

This study estimates the geometric accuracy of an aviation part's digital model constructed from a portrait. The task addressed is to reproduce the geometry of an aviation part based on its original dimensions.

A procedure is proposed for reconstructing the geometry of aviation parts that have wear or deformation (changes in size and shape from the rated ones) and assessing the accuracy of a digital 3D model using RE methods. An approach to digitizing test parts using RE is suggested in the form of a general algorithm for generating data on a digital 3D model of a test part. The algorithm includes 3D scanning, point cloud processing, polygonal model construction, analysis of "shadow zones", and additional iterations with a change in the position of the part. The latter allowed for high-precision identification of the geometry of the original test part for building a digital 3D model.

The approach was tested on the example of an impeller using a HEXAGON Absolute Arm coordinate measuring machine with an AS-1 laser scanner, which provided a scanning accuracy of ± 0.05 mm and a point density of up to 0.026 mm. Current geometry control and correction of deviations using a color map were carried out at each stage of the algorithm implementation. That has made it possible to minimize errors, eliminate "shadow zones", and restore the lost geometry of the original impeller when building a digital 3D model. The final control of the constructed model showed robustness of the results within the range of ± 0.05 mm.

The results could make it possible to prototype test parts with signs of wear or damage with a reproduced high-precision geometry within the tolerance for the manufactured size

Keywords: reverse engineering, 3D scanning, geometry reconstruction, geometry accuracy, reconstruction algorithm, digital model, surface control

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DEVISING AN APPROACH TO PROTOTYPING A WORN OR DEFORMED AVIATION PART BASED ON REVERSE ENGINEERING

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1. Introduction

The development of modern aviation technologies requires accurate reproduction of parts with complex spatial geometry, which is sometimes difficult and impractical to implement using conditional methods [1]. This has led to the design of computerized information and measurement systems, including intelligent and virtual measuring tools [2]. The latter is carried out by both contact and non-contact methods with integration into existing computer-aided design systems [3]. One of the most effective technologies in this respect is reverse engineering, which can combine the processes of contact control on a coordinate measuring machine (CMM) and non-contact 3D scanning [4].

Operation of such products under military conditions requires constant repair and replacement of worn, damaged, or deformed parts and subassemblies. Therefore, reverse engi-

neering becomes indispensable when it is necessary to quickly build polygonal models, construct surface and solid CAD models (digital 3D models), and control the accuracy of the restored geometry for small-batch parts [5]. This is especially true for complex-profile parts that operate under conditions of high loads and intense wear and require geometry restoration to build digital prototypes suitable for strength calculations using finite element methods (FEMs) [6, 7].

Therefore, worn, damaged, or deformed parts of complex shapes, especially when there is no design and technological documentation, require the reproduction of a digital 3D model with high accuracy. However, RE makes it possible to digitize and duplicate the geometry from the original at prototyping or reconstruction. Thus, it becomes relevant to conduct research to evaluate the resulting accuracy of the reconstruction of a digital 3D model from the original worn, damaged, or deformed part.

2. Literature review and problem statement

Optical scanning and computed tomography with different acceleration voltages were applied to construct a digital model of a turbine blade in [8]. The resulting file was used to manufacture a test part using selective sintering technology. However, despite the positive results of prototyping, only the original part is controlled for deviations from the geometry. In [9], the use of RE is demonstrated for prototyping an engine turbine blade, in which an analysis of errors between the data obtained from 3D scanning, measurements on a CMM, the constructed CAD model, and MESH data is performed. It is noted that the deviations between the scanning data, the CAD model, and CMM are within the permissible values (30 microns), and between the CAD model and the MESH data are in the range from -0.1 to $+0.1$ mm.

One should note the importance of MESH data in reproducing the geometry of the experimental part as MESH data is a grid or frame of a 3D object, which consists of vertices (points), edges (lines), and faces (polygons, usually triangles/quadrilaterals). The latter forms its surface for visualization, simulations, or engineering tasks. However, the authors of [9] neglected MESH data and used the resulting CAD model without specifying the geometry of vertices, edges, and faces for 3D printing.

An alternative is the results reported in [10], in which the correction of the geometry of the digital pump model was performed based on the results of FEM. The correction was also carried out at the stages of computational fluid dynamics (CFD) calculations to assess the performance of the centrifugal pump and calculate variables such as speed, pressure, and fluid flow in CAD/CAM systems. The only drawback is the high complexity of the work and the need for powerful computer technology.

The authors of [11] concluded in favor of 3D scanning of a composite blade of an automotive axial fan that changes shape in height during operation but did not give data on the resulting geometric accuracy. The basics of RE were also used to digitize a stainless steel lever part from an aircraft control unit with its subsequent manufacturing using additive technologies [12]. This presented the reproduction of the geometry of the part using standard software functions with the subsequent construction of a digital 3D model for the manufacture of samples using various technologies: sand casting and metal extrusion. However, in this case, we are talking about controlling the accuracy of the manufactured samples, rather than the reconstruction and control of the geometry of the digital 3D model.

Several papers [13, 14] highlight the importance of obtaining and refining a portrait with high accuracy to an "ideal" one, as well as the choice of an approximation method and processing the obtained surfaces by 3D scanning. Thus, in [13] it is shown that when obtaining data by a non-contact method, the properties of the surface being scanned should be taken into account and certain methods of matting it should be used, which could improve the density of the portrait point cloud. It should be noted that the scanning accuracy is affected not only by the surface properties (mirror and black color) but also by the possibility of a perpendicular approach of the laser beam to the surfaces, which was not taken into account by the authors.

