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Research Article

Application of reverse engineering approach on a damaged mechanical part

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ABSTRACT

Reverse engineering methods are important for remodeling or measuring damaged or non-damaged parts. Reverse engineering also enables the design of complex components, reducing actual product production time and prototype production time. With this method, damaged gear wheels can be modeled in a short time due to the regular geometry and symmetrical properties of the teeth and it is real models can be produced. In this study, the damaged motor cam gear was scanned with a three dimensional (3D) scanner and a mesh model was formed. Then, solid model of part was created and genuine prototype was produced with 3D printer. The deviations of geometric dimensions between the mesh model and the solid model were analyzed and the levels of convergence were determined. The three-dimensional prototyping method provides great convenience for the designer due to it gives quick feedback in product development process. At the end of the study, geometric values between solid model and prototype model were compared and deviations from actual value were determined.

1. Introduction

Reverse engineering is a field that is continuously expanding in recent years and interested in computer-aided geometric design [1]. It is used in many fields of industry to create geometric models of objects that do not have existing models. Reverse engineering is also used in engineering, medical sciences, restoration processes for the conservation of cultural heritage, and many other fields [1]. When engineering applications are taken into consideration, the main purpose of the reverse engineering is to create a 3D parametric solid model, which is best suited to the original of the object, by using raw data obtained from a 3D scanner. As another definition, reverse engineering is defined as a method of creating data of engineering design and documentation from existing parts and their assemblies in the fields of mechanical engineering and industrial production [2]. Whereas in the traditional engineering approach, engineering concepts and models are converted into real parts [3], in the reverse engineering approach, real parts are converted into engineering concepts and models [4]. In the field of mechanical engineering, the reverse engineering allows the re-creation of surface or geometric data of an existing part by using contact or non-contact measuring devices. With some exceptions, most of the techniques available in reverse engineering literature have specific steps [1, 5-7]. These are scanning the part with a 3D scanner, data collection, processing of original data, segmentation of point clouds/meshes, classification of regions defined in the segmentation step, generation of analytical surfaces and properties applied to generally classified surfaces, finishing operations (e.g. joining adjacent surfaces), reconstruction of the computer-aided design (CAD) model, and prototype creation (Figure 1). This framework is also used by commercial software systems where each step is performed using a specific tool or function.

Over time, automatic mesh algorithms used for 3D surfaces have become valuable tools in analysis and design processes. After the algorithm is applied, the resulting elements are used as input to the automatic triangle or quadrilateral mesh algorithm.

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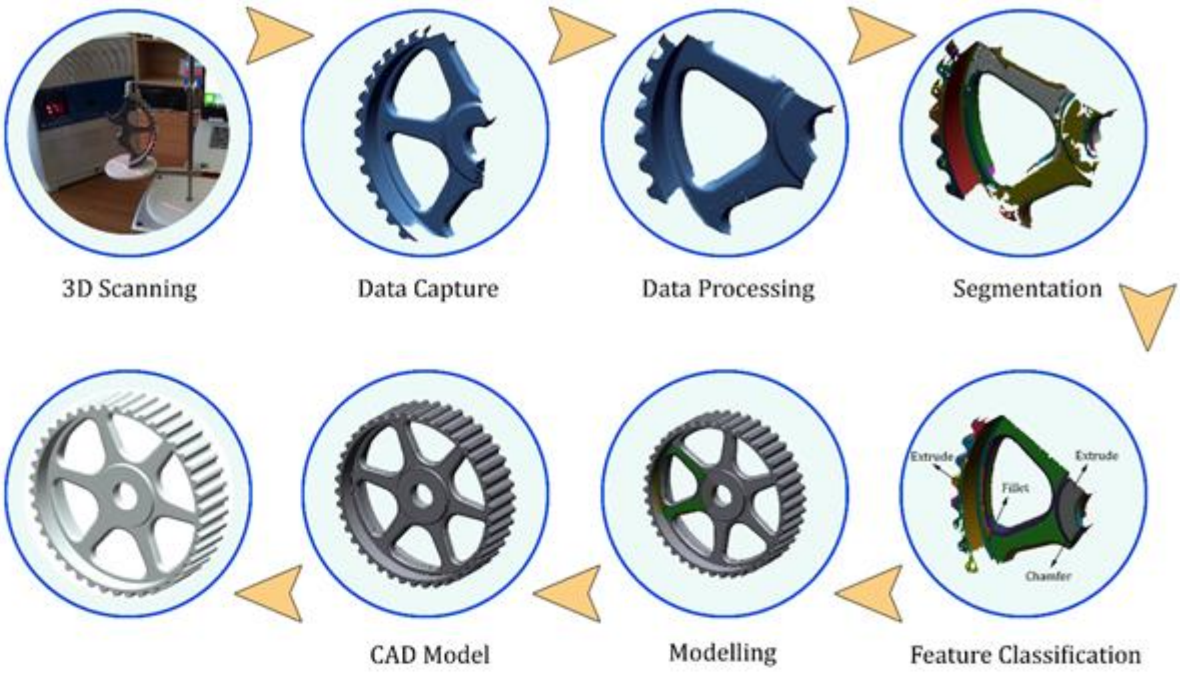


