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STUDY OF THE FEATURES OF PERMANENT AND USUAL REVERSE-ENGINEERING METHODS OF DETAILS OF COMPLEX SHAPES

The subject of the study is sustainable reverse engineering and conventional reverse engineering of aviation equipment (AE) samples. The object of the study is the geometric accuracy of the extracted portrait of a part of a complex shape in comparison with the constructed analytical standard (AS). The work is aimed at researching the methods of sustainable reverse engineering and conventional reverse engineering on the example of the digitization of the box of the AE steering machine, chosen as a part of a complex shape. For this, a portrait of the «.stl» and AS format file was created and compared by performing a control operation with the determination of the time spent. A structural and technological analysis of the box of the AE steering machine was carried out, which showed that the box has through holes of various diameters (from 10 to 41.6 mm) and shapes (square, trapezoidal, round); thin walls between holes (up to 1.6 mm); right angles and their rounding radii (up to 1–4 mm); the thickness of the body walls is 2.4 mm, etc. 3D scanner – ARTEC SPACE SPIDER (Luxembourg) was selected and scanning was performed. According to the analysis of research methods of reverse engineering, it was established that the use of permanent and conventional reverse engineering allows, in the first case, to quickly manufacture a part by 3D printing or milling on CNC machines, and in the second case, to create its AS with the provision of the specified geometric accuracy. The difference in time between permanent and normal reverse engineering was 8 hours in favor of the former. Control of the ideal portrait according to the AS of the AE steering machine body showed the maximum deviations from –0.30 mm to +0.23 mm and the minimum deviations from –0.04 mm to +0.08 mm. The smallest indicators were observed on vertical and horizontal planes, and the largest – in cities with plane slopes, corners and small radii. This made it possible to establish that the existing capabilities of the Geomagic Design X software for correcting the received portrait of the «*.stl» format file currently do not guarantee the provision of geometric accuracy requirements (up to ±0.5 mm) for the manufacture of an experimental part of a complex shape – the AE steering machine body with 3D printing. The resulting ideal portrait can be used to manufacture a part by milling on CNC machines, taking into account deviations at the stage of process model formation, which can become the topic of further research.*

Keywords: *stable reverse engineering, reverse engineering, 3D scanning, analytical standard, parts of complex shape.*

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1. Introduction

In modern economic conditions, the use of aircraft equipment (AE) is due to the increase in the efficiency of their service life, which is accompanied by repairs, replacement of parts, etc. At the same time, the largest number of AE was manufactured 10 years ago in the conditions of the development of technologies at that time. The current approach in aircraft construction is based on the use of digital technologies, therefore, for such samples, AE first of all starts with bringing the existing information into electronic format. That is why coordinate measuring machines (CMM) and scanners were and remain the most relevant and promising in the aerospace industry [1]. Today, technologies based on them have acquired the name «reverse engineering» and «sustainable reverse engineering». In order to distinguish the concepts further in the text, reverse engineering will be referred to as ordinary reverse engineering, and permanent reverse engineering will be left unchanged.

The most widespread is precisely the usual reverse engineering, which allows solving the reverse problem of forming – extracting the original source of information of the experimental AE sample – analytical standard (AS) [2, 3]. In this case, the AS is a model created using 3D scanning operations and CAD system tools using splines. That is, reverse engineering allows to reproduce an electronic model of ideal geometry from a physically existing sample of the AE, which may be damaged, worn, etc. Therefore, the parts and nodes of AE of different complexity, created by spline methods, have an unambiguous description in a single information space. This is especially relevant when repairing and modernizing the AE structure or for the integration of modern technologies into already existing production systems [4].

Sustainable reverse engineering consists of scanning and extracting the actual geometry of the experimental sample of the AE portrait, which is used, for example, for 3D printing or the production of a part on CNC machines. The portrait in this case is a virtual product with a grid of point clouds in the «*.stl» file format. The difference between this technology and reverse engineering is the absence of the need to create an AS. Only a portrait of the obtained real geometry is processed, the difficulty of which is precisely in ensuring its smoothness and continuity, especially in corners, places of protrusions and holes.

