.
2. Importing the point cloud into the CAD software (CATIA V5), Fig. 2c
3. Processing the point cloud
  - a. Filtering (the model was accurate with a meager amount of noise)
  - b. Optimization (reducing the number of points)
  - c. Defining the FOI
  - d. Creating the Set of Points for FOI
4. Developing a mesh model for the whole point cloud, Fig. 2c
5. Printing an original model by using an FFF printer (Wanhao Duplicator I3 plus 3D printer) and ABS plastic.
6. Developing a mesh model for FOI
7. Processing the mesh model and creating additional geometry (fixing the defect, while ensuring better strength of the part, marked in Fig. 2d)
8. Printing the final model by using the FFF printer (Wanhao Duplicator I3 plus 3D printer) and ABS plastic.

### 3.2 The feature extraction and processing

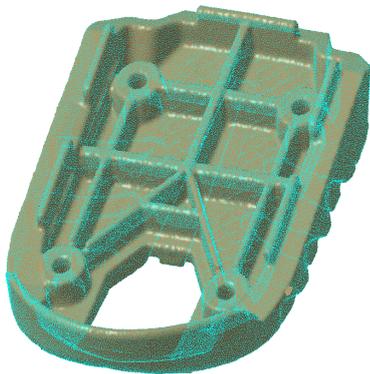
The next activity is to select the defective part of the model (Fig. 2d, which can cause mechanical failure) and to perform additional processing in CAD software. The first task is to remove unnecessary points from the point cloud model. These points are a result of high-resolution scanning, and removing them will not influence the model geometry and topology. The other important feature present on the original part is a cut shown in Fig. 2a and 2d. The cut results from the original part broken section and mesh manipulation and transformation (cutting mesh and mirroring) in CAD software. Two solutions can be applied to resolve this problem:



a) Broken thread part of a ski shoe heel



b) Scanning the part (Shining3D EinScan-SE)



c) Imported model and created mesh in CAD software



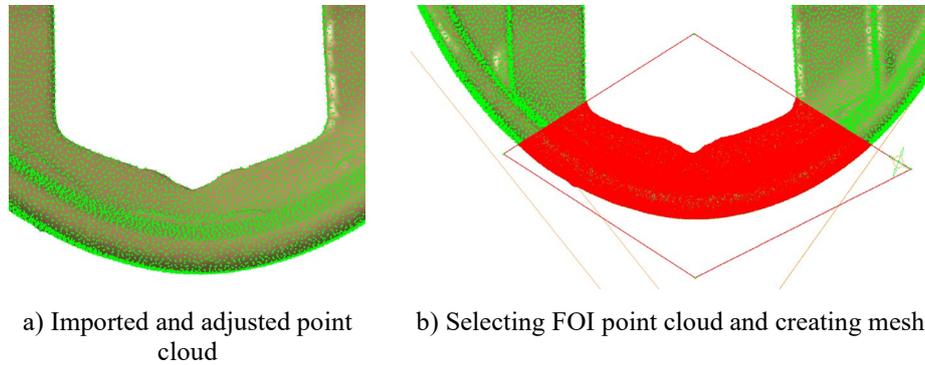
d) Printed model with visible defect

**Fig. 2** Creating the initial mesh model and its 3D printing

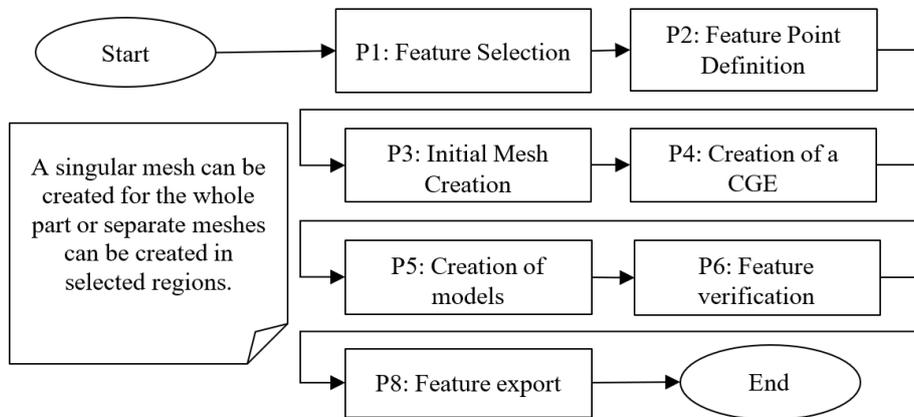
- To use CAD software technical features and correct it, which can be a time-consuming task.
- To perform a simple export and import of the point cloud. This solution is chosen because it is simpler, the required time is much shorter, and geometrical accuracy and topological correctness are preserved. The solution is reached by exporting the point cloud into the text file, opening a new file in CAD software, and performing an import. The imported point cloud is adjusted (Fig. 3a), and a new mesh model is formed, using the CATIA technical feature, as shown in Fig. 3b. The resulting model is geometrically and topologically valid (checked by CATIA tools), and the cut is eliminated.