Figure 1. Flow chart of general reverse engineering approach prototype

Since triangular mesh algorithms have simple, easy and provable mathematical features, they are widely used in the literature. Despite this, many researchers prefer quadrilateral elements, drawing attention to their superior features [8]. Simplifying quadrilateral networks create additional challenges. Because quadrilateral elements are less compatible and more sensitive structures than triangles, simplifying them leads to additional challenges [9]. In industrial applications, free-form surfaces of models are often represented by the B-spline surface. In the creation of the B-spline, first, many connected triangular surfaces are selected within the freehand drawing sections and these triangular surfaces are made compatible with the B-spline surface. The proper B-spline surface is taken as an input and the region is enlarged by adding corners that are not included but adjacent to the existing region [7]. Bicubic B-Spline surface is defined as follows;

$$S(u,v) = \sum_{i=0}^{m} \sum_{j=0}^{n} d_{i,j} N_{i,3}(u) N_{j,3}(v) \quad (1)$$

$$0 \leq u,v \leq 1 \quad (2)$$

$d_{i,j}$ indicates control points, and $N_{(i,3)}(u), N_{(j,3)}(v)$ represent the 3rd order univariate B-Spline basic functions in the u,v direction defined on the $U = \{u_0, u_1, \dots, u_{(m+4)}\}$, $V = \{v_0, v_1, \dots, v_{(n+4)}\}$ node vectors respectively [10]. It is developing day by day by modeling of machine parts and especially gear wheels with the reverse engineering method as parametric or non-parametric and then by producing with rapid prototype process [11-13]. The general purpose of these studies is to fill the damaged areas of parts in a virtual environment and obtain the whole part. The realization of these processes is targeted with the lowest precision and different modeling features are used. In our study, a damaged automobile cam gear was remodeled as 3D by the reverse engineering method, and then it was produced with the Fused Deposition Modeling (FDM) method, which is one of the rapid prototyping processes. The current aspect of our study is that the damage size of the cam gear is large and the modeling feature is carried out according to the polar duplication feature. In addition, in our study, it was aimed to produce the cam gear modeled by reverse engineering method in different scales with FDM method and to compare their deviation analysis.

2. Materials and Methods

The cam gear, which takes its movement from the crankshaft by the help of the timing belt, transfers its motion to the camshaft. The purpose of the camshaft is to determine the opening and closing time of the valves. In this study, it was aimed to perform 3D modeling of the damaged cam gear that was taken from the industry and to reproduce it with the help of the rapid prototyping method. For this purpose, the cam gear was modeled primarily as 3D by the reverse engineering method. In general, a specific plan should be created for the part in the reverse engineering process. Within the framework of this plan, the part was first cleaned with the help of certain liquid solutions, markers were placed in certain places on the part, and then powdering was done to make the part surface matte (Figure 2)

Figure 2. Schematic representation and preparation of the cam gear for 3D scanning