In study [14], the dimensional and geometric accuracy of the final 3D models obtained by RE by contact and non-contact methods was assessed, in which the resulting error varied from 0.02 mm to 0.2 mm. However, the authors did not take into account the fact that during the manufacture of the part

there is an error and the final total error should be evaluated for the positivity of the results. The latter suggests that deviations from the geometry can increase many times, so the theory of the authors described in [14] should be verified by full-scale experiments. However, for complex-profile parts (double-curvature blades), such experiments are always expensive and require high qualifications of the performers. Therefore, the adequacy of the adopted engineering solutions for prototyping when processing the portrait point cloud and rebuilding a digital 3D model based on it is most determined by the results of assessing the accuracy of the reconstruction of the geometry of the original part.

Therefore, there is a need to devise an approach to prototyping such parts while providing a predefined geometric accuracy at the stages of constructing a digital 3D model using RE technology.

3. The aim and objectives of the study

The purpose of our research is to provide the geometric accuracy of a digital 3D model by devising an approach to reconstructing the geometry of worn, damaged, or deformed aviation parts and assessing the accuracy of a digital 3D model using RE methods. This will make it possible to quickly implement RE engineering solutions for refining and rebuilding polygonal and digital 3D models, as well as for increasing the accuracy of the production of a full-scale part.

To achieve the goal, the following tasks were set:

- to develop a general algorithm for generating portrait data on an experimental part;
- to build a polygonal model based on the resulting portrait;
- to construct a digital 3D model based on the polygonal model of the experimental part enabling control over the resulting geometry.

4. Materials and methods

4.1. The object and hypothesis of the study

The object of our study is the geometric accuracy of a digital 3D model extracted and constructed from the portrait.

The principal hypothesis assumes that the geometric accuracy of a portrait is achieved under the condition of full contact of the laser beam with the surface of the test part. Full contact denotes angles in the range of $90^\circ \pm 15^\circ$ and those that do not produce shading of the object. It is assumed that the tolerance for deviations in the shape and location of the surfaces of the test sample is limited by the tolerance field for the size from the reference data generally accepted in mechanical engineering [15] and for the cases of prototyping based on RE established by the authors of [16].

The study was carried out in the following steps:

- 1 – selection of the necessary measuring technological equipment;
- 2 – 3D scanning;
- 3 – processing of the acquired data on the scanned surfaces and construction of a portrait;
- 4 – construction of a polygonal model from the geometry of the data on the obtained portrait;
- 5 – construction of a digital 3D model of the impeller based on data for the polygonal model;
- 6 – control of the constructed models of the experimental part;
- 7 – analysis of the results and drawing conclusions.

4. 2. Subject of the study

The subject of our study is the reconstruction of the geometry from the original complex-profile part of an aircraft using RE technologies. An impeller was selected for the experiments (Fig. 1). According to the structural and technological analysis, the HEXAGON Absolute Arm (France) CMM with an AS-1 laser scanner was selected as the means of technological equipment (Fig. 2) [17]. The selected CMM with a scanner has a scanning accuracy of 0.05 mm and a point density of up to 0.026 mm, which satisfies the tolerance field for the size of the experimental part.



Fig. 1. Impeller



Fig. 2. HEXAGON Absolute Arm CMM with AS-1 laser scanner

A "digital 3D model" designates a model constructed by means and tools of CAD systems using spline geometry [18].

A polygonal model consists of polygons (most often triangles) constructed on the basis of point clouds obtained by scanning [19].

A point cloud is the basic result of 3D scanning, which is a set of small points in three-dimensional space, each of which has its own X , Y , Z coordinates. The point cloud provides information about the geometry of the surface and the representation of the external surface of the object, i.e., its shape.

The parameters for monitoring and comparing the resulting model were taken as "deviation of the shape of a given profile" according to the definitions given in [20]. The geometric parameters of such deviations are the largest deviation of the points of the real profile from the corresponding points of the rated profile, which is determined by the normal within the normalized area.

Scanning and processing of the acquired data were performed using the PolyWorks software (Canada), applying the HEXAGON Absolute Arm (France) CMM with the AS-1 laser scanner. The PolyWorks IMAAlign module (Canada) was used for 3D scanning, and the PolyWorks Inspector module (Canada) was employed for constructing a polygonal model and aligning it with the inscribed primitives [21].

The modeling and current control of the digital 3D model with a polygonal mesh was performed in Geomagic Design X (USA) using the Deviation Color Map. The control of the digital 3D model was performed in Geomagic Control X (USA) [22].

5. Results of research on devising an approach to geometry reconstruction when prototyping worn, damaged, or deformed parts

5. 1. Development of an algorithm for generating part portrait data

Fig. 3 shows a general algorithm for generating portrait geometry data.

Thus, stages 1–3 are always performed for any shape of the test part. At stage 1, 3D scanning is implemented. Stages 2–3 are technical stages, based on the analysis of which a decision is made on the completeness (continuity) of the scanned surfaces and edges of the test part. For simple shapes of test parts, a full chain of stages 4–5–6–7–8–19 is then implemented.