The main reasons for the mechanical failure of the actual part are small part thickness and the foot's pressure on the ground during walking. Therefore, resolving FOI thickness to eliminate breaking during walking is the only issue left. The FOI is defined on

a newly formed point cloud and is present in Fig 3b. This feature can consist of many points (or faces) which will be used as a basis for creating future geometry. The procedure for the complete FOI remodeling process is presented in Fig. 4



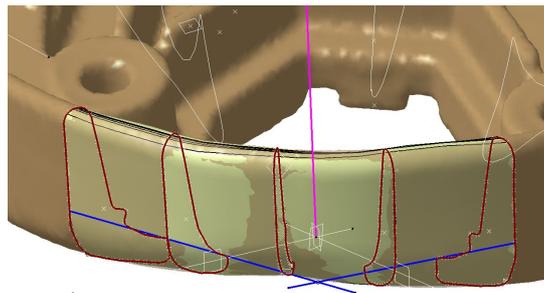
**Fig. 3** FOI selection and initial FOI mesh model



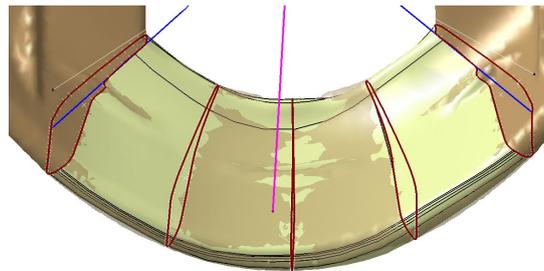
**Fig. 4** The remodeling procedure for FOI

The feature selection is already performed, points are defined, and the initial mesh is created, as shown in Fig. 3b. The following activity is CGEs (Constructive Geometry Elements) creation. CGEs are the lines, planes, curves, or other geometrical elements that can provide a basis for the creation of future models (surface or solid). For this purpose, remodeling of the feature is performed by using spline curves and considering the part's functional and mechanical requirements. The part geometry must conform to that of the ski shoe hill, so it can be attached. Spline curves were created by using selected points on FOI, which are placed in planes that follow the form of the part in that section – positioned in rotational planes. A mesh model with spline curves and created surface patch for FOI is presented in Figs. 5a and 5b. The final volume model is created by using a close surface

technical feature from CATIA. As a result of the remodeling process, the FOI can be defined (represented) by using the following entities: point cloud, mesh model, surface patch (NURBS), and volume model. In this case, surface patch points and the rest of the part mesh were used to define a new point cloud model with improved geometry, thus forming the STL model presented in Fig. 6a. The improved STL model was imported to CURA software to prepare it for 3D printing (Fig. 6b), the model proved to be more than satisfactory. The part is oriented so the detailed geometry which ensures traction when walking faces upwards. The printed model is presented in Fig. 7, with 100% infill and ABS material. The model was printed, and the ski shoe was assembled and tested. The part completely satisfied initial functional, mechanical, and geometrical requirements.

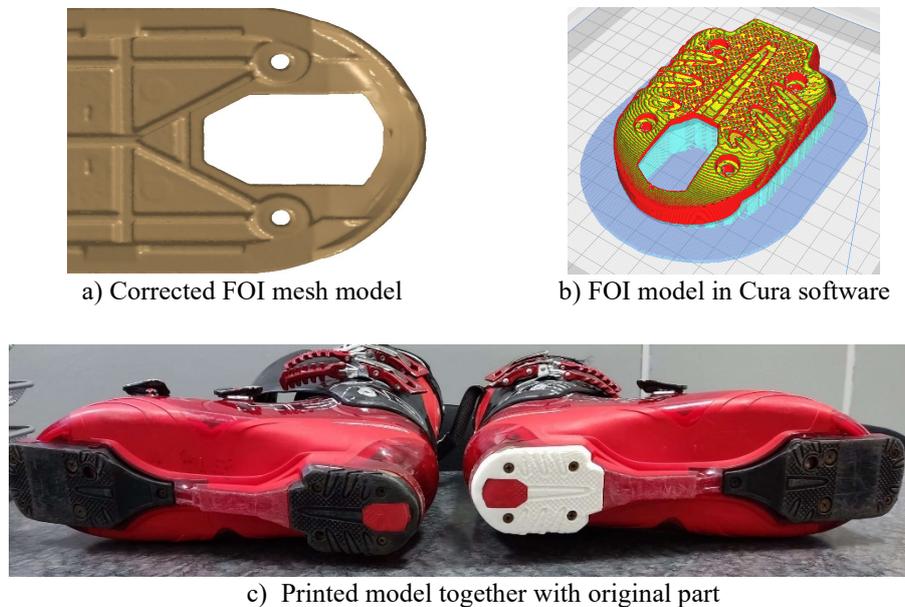


a) FOI mesh and surface models (front view)



a) FOI mesh and surface models (top view)

**Fig. 5** Forming the mesh and surface (NURBS patch) models of FOI



**Fig. 6.** Form corrected mesh model to 3D printed (FFF) real model

#### 4. CONCLUSION

In this paper, the Characteristic Product Features (CPF) method was described and applied to remodel the ski shoe heel. Initially, the CPF method requires extra time to define the feature(s) and their properties (geometrical, functional, etc.). Still, in the end, it enables the creation of models adequate for a specific purpose. The shoe heel model was scanned using a structured light scanner, then imported into the CAD software and filtered. The feature(s) of interest (individual FOI or multiple FsOI) was defined, remodeled, and geometrically improved. The final reengineered feature was created to satisfy two main demands: to provide walking stability and enable ski mounting. Both requirements were met, and the CPF method was proven adequate for this specific purpose. Future work presumes two main activities: the application of the technique to other particular cases with different demands and the improvement of the method by forming the parametric models of the FOI with different parameterization methods. These two additions will help to create a fully adaptable method to various applications, which is, as already stated, the primary goal of this research.

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