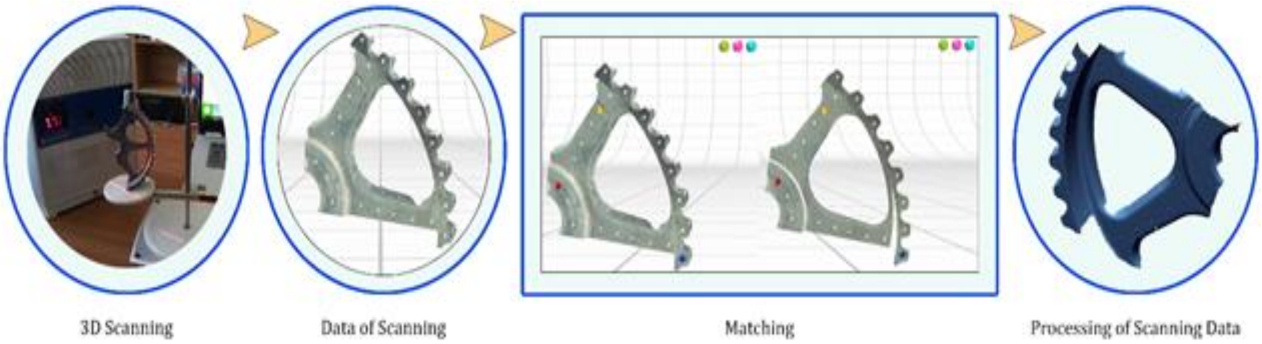


Figure 3. Data processing stages of 3D scanning data

The part surface cleaning process involves removing unnecessary small particles on the part surface during 3D scanning. At the end of this process, the part was left to dry and then marking was performed to create a reference on the important regions of the surface. When multiple scans are performed, the marking process ensures that the scan data overlaps. The finishing of these processes is powdering. In this finishing, the surface was matted to prevent laser beams from reflecting off the part surface during scanning. The level of delustering varies based on the person performing the 3D scanning process and the scanning data generated.

2.1 3D Scanning, Data Capture and Data Processing

3D data collection methods used for 3D modeling of objects are performed by many devices such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Ultrasonic Imaging, Photogrammetry, Computerized Coordinate Measuring Device (CMM), and Laser Scanner. These devices are used also assertively in the field of reverse engineering as well as their own functions. Each of these devices has advantages and disadvantages over each other. These devices can be separated into two as contact and non-contact depending on the data obtained [14]. In the contact method, an object is contacted with the help of a physical sensor and the data of the point of contact is received. In the noncontact method, images acquired previously with the help of digital cameras are processed. Surfaces formed with the help of data obtained through data capture and data processing are smoothed, the number of data is optimized, and unnecessary data is eliminated. In this study, the NextEngine (NextEngine Inc.) device, which performed noncontact scanning, was used. The processes from 3D scanning to data processing are shown in Figure 3. A good strategy should be determined at the beginning of the 3D scanning process. Although doing too many scanning processes may seem like an advantage, the processing speed of the computer may decrease due to the excess data. Therefore, a good planning is needed to complete these processes in a short time. The processes described in this study were optimally completed.

On the data images of the cam gear scanned from different angles, the matching process is performed by determining a minimum of three points on both images. As a result of the matchings, real scanning data is obtained. The hierarchy of the 3D-scanned data in Geomagic Design X software (3D Systems, Inc.) used in this study is shown in Figure 4. Sections considered as noise in the data obtained from the scan device are corrected in the mesh improvement section. If there are missing corrections, correction can be made again in the next steps, the existing triangular edge length determined in the global re-mesh assignment section can be changed, and open meshes can be closed. In this section, when the surface properties are desired to be more specific, it is desired that the triangular edge length is below the current length value. As a result of these processes, the mesh number can increase and it can slow down the computer used.