That is, with positive results (stage 4) provided that one position of the part is sufficient, i.e., at $i = 1$ (without its rotation and change of location), stages 5–6 will follow. At stage 5, all the obtained portraits of one group are combined into a single portrait with the subsequent construction of a polygonal model of the file format "*.STL". At stage 6, the resulting geometry accuracy from the original part is controlled. Satisfactory indicators of stage 6 will allow one to make a transition from the CMM coordinate system to the polygonal model built in stages 1–6 and export it to a CAD program (stages 7–8) with the subsequent construction of a digital 3D model (stage 19). With negative data from stage 6, a change in the position (location) of the test part and 3D scanning should be performed (stages 6–17–18). A similar case is for the stage of analyzing the continuity of a group of portraits obtained from the part, i.e., the position of the part is changed so that there is access for 3D scanning and an acquisition of lacking geometry (stages 3–9–18).

For complex-profile parts such as the selected experimental impeller (Fig. 1), stages 1–4 are retained. However, the number of groups in this case becomes more than one, i.e., $i = 2...n$, where n is the total number of changes in the impeller positions. The next steps are the alignment of portrait groups in the position of the impeller shape (stage 10), their alignment (stage 11), and grouping (stage 12). Positive results from the analysis of the continuity of the processed groups of portraits (stages 13–14), obtained from the original part, make it possible to construct a single portrait, and after it – a polygonal model "*.STL" and perform geometry control (stage 6). Satisfactory geometry data of the single portrait will make it possible to complete the work on forming portrait data and exporting it to a CAD program (stages 7–8) with the subsequent construction of a digital 3D model (stage 19).

Negative results from the continuity of the processed groups of portraits (stages 13–15) will require a change in the position of the part and its re-3D scanning with the next set of data. A similar situation will occur at the stage of controlling the geometry of a single portrait (stages 6–17–18).

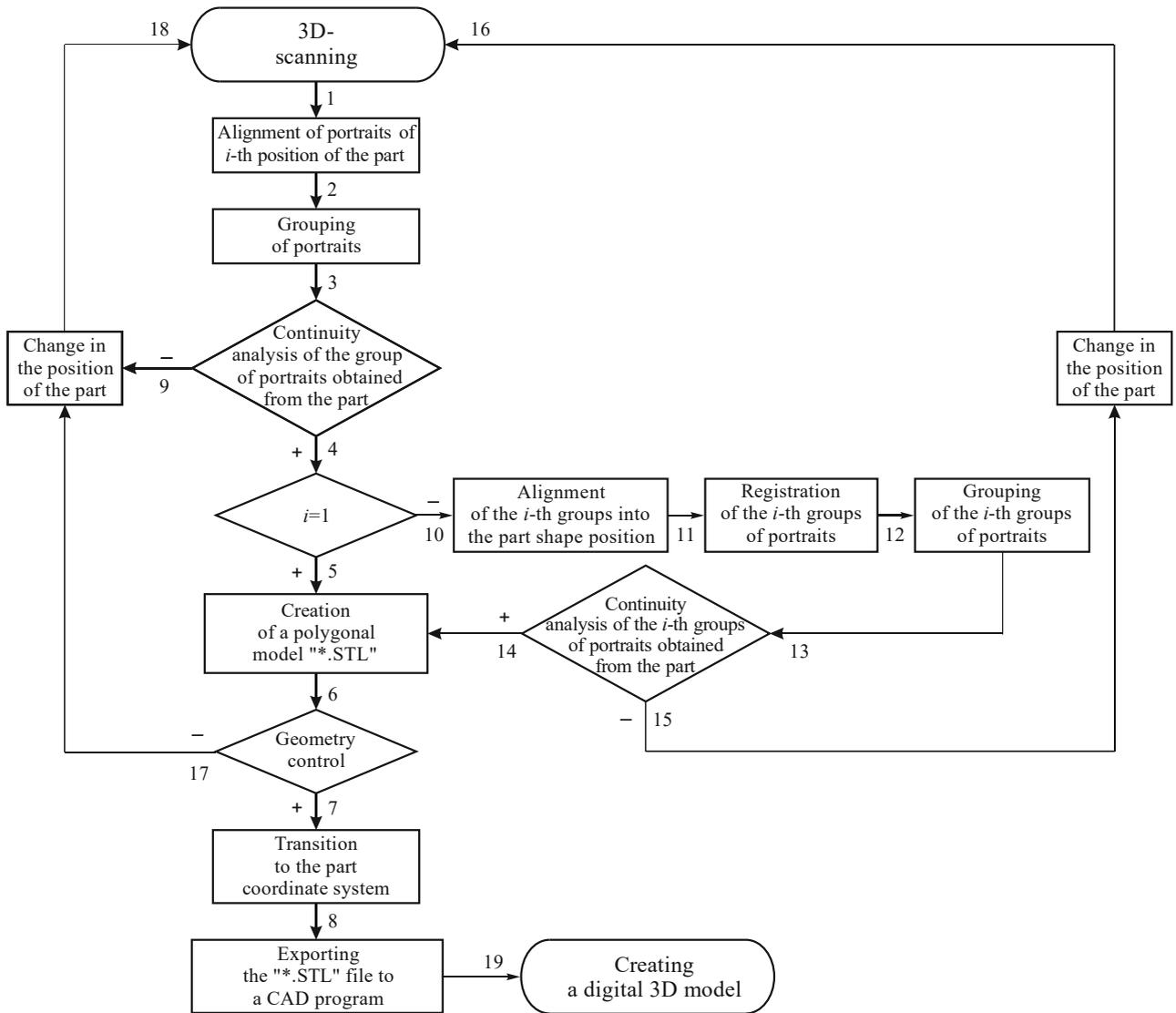


Fig. 3. General algorithm for generating data on a 3D digital model of a test part