Analysis of literary data shows the following. Conventional reverse engineering in modern production is a complex of operations that involves not only the AS reproduction, but also control at various stages of the life cycle of an AE sample [5] and in automation systems [6]. The authors of works [7, 8] describe the possibilities of reverse engineering technology, in particular prototyping, for cases when there is no technical documentation for a physically existing part. The process of working with a cloud of points and recognizing surfaces by segmenting them to reveal their geometric essence is highlighted separately. In particular, the technique of developing a database from point clouds and a method of rapid integration of reverse engineering technology into CAD/CAM/CAE systems are proposed, but their use is possible only in special software on a commercial basis. The work [1] shows the effectiveness of the use of CVM and scanners to ensure the accuracy of measurements of parts surfaces at the level of 0.01–0.05 mm. This will make it possible to reproduce the AS without additional geometrical constructions, but it does not preclude the existence of an additional stage in its creation. In [9], technical solutions regarding the peculiarities of the AS creation in the form of a collection of 3D models, which reflect the physical essence of the prototype of the AE in the CAD/CAE system, are provided. However, the specified solutions imply the availability of design documentation and require further refinement. The study [10] analyzed the concepts of recovery and repair based on reverse engineering and defined technological stages in them, consisting of the analysis of the technical condition and the identification of the AE prototype. A method of working with the received scanned surfaces – portraits – is also proposed. Using this technology, it is only possible to obtain results from the geometry and shape of the AE test sample, and it is not clear whether they are sufficient for conclusions on the adequacy of control. Therefore, in this case, it would be expedient to create an AE that would simplify control based on reverse engineering technologies by scanning a real existing experimental AE object and comparing the obtained portrait with the AS. The complexity of creating an AS is confirmed by work [11], which shows its construction according to the axioms of metric geometry of Euclid, Hilbert, or Kirchhoff. Today, reverse engineering technologies belong to a number of tools for solving the modern task of creating a virtual product, its production and control in a single information space. However, it is the desire to ensure high indicators of production terms while maintaining quality that created the prerequisites for simplifying reverse engineering in the stable. The only difficulty is working with the resulting portrait, as a result of which researchers offer one or another method of their processing using appropriate software. Thus, in [12] a methodology based on MATLAB algorithms is presented, which performs surface generation under user control. This methodology was tested on a real model of the element of the protective toe of the boot. It should be noted that the experimental surface did not have complex geometric structures, for example, sharp corners. Therefore, regardless of the practical significance of the obtained results, the technology of sustainable reverse engineering has not been sufficiently considered. An option to overcome this problem can be the use of the methodology according to the recommendations of the work [13]. To work with the obtained portrait, it is suggested to first break it into simple geometric shapes, separately process their coordinated point clouds, with the next step of combining such shapes into a single grid, that is, a portrait in «*.stl» format. Despite the positivity of the obtained results, which was confirmed during the control of the manufactured part using additive technologies, the use of the presented methodology raises doubts when it is necessary to ensure higher accuracy. Therefore, the question of understanding the use cases of this or that technology – permanent and usual reverse engineering in the aviation industry – with the aim of reducing the time and, accordingly, the cost of works, remains open, which is actual research. This fact gives reason to assert that it is expedient to carry out research comparing the use of permanent and conventional reverse engineering on the same part that has different complex geometric solutions (holes, corner radii, etc.).

The aim of research is to study the methods of sustainable and conventional reverse engineering on the example of digitizing the body of the AE steering machine without damage. This will allow the user to understand the expediency of using one or another technology based on the selected parameters of time, geometric accuracy and the method of manufacturing the part.

To achieve the aim, the following scientific objectives have been defined:

- create a portrait of the «*.stl» format file of the AE steering machine box with the determination of the time for its completion;
- create an AS of the AE steering machine box with determination of the time spent on its construction;
- control of the created portrait for AS of the AE steering machine body.

2. Materials and Methods

The subject of research is permanent and conventional reverse engineering of AE samples.

The object of research is the geometric accuracy of the extracted portrait in comparison with the AS of the AE steering machine body.

The research is based on the general principles of AE production technology. During the execution of the work, the methods of general scientific and empirical research on analysis and synthesis were applied – for the preliminary formulation of the problem, determination of the direction and assumptions of the search area, as well as field experiments and control.

The research was carried out in the following steps:

1 – structural and technological analysis of the experimental sample – AE steering machine body;

2 – selection of the necessary scanning device;

3 – scanning;

4 – processing of the received scanned surfaces and creating a portrait of the «*.stl» file format;

5 – AS creation from the geometry of the received portrait data;

6 – control and comparison of the portrait with AE;

7 – analysis of the obtained results and conclusions.