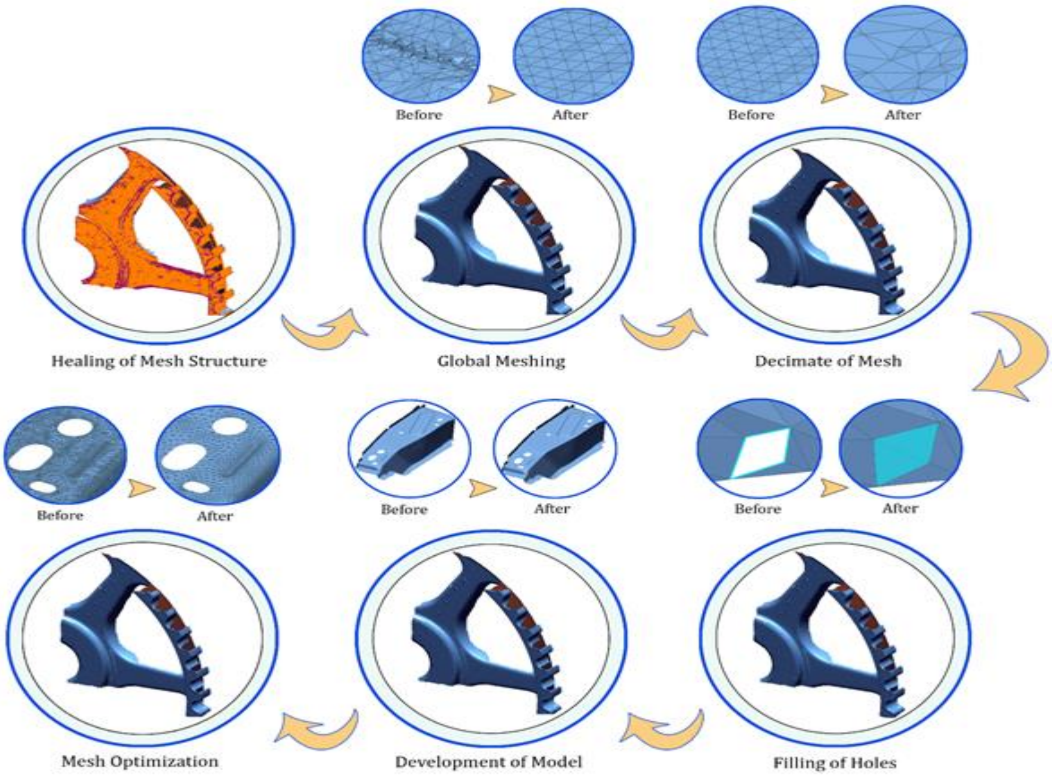


Figure 4. Flow chart of data processing section in reverse engineering

To reduce the increasing number of mesh, the mesh editing process uses algorithms that contain multiple surface counts or allowable deviation parameters. Filling the gaps ensures that the gaps in the mesh surface sections of the part are filled. These gaps may be in straight or curved forms. In terms of filling the gaps, a healthy process can be realized by taking into consideration the gap curvature. The shape developing process is used to increase the overall smoothness and clarity of the mesh structure. In the mesh optimization section, it is ensured that the uniform mesh structure with desired size is created on the part. This part should be analyzed well and the most ideal mesh structure should be created for the part.

2.2 Segmentation and Feature Classification

The segmentation process searches the nearest neighbors with a fast algorithm by using the received data and it includes the prediction of first and second order surface properties [15]. As a result of this process, the surfaces are divided into separate regions. The segmentation process is an important factor in the healthy creation of CAD reconstruction. The segmentation process regulates the parameters that affect the type and size of the defined regions [16]. There are many studies on segmentation processes in the literature. In the most comprehensive study, the segmentation process was examined in 10 steps (clustering, region growing, surface fitting, topology, spatial subdivision, spectral analysis, boundary detection, motion characteristics, probabilistic models, and co-segmentation) [17]. Since the feature classification process is used as a result of the segmentation method and depends on the segmentation features, it should be considered with it. In our study, after the data processing section, the segmentation process was applied on the cam gear (Figure 5). In the data processing section, part surfaces were stabilized and smooth regions were created. Based on the modeling strategy, the formation of suitable surfaces (segmentation) and their modeling properties (feature classification) were determined (Figure 5). It was thought that it would be appropriate to model the hub of cam gear with the Extrude feature and the diameter parts of the hub with the Chamfer feature. In addition, the Fillet feature was used in the corners of the support parts used in the gear and the Extrude feature was also used in the thickening of the gear parts.