5. 2. Building a polygonal model of the impeller

Fig. 4 shows the process of 3D scanning the impeller (stages 1–4, Fig. 3) and constructing a single portrait of the part in the "*.STL" file format (stages 10–14, 6–8). Note that stages 3–9–18 and 13–15–16 were implemented about eight times before the final completion of the file export to the CAD program – Geomagic Design X (stages 6–8–19). That made it possible to

fully cover hard-to-reach areas of the surface with subsequent alignment of the point clouds into a single part shape (Fig. 5).

The polygonal model of the impeller was imported into Geomagic Design X with additional checks of the integrity of the portrait, as well as correction of topological defects and orientation of the model in the coordinate system for further construction of axial elements.

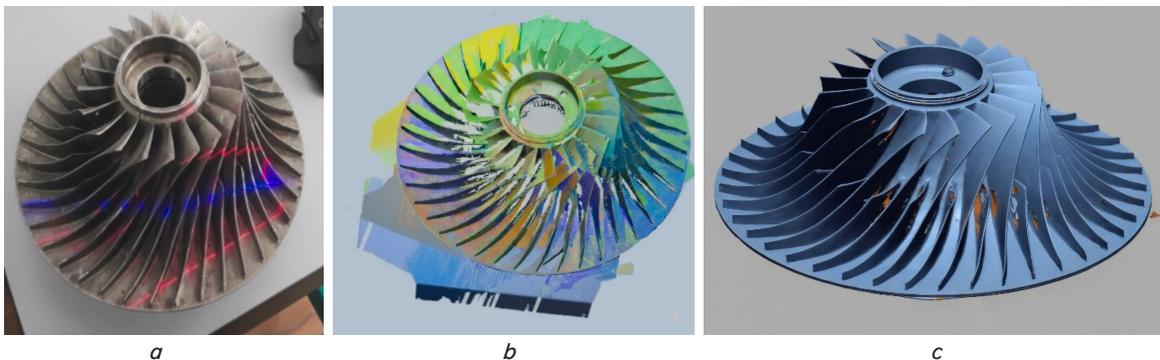


Fig. 4. Constructing a single portrait of the impeller: a – 3D scanning; b – grouping of portraits; c – polygonal model of the impeller "*.STL"

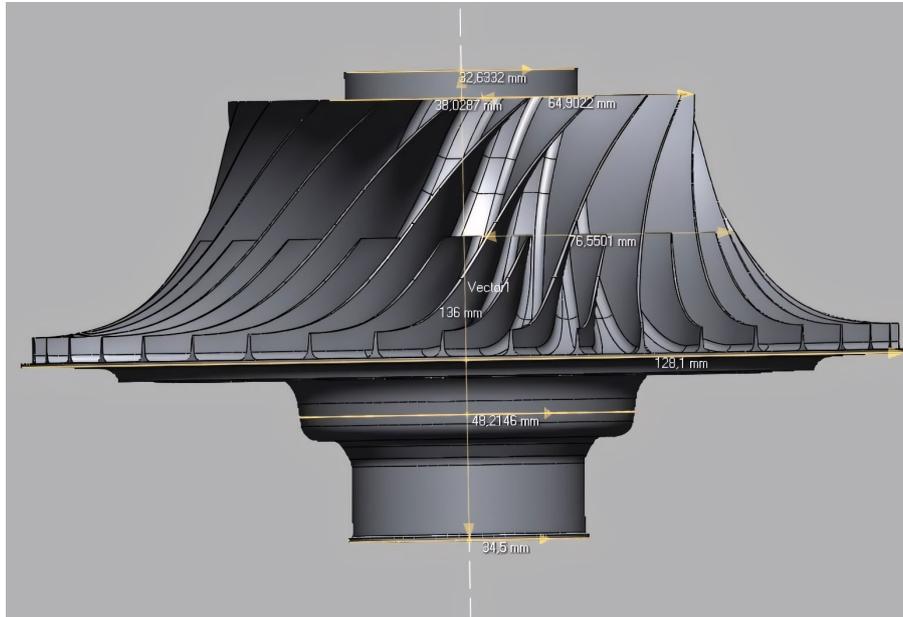


Fig. 5. Resulting structural parameters for a digitized/scanned part of the "impeller" type based on the original dimensions

5. 3. Construction of a digital 3D model of the impeller and control over geometry accuracy

The next stage was the reproduction of the basic geometry of the central part of the impeller using a polygonal model. We found a deviation from the roundness of its inner diameter, which was taken into account when constructing the 3D model (Fig. 6).

