Reverse engineering based on information model

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Abstract. This article is focused on application of the information model during the process of reverse engineering in order to advance it both as part of theoretical research and for practical purposes. Reverse engineering technology is presented in detail. Complete solid 3D model of a workpiece is created on the basis of mathematical model consisting 3D point cloud produced using the results of 3D scanning. Reverse engineering of the workpiece is carried out in Siemens Solid Edge CAD system. Quality of the final 3D model depends on the number and density of facets in an obtained mesh model of an object. Therefore, the mesh model is adjusted and optimized using tools of Siemens Solid Edge CAD system, and it is used as a fundament for making a virtual prototype of the workpiece. After the steps for creating a suggested information model are analysed and examined in detail, they are applied to the process of reverse engineering of an implant for thigh bone reinforcement. As a result, information model undergoes significant changes, particularly for the shape analysis and stress simulation stages. Along with creating a virtual prototype of the real object on the example of thigh bone, further designing of anatomically shaped implant is also considered. Thus, applying information model for creating an object provides advantages in reverse engineering process.

Keywords: Information model, Reverse Engineering, Mesh-model.

Introduction

An information model includes all the information necessary for each step of creating an object with the use of reverse engineering technology [1-3]. Reverse engineering concept can be applied in mechanical engineering for producing specific workpieces, in medicine for designing bones of a skeleton, in architecture in order to restore parts

of the buildings and decoration, for the purposes of cultural heritage preservation etc. There are frequent situations that require applying reverse engineering as it is an optimal or even the only way to solve challenging problems in technological progress of the modern world [3]. As part of mechanical engineering, reverse engineering is often used to generate digital copies of different models in the process of searching for the form of completely new objects, in the design, modernization and repair of equipment, as well as in cases when the required workpiece is very difficult or impossible to obtain. Reverse engineering method is applied to create computer 3D model, according to which a new object can be easily designed with the use of additive technologies [1, 2, 4].

Literature review and problem statement

Reverse engineering process starts with 3D scanning which enables generation of mathematical image consisting of 3D point cloud. This point cloud is processed in CAD system and restructured with NURBS into sets of polygons [5-7]. The result of 3D scanning is a polygonal model that is never perfect (see Fig. 1) [5,7], regardless of the ideal shape of scanned object and advanced technological opportunities of 3D scanner. That happens because the obtained model consists of a large number of single surfaces which are not parallel or perpendicular to one another. Besides, there are problems with inner «pockets» scanning [5,6] and surfaces closure [7]. Thus, the final objective of 3D scanning is to get high-level model of the general form of an object.
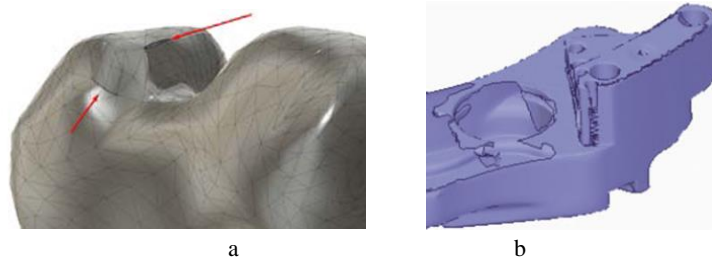

| a | b |

Fig.1. Examples of disadvantages of the polygonal model in scanning process: a – open polygons; b – some surfaces are fully or partially missing.

The aim of the presented research is to develop information model and apply it in the process of reverse engineering of a real object. Such an approach is expected to reduce the time required to analyse, design and carry out stress testings of the model.

Information model developing requires gathering data which describes important properties and parameters of an object, correlations between them, and allows to simulate possible changes of state of an object [8-10]. In this study information model of reverse engineering process is presented. Practical application of the suggested technology is considered for a typical workpiece and a skeleton bone, that will be used in further development of adaptive parametric models.