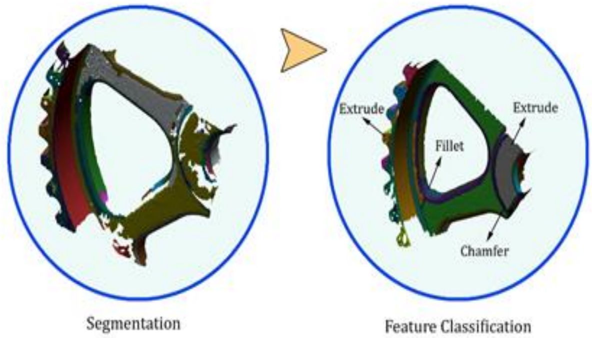


Figure 5. Application of Segmentation and feature classification processers cam gear

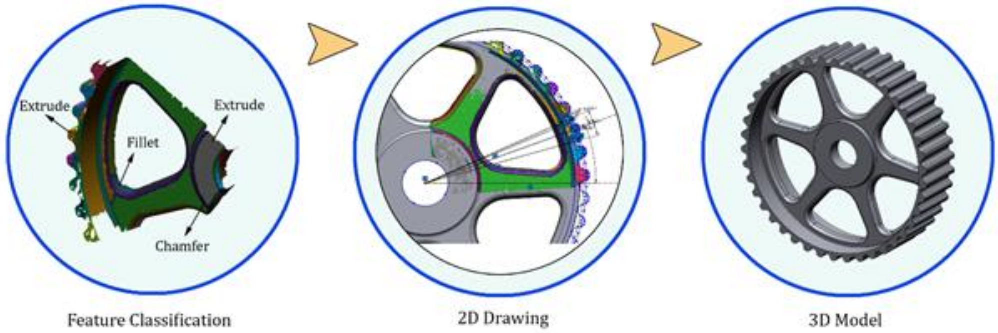


Figure 6. Modelling operation in reverse engineering

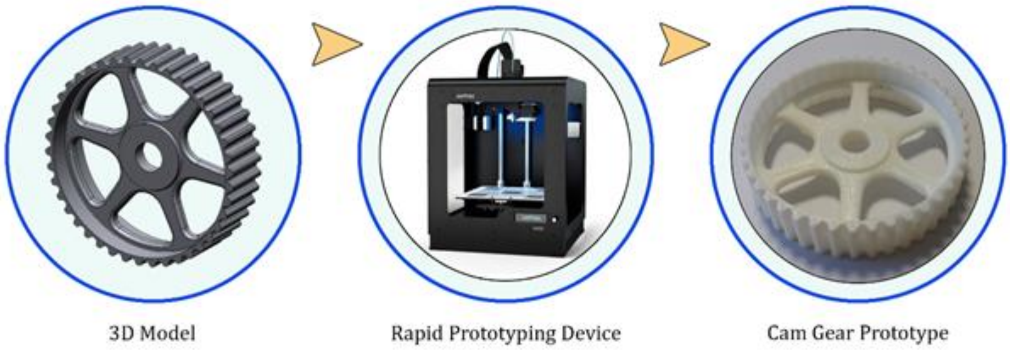


Figure 7. Reverse engineering process of the cam gear

2.3 Modelling

In this section, as a result of determining the mesh model features, a plane is created by using these features and geometric drawings are made. In order to make this process healthy, the feature classification process should be performed optimally. In our study, modeling features were determined, plane and 2D drawings were created and modeling operations were carried out (Figure 6).