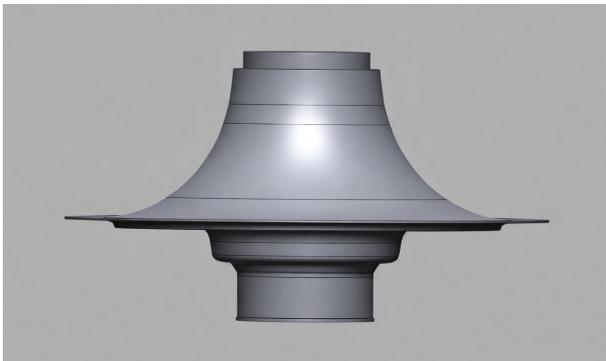


Fig. 6. The reproduced basic geometry of the 3D model of the central part of the impeller

For this purpose, a set of tools in the Geomagic Design X program (USA) was used: Mesh Sketch and Revolve. The profile of the bushing was built by forming a sketch according to the "silhouette" acquired from the polygonal model. The rotation operation around the axis enabled the formation of an accurate axisymmetric part of the part. At this stage, special attention was paid to the correct location of the axis since it sets the basis for further replication of the blades and determines the geometric center of the entire model.

Next, the main working elements – blades – were reproduced. Their shape is characterized by a complex three-dimensional curved surface that changes the angle of attack and curvature along the length. To construct one large and one small blade, surface modeling was used by applying the Surface Modeling tools and the Loft and Mesh Fit operations in the Geomagic Design X program (USA) (Fig. 7).

Before constructing the surfaces of the digital 3D model, the polygonal model was segmented – the selection of individual areas corresponding to each blade was performed, which allowed us to obtain clear contours for construction (Fig. 7, a). Based on the obtained profiles, guide curves were constructed for the formation of surfaces, which ensured a smooth transition from the root part of the blade to its original edge.

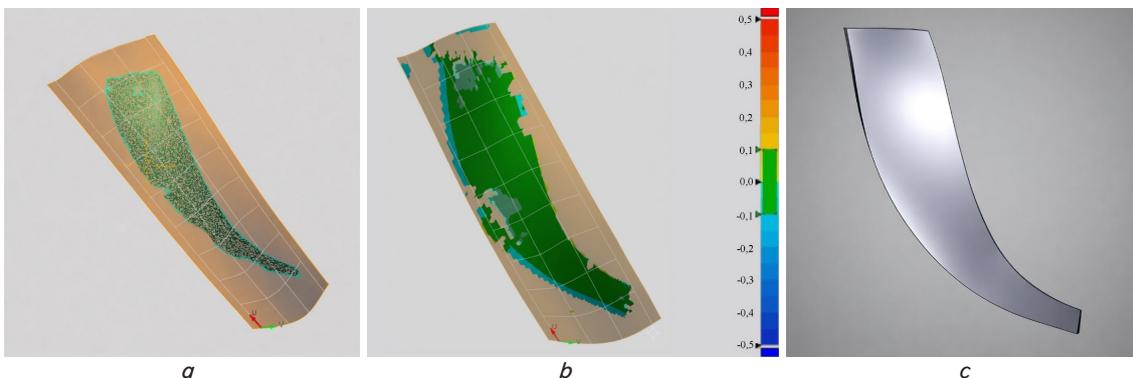


Fig. 7. Step-by-step construction of a digital model of the impeller: *a* – superimposing the surface on the selected area (Mesh Fit); *b* – current control over the surface construction by building a color map of deviations; *c* – the first iteration of making a 3D model of the impeller

In places where minor damage was observed on the polygonal model, wear or knocked down edges, contours were restored using interpolation and extrapolation of surfaces. In places where such restoration was not possible (bursts, deflections with loss of profile in the cross section, etc.), that is, a complete reconstruction of the surface geometry was required, the geometry of the corresponding surviving areas of the blades from the original undamaged part was used. After each stage of modeling, the geometry of the surfaces was controlled by constructing a color map of deviations (Fig. 7, *b*). After each iteration, the geometry of the impeller blades was checked using a color map with a final geometry reconstruction (Fig. 8).

The formation of a complete digital 3D model of the impeller while preserving the mutual arrangement of all elements is shown in Fig. 9.

After constructing the reference surfaces of the large and small blades, a data array was formed around the axis of rotation. For this purpose, the Circular Pattern tool from the Geomagic Design X program (USA) was used, which allowed us to automatically multiply the constructed blade models around the central axis. The angular step was determined based on the number of blades recorded during scanning, which allowed for an exact correspondence of the spatial arrangement to the original part.

It should be noted that we do not know the value of the geometric accuracy of the manufactured part, so it was decided to use reference data generally accepted in mechanical engineering. Thus, according to recommendations from [16], in the absence of instructions on permissible deviations in the shape and location of surfaces, such deviations are limited by the tolerance field for the rated size of the part. It is assumed that the impeller is manufactured to the eighth quality of accuracy.

At the final stage, a current control of the geometric accuracy of the model was performed. For this purpose, the built-in Accuracy Analyzer (Deviation Analyzer) module was used in Geomagic Design X, which makes it possible to compare the constructed model with the original polygonal data in real time. The deviations were visualized in the form of a color map (Fig. 10), which demonstrates the differences between the restored geometry and the original surface.

Based on this analysis, local correction of curves and surfaces was additionally performed, which made it possible to achieve high accuracy of reproduction, with permissible deviations of no more than ± 0.05 mm, taking into account the adopted eighth quality.

At the final stage, the geometric accuracy of the digital 3D model was finally checked in the Geomagic Control X software, subject to a tolerance of ± 0.05 mm. The check results are shown in Fig. 11.