Research methodology

In many scientific works the research is aimed at the development of information model of an object, however, they lack sufficiently accurate analytical solutions of the problems of reducing time spent on designing, testing and analysing stress distribution [9-10]. As a result of studying this question, information model of a virtual object creating (see Fig. 2) was developed and suggested not only as part of theoretical research, but also for practical use.
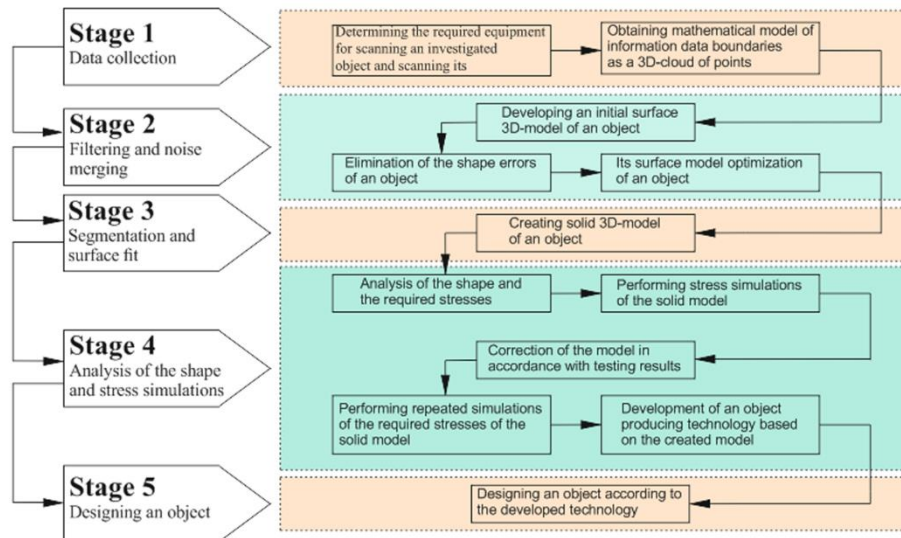

Fig. 2. Information model of designing an object using reverse engineering.

Designing an object is thoroughly considered using modern technology of reverse engineering in Siemens Solid Edge. In order to obtain the input data at the first stage of information model development, a real workpiece is scanned (see Fig. 3a) using a modern 3D scanner. As a result, we obtain a sufficiently high-quality mathematical model consisting of a 3D point cloud. At the second stage of information model development the received geometrical dimensions are imported into the Solid Edge software application as a mesh model (see Fig. 3b). The mesh model consists of triangular polygons called facets (see Fig. 3c).
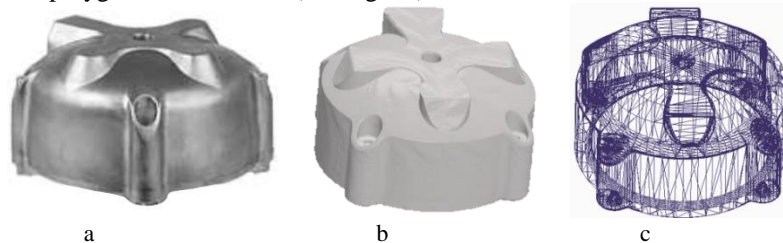

a   b   c

Fig. 3. Photo of the original workpiece (a) and the imported mesh model obtained by 3D scanning (b, c).

Quality of the 3D model depends on quantity and density of facets [3-6]. However, there are still disadvantages on the surface of the obtained model such as open polygons and errors during inner pockets scanning [5]. Thus the surface should be optimised in order to eliminate these disadvantages and reduce number of polygons in homogeneous areas. All the holes on the surface are also removed to make the surfaces completely cylindrical and concentric as required by the construction [3-6].

At the stage of creating a solid model of a workpiece, the mesh model is firstly investigated to identify areas that appear to be planar, cylindrical, conical, spherical. In Solid Edge, flat polygon collections are coloured in yellow, cylindrical in pale blue, spherical in dark blue and conical in red. Both automatic surface recognition (see Fig. 4a) and manual mode are available. As for purple polygons, the system has not been able to determine their analytical form because they often represent a "boundary" between different forms of the model which can be identified. Some areas of the model are identified incorrectly, so its borders are highlighted in purple and painted in corresponding color. Thus, all the surfaces are manually determined in this way (see Fig. 4b) [3-6].
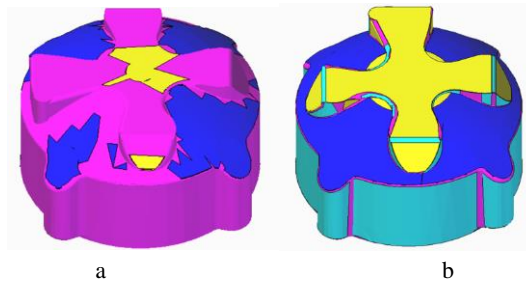
a   b

Fig. 4. Mesh model after automatic surfaces recognition (a) and identification of all areas on the body of the model with the applied boundaries between them (b).