2.4 CAD Modelling and Rapid Prototyping

In this section, before the rapid prototyping process, the final state of the model created by using the feature classification process is created. By considering subsequent processes, the formation of the CAD model can be performed as parametric or non-parametric. With the help of the features used in the model section, the geometry of the part can be in surface or solid form. Clamping of adjacent surfaces, forming of radius and chamfers, and performing geometric constraints can be shown as the other operations of this section [18]. The prototype of the occurred 3D modeling can be created according to the desired rapid prototyping method, the desired material and mechanical characterization. Many processes related to rapid prototyping have been developed and introduced in the last few decades. These process types are gradually developing and their variety increases with the developing technology. There are some rapid prototyping processes that are generally known in the literature [19-21]. These are known as Stereolithography (SLA), Electron Beam Melting (EBM), Direct Metal Laser Sintering (DMLS), Fused Deposition Modelling (FDM), Melting (SLS/SLM) or Selective Laser Sintering, Three Dimensional Printing (3DP), Laminated Object Modelling (LOM). In our study, the prototype model of the cam gear which was created with the help of reverse engineering, was carried out using the FDM method (Figure 7). In this method, many parameters affect the surface roughness and mechanical characteristics of the part.

3. Results and Discussion

In this study, a damaged cam gear was scanned with a 3D laser scanner and converted into a mesh form, and then a CAD model and prototype were created with the help of certain reverse engineering and rapid prototyping processes. Reverse engineering processing time and difficulty vary according to the damage level of the part. If the damage is only at the tooth region of the cam gear, the processing time will be slightly shorter. However, in our study, the large damage on the cam gear part increased both the processing time and the processing difficulty level. In the reverse engineering process, since backward modeling is performed, the dimensional accuracy of the geometrical parts becomes important. The combination of errors emerging due to the device, software or operator used in each stage gives us the total error in the resulting model. Therefore, a detailed examination is required for each stage. Accuracy analysis between the mesh model and the solid model created in reverse engineering is given in Figure 8.

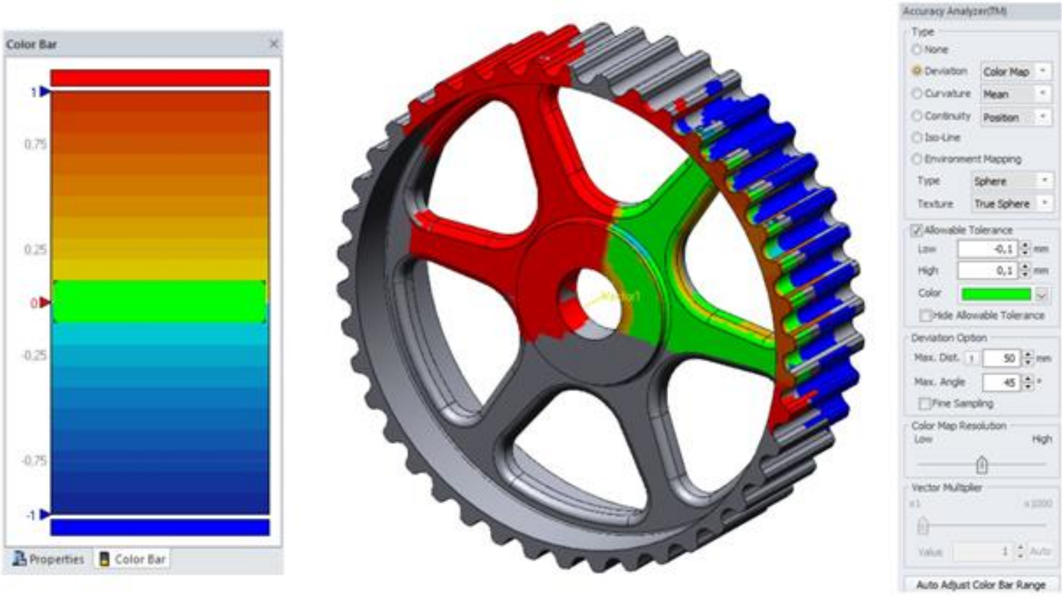
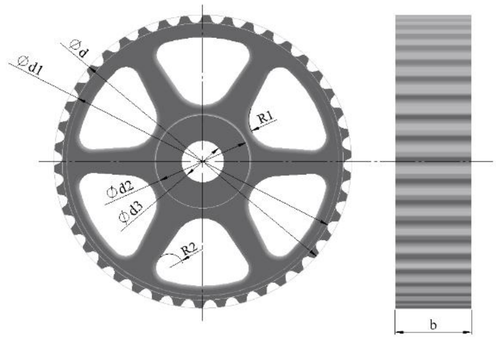


Figure 8. Accuracy analysis between mesh and solid model

Table 1. Dimensional comparisons between the damaged gear and the rapid prototype gear.