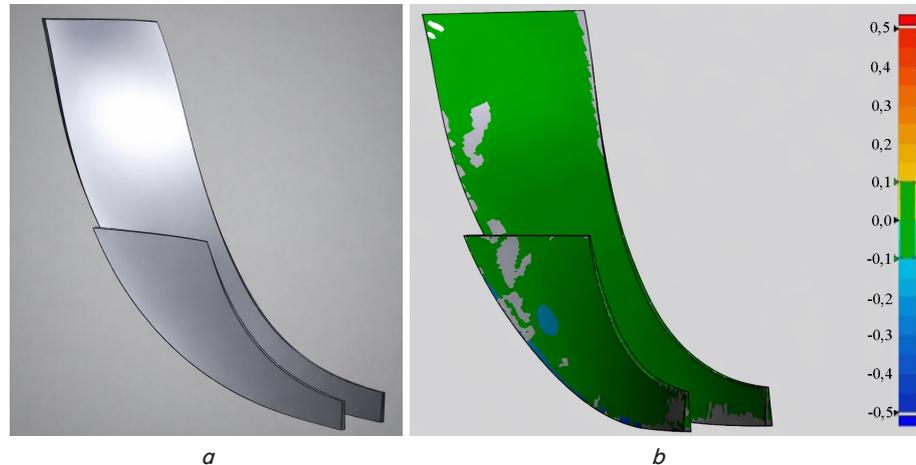


Fig. 8. Digital models of blades: *a* – large and small blades; *b* – current quality control using a color map of blade construction deviations

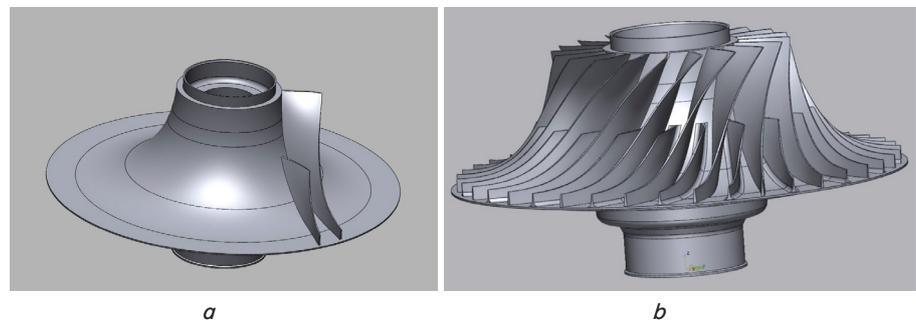


Fig. 9. Complete digital model of the impeller: *a* – basic digital 3D model of the impeller before replicating the blades; *b* – digital 3D model of the impeller

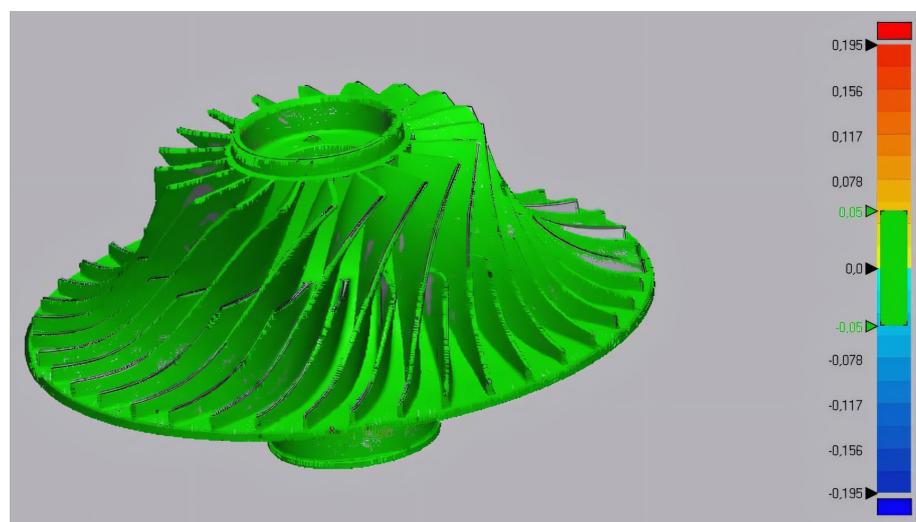


Fig. 10. Current control of the geometric accuracy of the constructed digital 3D model of the impeller using a color deviation map