Fig. 1 shows an experimental sample – the AE steering machine body.


a *b*

Fig. 1. AE steering machine body: *a* – inner side; *b* – the outer side

This body was chosen for research as having a complex shape (through holes of various shapes and sizes, corners, intersecting surfaces, etc.).

3. Results and Discussion

Structural and technological analysis shows that the body has:

- through holes of various diameters (from 10 to 41.6 mm) and shapes (square, trapezoidal, round);
- thin walls between holes (up to 1.6 mm);
- 90° corners and their rounding radii (up to 1–4 mm);
- thickness of the body walls was 2.4 mm;
- center distance of the holes was (from 58.2 to 83.9 mm);
- wall thickness between the edge of the part and the hole (up to 5 mm).

An ARTEC SPACE SPIDER (Luxembourg) 3D scanner with a scanning accuracy of 0.05 mm and a resolution of up to 0.1 mm was chosen for scanning [14]. Such a scanner satisfies the field of tolerances of the dimensions of the experimental part in accordance with its structural and technological analysis.

In order to obtain a closed scanned surface of the AE steering machine body, scanning was done first from one side, and then from the other (Fig. 2), which created different coordinate systems for each of them.

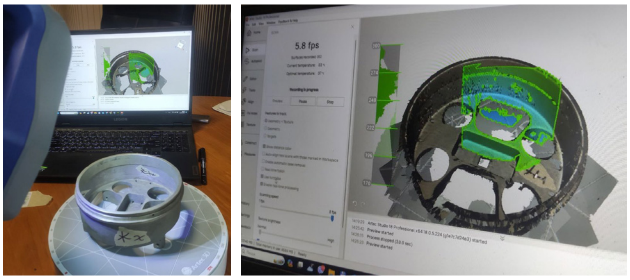
a *b*

Fig. 2. The process of scanning the AE steering machine body with the Artec Space Spider 3D scanner: *a* – body scanning; *b* – the appearance of scanning surfaces in the Artec Studio program

Markers in the form of signs on pasted tape (Fig. 2) were used to assemble the obtained scanned surfaces of different sides, which facilitated the creation of a single polygonal grid in the Artec Studio software. Thanks to them, the equation of the scanned surfaces was performed according to the obtained geometry (Fig. 3) and a real portrait of the detail of the «*.stl» file format was created (Fig. 4).

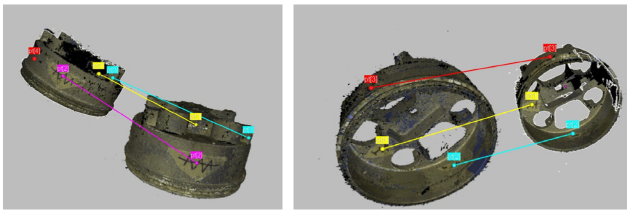

Fig. 3. The process of aligning the scanned sides with each other

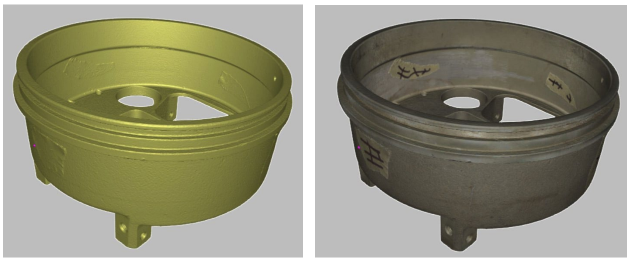
a *b*

Fig. 4. A real portrait of the AE steering machine body: *a* – without texture; *b* – with texture

The processing of the real portrait (cleaning from noises, correction of holes and errors of the polygonal mesh, reduction of the number of polygons without changing the basic shape of the object, etc.) was performed in the Geomagic Design X program. The following tools were used:

1. «Healind Wizard» was used to remove false polygons, outliers and other artifacts resulting from the creation of a polygonal model, which detected and corrected self-intersections, spikes, small components, tunnels and holes.
2. «Decimate» function was used to reduce to the desired number or percentage of polygons in a polygonal mesh without deteriorating its detail.
3. To obtain more uniform triangles, the mesh was optimized using «Optimize Mash».
4. To remove from the surfaces of markers that were applied for tracking during scanning, unnecessary holes and some defects – the «Defeature» function, which removes and restores the selected area using intelligent algorithms.
5. «Fill Holes» was used to fill unnecessary chips and holes, as well as to level their faces. This function is useful when there is a need to fill «complex» holes (if it is necessary to use such additional functions as building bridges, filling pits, smoothing faces, etc.).