Dimension Name	Specimen (mm)	Prototype Sample 1 (1/1)) (mm)	Prototype Sample 2 (1/2) (mm)	Prototype Sample 3 (1/4) (mm)	Deviation 1 (1/1) (%)	Deviation 2 (1/2) (%)	Deviation 3 (1/4) (%)
d	123.31	123.25	61.82	30.97	0.999513	1.002676	1.004866
d1	116.48	116.35	58.37	29.25	0.998884	1.002232	1.004636
d2	39.17	39.47	19.89	10.05	1.007659	1.015573	1.026551
d3	17.49	17.32	8.86	4.48	0.99028	1.01315	1.025157
R1	12.05	11.94	6.17	3.11	0.990871	1.024066	1.033195
R2	5.6	5.54	2.87	1.45	0.989286	1.025	1.039286
			Average Accuracy		99.60823	98.64831	97.83683

In the accuracy analysis, the average deviation values between mesh surfaces and solid surfaces were obtained by the help of the algorithm in the Geomagic Design X software (3D Systems). When we look at the color scale shown in the figure, it is seen that most of the solid model we obtained from the mesh model is shown in green color (average deviation: ± 0.1 mm). Although slightly different colors (average deviation ≈ 0.1-0.2 mm) may appear in the radius regions of the gear part, it was understood that the deviation is not too much. Because the mesh model is small and the solid model created with the help of the mesh model is large, a large region of the part does not contact with each other. Therefore, the regions where mesh and solid model do not overlap are the regions where blue and red colors dominate.

There are two important strategies for creating a 3D model in reverse engineering applications. These are solid feature-based and surface feature-based methods [2,7,22-24]. They are also divided into many stages within themselves. In this study, the cam gear was modeled by using the features in the solid feature-based modeling content. It is important to choose a solid feature-based strategy for modeling mechanical or non-mechanical parts with the regular geometry. With this strategy, since fewer elements are used in the modeling process, both the file size will be reduced and the smoothness of the part surfaces will be ensured. In the surface feature-based modeling, the number of elements should be high in order to define the surfaces in detail. This increases file size and surface irregularity. In defining these surfaces, it will be appropriate to use NURBS (Non-uniform rational B-spline) surface elements used to define irregular surfaces in detail [21]. Based on the FDM method, which is one of the rapid prototyping methods, the gear, created with the help of solid feature-based modeling, was produced in three different scales (1/1, 1/2 and 1/3) (Table 1). The size comparison of the gear was made with the variables of d (major diameter), d1 (minor diameter), d2 (hub diameter), d3 (bore diameter), R1, and R2. The deviation of all three prototype parts from the real models and average accuracy values between models are given in Table 1. Dimensional measurements of the parameters determined on the prototype models were carried out with the help of an Insize (Insize Co.) trademark digital caliper with an accuracy of 0.01 mm. According to the results given in Table 1, considering the 1/1 scale, the average accuracy value between the real model and the prototype model was found to be 99.60%. Considering the 1/2 scale and the 1/4 scale, this value was found as 98.64% and 97.83%, respectively.

4. Conclusions

When we look at the reverse engineering hierarchy in general, we see that each stage has its own process steps and specific details. Here, the knowledge and experience history of the person performing this operation is important. The person performing the modeling process must initially determine a modeling strategy for the part. According to this strategy, he/she should analyze each step in detail and complete the sections in a healthy way. In addition, the variation of the method used in 3D printers, the material used, the temperature of the environment during production in the 3D printer, and the sensitivity of the electronic and mechanical system affect the results of deviation analysis.

As a result of modeling processes, considering the average accuracy values between the real model and the prototype model, it was seen that 1/1 scale production was more accurate. It is observed that the average accuracy rate gradually decreases as the scale factor value decreases. While the results are being evaluated, it will be also appropriate to evaluate the other methods in the production of parts considering the roughness created by the FDM method, which is one of the rapid prototype methods.

Declaration

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

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