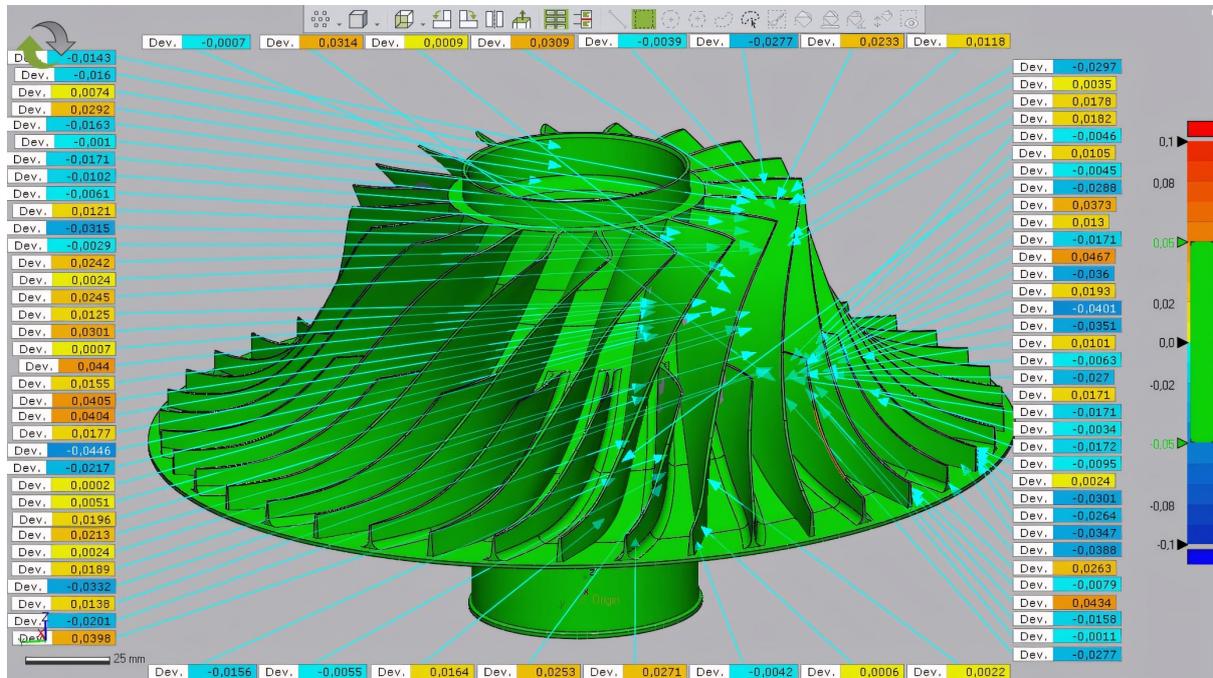


Fig. 11. Checking the geometric accuracy of the digital 3D impeller model

The range of deviations in the geometry of the digital 3D model of the impeller was obtained, from -0.0388 mm to $+0.0467$ mm. The smallest deviations were 0.00101 mm and $+0.0002$ mm on the side edges of the large and small blades. The largest deviations of -0.0388 mm and $+0.0467$ mm were observed on the outer surfaces of the large blade when it was twisted. The general pattern of geometry deviations over the entire area of the digital 3D model of the impeller is represented in the form of a histogram (Fig. 12).

The histogram demonstrates what percentage of the impeller area of the total area is in the ranges:

- from 0 to -0.025 mm – 37.60%;
- from 0 to $+0.025$ mm – 36.05%;
- from -0.025 to -0.05 mm – 9.88%;
- from $+0.025$ to $+0.05$ mm – 13.18%.

The smallest percentage of area in the deviation ranges from -0.05 mm to -0.0833 mm: 0.78%; and from 0.05 mm to 0.0833 – 0.97%.

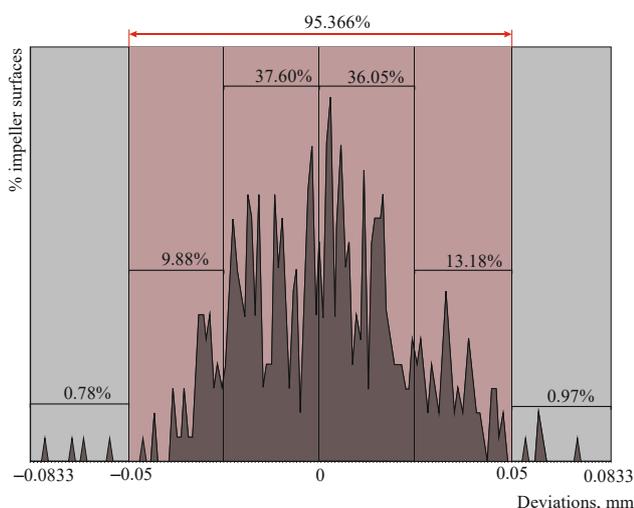


Fig. 12. Histogram of surface deviations in the digital 3D impeller model

6. Discussion of the results of devising an approach to reconstructing the geometry of an impeller that has signs of wear and deformation at prototyping

3D scanning of the original impeller (Fig. 1) was performed on the HEXAGON Absolute Arm CMM with an AS-1 laser scanner (France) (Fig. 2). That has made it possible to recognize the original geometry of the damaged part with high accuracy, namely ± 0.05 mm. It should be noted that, compared with control data reported in [9], our studies took into account MESH data of vertices, edges, and faces. The latter had a positive effect on the accuracy of the resulting geometry of the edges of the impeller blades. Thus, the smallest deviations were obtained on the side edges of large and small blades in the range from -0.00101 mm to $+0.0002$ mm, which, in turn, corresponded to a tolerance of ± 0.05 mm.

According to the general algorithm developed for generating data on the original geometry (Fig. 3), the phasing of RE activities for digitizing the test part was determined. The defined approach to the algorithm allowed us to structure and systematize the operator's work and minimize the number of stages 1–4 of scanning for the collection of missing geometry. It should be noted that analysis after each completed stage 3, 6, or 13 (Fig. 3) allowed us to immediately detect gaps in 3D scanning data, which arise due to the lack of approaches to the scanning location and the formation of "shadow zones". And the corresponding stages 9, 7, or 15 implemented the necessary additional 3D scanning of hard-to-reach surfaces.

Thus, the RE approach has been tested in the form of an algorithm, on the example of a research impeller, which showed the positive results of geometry reconstruction on a polygonal model, which could be useful for work [10].