The next step of designing a solid model of the workpiece is stretching the required surfaces from the mesh model and extending them to complete intersection. It is possible to stretch surfaces both in automatic (see Fig. 5) and manual mode (see Fig. 6).
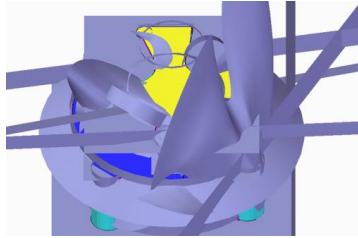
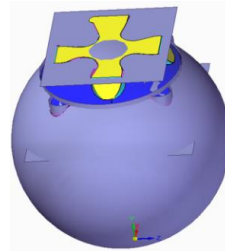**Fig. 5.** Surface stretching in automatic mode.

Fig. 6. Manual stretching of surfaces required to determine the general shape.

The applied software allows to create a solid model that is formed by the nested set of selected surfaces (see Fig. 7). When the mesh model is imposed on the solid body of a workpiece, it is possible to verify how closely these two objects correspond each other (see Fig. 8). The same way all other surfaces in the mesh model are stretched

and expanded. After solid model components are formed, all the structural elements, such as holes, threaded holes, chamfers and joints are completed (see Fig. 9).

At the stage of the shape analysis and required stress simulations, material properties are attributed to the created solid model and a virtual workpiece is fixed at the mounting points. The stresses are applied according to the subassembly documentation in order to determine their effect on the model. The obtained results of simulations are analysed to indicate the sufficient and necessary strength of the designed product. Then the model can be transmitted to 3D printer or it can be machined for further application.
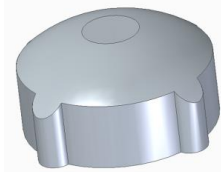

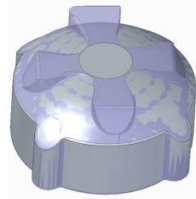**Fig. 7.** The solid model formed of selected mesh surfaces.

Fig. 8. Mesh model imposed on the solid body of a workpiece.

Fig. 9. The result of reverse engineering.

Results

Along with available and verified information model, presented method might be used for other practical applications. As an example, reverse engineering technology is considered in a process of creating an implant for thigh bone reinforcement [7, 11, 12]. Thus, stages of information model development (see Fig. 10) are adapted according to the specificity of the process of implant design based on computed tomography scanning of a limb and imply other operations compared to mechanical engineering.
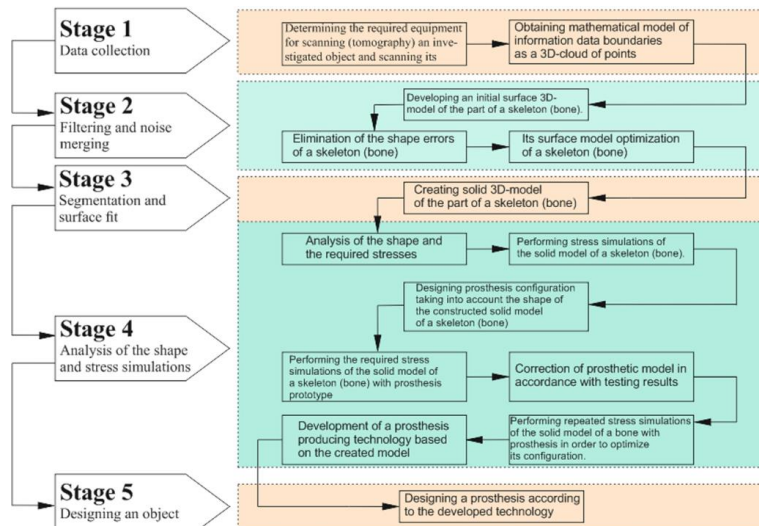

Fig. 20. Information model for creating a part of a skeleton using reverse engineering approach.

The first stage of information model development is data collection that consists of several steps. Images obtained using computed tomography scan methods provide a basis for a femur design. After being analysed with InVesalius 3.1 computer software, these images form a 3D point cloud (see Fig. 11) [12], which describes edges of the femur. The point cloud is a basis for virtual model development of this bone in the computer simulation system. Since mathematical model of a thigh bone is created as a virtual object, it is imported into Fusion 360 software for further editing [7, 11, 12].

Fig. 31. Model of a bone obtained using 3D scan.