In Fig. 5, for comparison, a real portrait and an ideal – cleaned and closed portrait without flaws, obtained as a result of transformations are shown. The latter can be used to fit parametric surfaces in order to construct AS.

The next step was the creation of an AS from the obtained ideal portrait of the AE steering machine. For this, the same Geomagic Design X software was used in the following sequence of operations:

1. Surfaces were divided and classified into primitives (plane, cylinder, cone) using the automatic segmentation function «Auto Segment». Surfaces that could not be determined by the classifier of primitives were marked as arbitrary (curvilinear).
2. Aligned the grid using the Interactive Alignment function.

3. With the help of a sketch on the polygonal grid «Mash Sketch», a 2D silhouette of our model in the selected section is obtained, which is further described using standard elements of the sketch (line, circle, arc, etc.).

Fig. 6 shows a sketch of a polygonal grid, and Fig. 7 shows a built sketch of this silhouette, which was built to create an AE [7].

4. The next stage was the creation of a solid body (Fig. 8) using the rotation function.

5. Similarly to 3, sketches of holes in the corresponding cross-sections are constructed and holes are created using the «Extrude» extraction/cutting function to the required size (or through) (Fig. 8).

6. During the modeling process, surface control was constantly performed using the «Accuracy AnalyzerTM» function [10]. Fig. 9 shows an example of step-by-step control of AS construction according to the portrait of the experimental part.

7. The last stage is the rounding of the faces using the Rounding function. Fig. 10 shows AS of the AE steering machine body saved in one of the available formats.

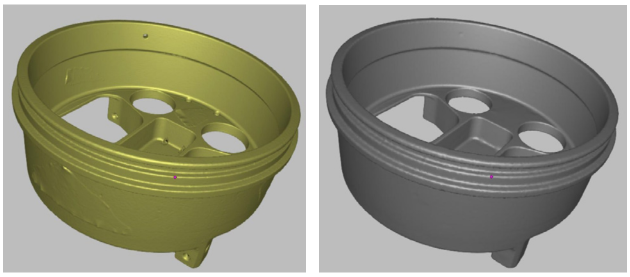
a *b*

Fig. 5. Portrait of the AE steering machine body in the «*.stl» file format: *a* – real; *b* – ideal

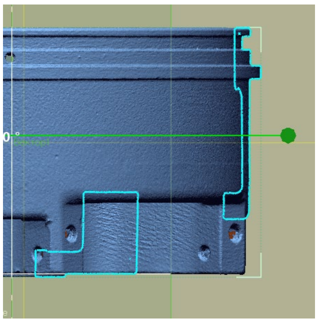

Fig. 6. Sketch on a polygonal grid of a portrait of an experimental detail

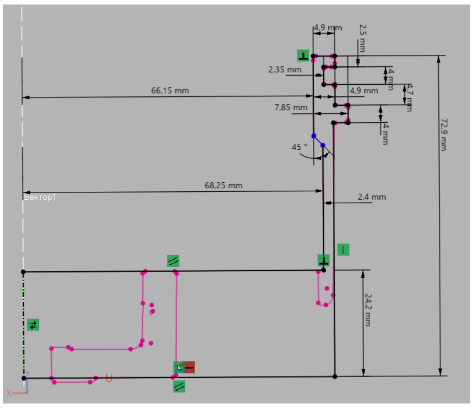

Fig. 7. Constructed sketch of the silhouette that was removed from the section

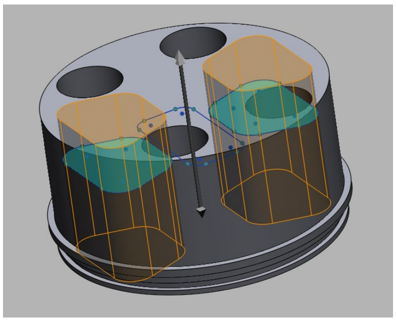

Fig. 8. Pull out (cut) through trapezoidal hole operation

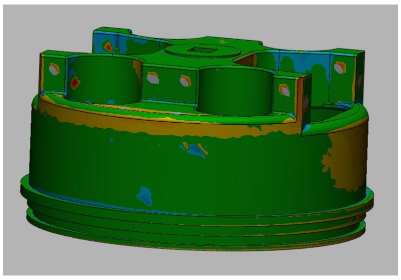

Fig. 9. Control of the construction of the future AS according to the portrait of the experimental part