Unlike the approach to constructing and controlling a digital model described in [13], the lost geometry (deflections with loss of profile in the cross section, etc.) of the original part was partially reconstructed. Thus, in places where the geometry of minor damage, wear, or knocked-down edges was observed, contours were restored on the polygonal model

using interpolation and extrapolation of surfaces. This approach allowed us to compensate not only for scanning defects but also to obtain a continuous geometry with a high degree of smoothness. The latter allowed us to increase the accuracy of constructing a digital 3D model, which, in turn, will positively affect the accuracy of the manufactured real part.

A feature of the proposed approach is overcoming the issue of "shadow and invisible zones" and enabling the smoothness and continuity of the restored surfaces. The integration of current control at each stage made it possible to minimize errors, which is especially important for parts with such critical geometry as an impeller, i.e., for blades with torsion.

It should be noted that the digital reconstruction of the geometry on the example of an impeller was carried out in the Geomagic Design X software (USA), specialized for RE. A feature of the choice of such software is the combination of tools for working with polygonal models and means of accurate parametric CAD modeling, as well as built-in modules for analyzing deviations. The use of Geomagic Design X (USA) made it possible to construct a high-precision three-dimensional model of the impeller and, at the same time, form a parametric construction history for the possibility of reconstruction and integration into any existing CAD systems of the enterprise without loss of geometry accuracy. The use of such software could be recommended to the authors of [14], which would increase the accuracy of the final digital model from 0.2 to 0.1 mm and more.

The check carried out in the Geomagic Control X software (USA) demonstrated the positivity of our results from the reconstruction of the geometry of the deformed impeller. It was established that in the range from -0.025 mm to $+0.025$ mm there was 73.65% of the area, where the smallest deviations from -0.00101 mm to $+0.0002$ mm were on the side edges of the large and small blades. In the ranges from -0.025 mm to -0.05 mm, 9.88% of the area was established, and from $+0.025$ mm to $+0.05$ mm -13.18% of the area. The resulting values were within the tolerance for deviations in the restored geometry, i.e., they were within the range of ± 0.05 mm.

The smallest percentage of area in the deviation ranges from -0.05 mm to -0.0833 mm is 0.78% and from 0.05 mm to $0.0833 - 0.97\%$. This percentage is so small that it can be neglected.

Therefore, if rapid prototyping of a deformed complex-profile aviation part is required, it is recommended to manufacture it using additive or extractive technologies that provide high manufacturing accuracy, i.e., ± 0.05 mm and more. Therefore, the devised approach becomes indispensable; our results may prove useful for improving existing RE methods and approaches for prototyping parts of aviation articles.

The applicability of the proposed approach is limited by the individuality of the decisions made, which is caused by the peculiarity of the geometry for a specific experimental part. In the absence of a part or parts of the original part during its digitization, it is advisable to perform shaping and restoration of the geometry directly at the 3D modeling stage.

The disadvantage of using the proposed RE approach is the increase in the complexity of the work. However, the construction of a high-precision polygonal model will make it possible to increase the accuracy for constructing a digital 3D model, which, in turn, affects the accuracy of production of the original part, which is prototyped using RE.

Further research should involve expanding the approaches to prototyping damaged and deformed surfaces of parts of dif-

ferent geometries, as well as for complex-profile parts that have missing surface parts, using a connected corresponding part.

7. Conclusions

1. A general algorithm for generating portrait data of the original part has been developed, which was tested on a complex-profile part such as an impeller. Analysis of the geometry and shapes of the impeller allowed us to choose the HEXAGON Absolute Arm model of CMM with an AS-1 laser scanner (France) with a scanning accuracy of ± 0.05 mm. It has been shown that accurate reproduction of complex aerodynamic elements such as impeller blades is not possible without changing their positions and locations, which, in turn, creates an identical number of constructed portrait groups. This approach increased the accuracy of geometry reproduction and allowed us to overcome the issues of "shadow and invisible zones". Integration of precise control over the color map of deviations at each stage made it possible to minimize errors, which is especially important for parts with such complex geometry as an impeller.

2. A polygonal model of the experimental impeller was built using standard tools from the PolyWorks software (Canada), namely using the PoliWorks Inspector module (Canada). When building a polygonal model, it is recommended to use additional iterations of 3D scanning (>1) with analysis of "shadow zones" to increase the density of the point cloud with subsequent refinement of MESH data. Such additional stages of RE allowed us to increase not only the density but also the uniformity of the location of the points of the polygonal model geometry, which in turn affects the accuracy of constructing a digital model.

3. Based on the data obtained from the polygonal model, a digital 3D model of the impeller was constructed with high accuracy (± 0.05 mm). The reconstruction of the lost geometry of the part (cracks, deflections with loss of profile in the section, etc.) was shown. Such places were restored using standard surface interpolation and extrapolation modules in the Geomagic Design X software (USA) with step-by-step current control and final control over the model in Geomagic Control X (USA). This solution allowed us to compensate for scanning defects and obtain continuous geometry with a high degree of smoothness. The proposed RE approach could be used for rapid prototyping and manufacturing of damaged parts using additive technologies applying laser melting or milling on a CNC machine tool.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Authors contributions

Kateryna Maiorova: resources, supervision & writing – original draft; **Sergiy Zaklinsky:** conceptualization & visualization; **Oleksandra Kapinus:** formal analysis, investigation & visualization; **Artem Suslov:** methodology & validation; **Oleksandr Skyba:** investigation, data curation & project administration.

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