The next step in the process of 3D editing is a point processing. During this stage it is necessary to reduce noise in order to decrease the number of points of the scanned data in uniform areas. Model simplification allows to significantly reduce time of the model processing as well as makes it possible to control accuracy of geometrical constructions. Simplification was accomplished in MeshLab software which enables to carry out different types of editing of three-dimensional models. The model consists of 6 552 polygons. This number of polygons makes calculation of the model significantly more complicated and slows down further research, especially in the reinforced state. Number of polygons should be reduced by 6 times to prevent holes forming in the created model [7,11-17].

At the stage of segmentation mesh model is built of triangles controlled according to the requirements of the program. In order to obtain the model of acceptable quality, density of the mesh model should be adjusted. The reason for that is inaccuracies in the form of open polygons that occur when the object is being created using 3D scanning. With the help of Fusion 360 the deficiencies are eliminated and density of the mesh model is changed [12]. As a result, the complete mesh model of a bone is finalized.

In order to receive an acceptable and correct result of stress simulations, computer model of a bone should consider physical characteristics that approximate real features of the material as closely as possible. Since bone tissue is a complicated multi-layered biocomposite material, it is simplified to two-layer computable model. An outer layer is a hard tissue determined by its homogeneity and density. Inner layer is cancellous bone material which is more porous and flexible.

Designing of the outer layer of a bone requires to transform mesh-body into a B-Rep model (see Fig. 12) [12]. Solid models in Fusion 360 are presented with a set of surfaces that form tightly closed volume. This model enables to calculate volume, physical properties of the object and to determine the center of mass. Creating of inner layer of thigh bone requires offset of each polygon in the model by about 10%. Determining the centre of the model for that is carried out using the center of mass search instrument and applying Scale tool with appropriate settings. After that, inner layer is separated from the outer one with the help of relevant function with settings that allow to select the main body and the instrument body (see Fig. 13) [11-12].
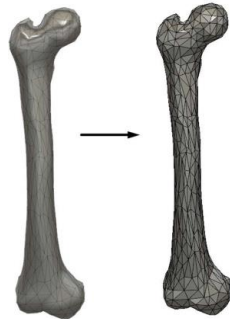
Fig. 42. Demonstration of applying transformation of the Mesh model into B-Rep.

Fig. 53. Result of applying function of combining bodies.

The last stage of 3D editing is a phase of designing. At this stage the model is transformed into NURBS surfaces that represent shape segmentation. All of the segments fit closely to one another which provides shape smoothness. After this stage is complete NURBS surface (see Fig. 14) [11] can be exported into STL, IGES or STEP file depending on the type of the program [13-17].

Fig. 64. Created solid model of thigh bone.

Analysis of the shape and the required stresses for the created solid model of a bone is provided for the whole proximal including greater trochanter and the neck of the femur because implants and their effect on stress distribution are considered in motion. Calculation of the stress distribution is performed in Fusion 360 software, but ANSYS application might be also used for its finalization and correction. Required stress simulations of the solid model of a bone are carried out in three directions (for horizontal, vertical and rotational force application). Results received during these testings are shown in Fig. 15 [7,11,12].

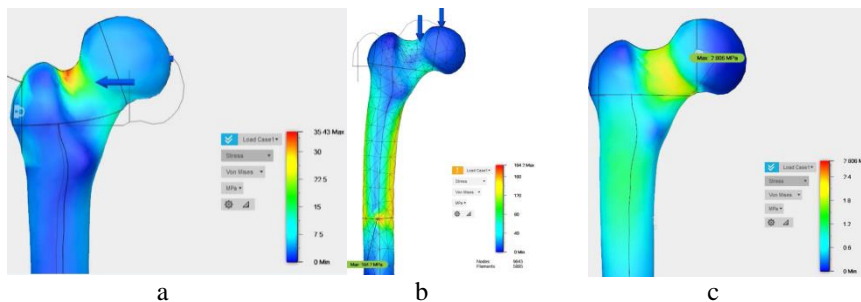a   b   c

Fig. 75. Results of simulation of stress distribution in the model of a bone for the cases of horizontal (a), vertical (b) and rotational (c) force application.

Proximal femur reinforcement is performed to strengthen biocomposite material and prevent hip fracture of the femur for patients belonging to high risk group. Shape of the implant is designed in Fusion 360 software based on the constructed solid model of thigh bone. The device consists of bended flexible trihedral spokes, inner guide bushes, diaphyseal plate and monocortical screws. Optimal model of an implant that meets all operational requirements is designed applying geometric and polygonal modelling. Process of the plate designing and positioning of created components of an implant is presented in Fig. 16 [7,11,12].
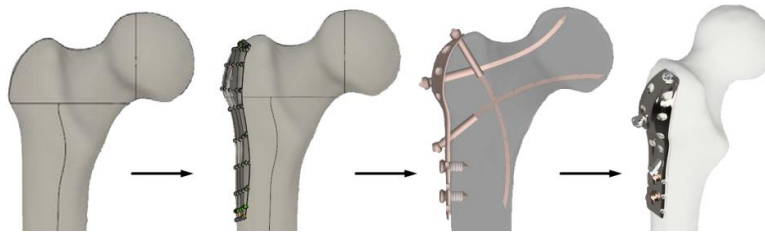

Fig. 86. Process of the plate designing and positioning of created components of an implant.

At the stage of required stress simulations, material properties attributing to the solid model of a bone with an implant is essentially important. After that either knee joint or part of the greater trochanter and one third of diaphysis are fixed. In this case stress distribution also takes place in three directions (see Fig. 17) [7,11,12].
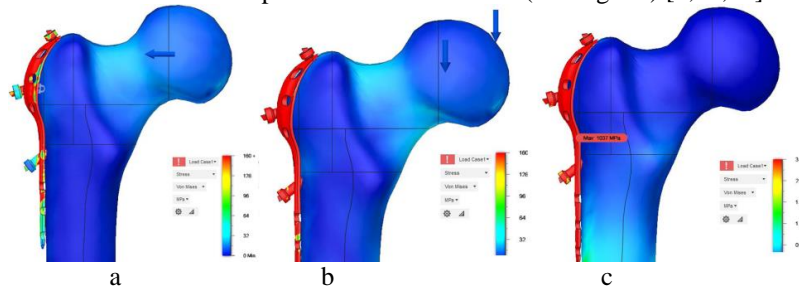

a   b   c

Fig. 97. Results of simulation of stress distribution in the model of a bone with an implant for the cases of horizontal (a), vertical (b) and rotational (c) force application.

As can be seen from comparison of stresses, applying an implant significantly reduces level of strain in a bone as it accepts maximum general stress in all cases. The bone remains in its natural state and does not deviate due to the implant installation. Figure 17 shows areas that experience maximum stresses in a bone and in an implant. Correction of the implant design is carried out repeatedly according to the testing results in order to obtain a reliable but still anatomically correct construction [11-17].

At the final stage real implant for femur reinforcement is created using additive or other modern technologies. Therefore, reverse engineering makes it possible to design an implant using computed tomography scan method in order to fit individual customer demands. If the suggested implant does not show an appropriate result, another type of the implant construction can be used for this purpose (see Fig. 18) [12]. In case of difficult injuries of the proximal or missing parts of a bone spherical metallic

implant might be also applied (see Fig. 19) [7,11,12].

Fig. 119. Spherical metallic implant installation.

Fig. 108. Alternate version of proximal femur reinforcement.

Conclusions

This study is focused on a new approach to development, analysis and application of information model, which includes the entire data for each step of creating an object using reverse engineering technology. Reverse engineering concept is presented in detail and applied to a typical workpiece. The problems of creating solid model of an object on the basis of mathematical model obtained as a result of 3D scanning are considered through improving reverse engineering technology into a 3D model of sufficient quality.

Applying an available and verified information model, this approach is suggested to be used in other areas, for instance, in a process of designing an implant for femur reinforcement which is based on reverse engineering technology. In this case, information model is transformed in order to solve the specific problem. Along with creating a virtual prototype of the real object, further design of anatomically shaped implant is also considered to make an implant fitting closely to the complicated surface of a bone. The most probable variants of applied force direction (horizontal, vertical and rotational) have been taken into account during stress simulations. Analysis of the results received in Fusion 360 software prove that applying an implant significantly reduces level of strain in a bone as it accepts maximum general stress. ANSYS software tools may be used for the model development in order to get more detailed results of the simulations.

Applying information model of the object's life cycle is proved to be feasible in reverse engineering process. It reduces the amount of time needed to design, analyse and carry out stress testings of the model both as part of theoretical research and for practical purposes. Presented information model might be developed in order to design objects which have missing parts of the shape that happens as a result of injuries or surgery. This method of design allows to advance the process of prosthetics and patients' recovery.

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