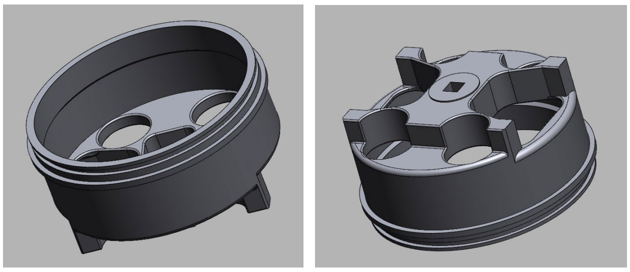
a *b*

Fig. 10. Ready-made AS of the AE steering machine body: *a* – on the one side; *b* – on the other side

It should be noted that, if necessary, it is possible to export the AS construction tree from the Geomagic Design X software to the following programs: SOLIDWORKS; Creo (Pro/E); Inventor; NX; AutoCAD.

Fig. 11 presents a comparison of the geometric accuracy of the obtained ASs and the portrait of the AE steering machine body.

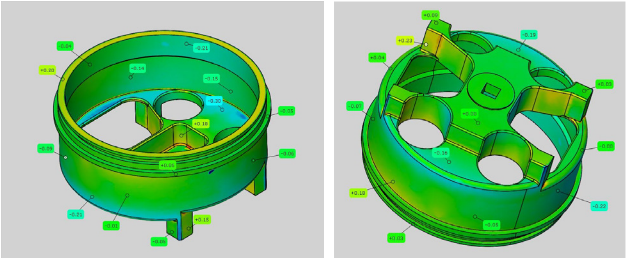
a *b*

Fig. 11. Control and comparison of the ideal portrait and the AS body of the AE steering machine built according to it: *a* – on the one side; *b* – on the other side

It was established that the maximum deviations of the latter are from –0.30 mm to +0.23 mm, that is, the obtained AS has no deviations, while the portrait has them.

The smallest deviations were observed on vertical and horizontal planes (from -0.04 mm to +0.08 mm), while the largest deviations were observed in the cities of plane inclinations, corners and small radii.

The experience of the authors of the work [15] shows that the obtained geometric accuracy of the manufactured part by additive technologies also has a deviation in sizes from –0.37 mm to +0.14 mm, which is within the tolerance for the part, which was ±0.5 mm. The existence of deviations during 3D printing was also confirmed in studies [16]. This makes it possible to assert that the obtained portrait of the AE steering machine body – the «*.stl» file format – does not guarantee geometric accuracy during the production of the part by 3D printing, and it is not desirable to use it even when processing on CNC machines. Therefore, it becomes logical to draw conclusions about the need to finalize the portrait based on the received control data and compare it with the AS geometry, provided that the tolerance is ±0.5 mm. However, this means that for the considered part, the use of sustainable reverse engineering technology will not ensure the specified geometric accuracy of ±0.5 mm for its manufacture. Therefore, it is recommended to use a full cycle of work based on reverse engineering for similar parts such as the body of the AE steering machine, which have a complex geometry of rounding radii (up to 0.5 mm), corners, etc. Having AS, the next step is to save this data in the «*.stl» file format, which can be used in additive manufacturing or manufacturing parts by milling on CNC machines.

Analysis of the time spent for sustainable and conventional reverse engineering of the selected part showed the following. The total time for the usual reverse engineering of the AE steering machine body was 13 hours, where the following was used for each stage (Fig. 12):

1 – scanning of the Part detail and processing of the portrait of the P_p detail – 2 hours;

2 – description of the model of processes and functions of the M_{Pp} detail – 2 hours;

3 – creation of AS detail AE_p – 8 hours;

4 – creation of a 3D model for the selected part manufacturing technology – 30 minutes;

5 – creation of a «*.stl» format file for manufacturing a part using additive technologies or using CNC machines – 30 minutes.

The total time for permanent reverse-engineering of the AE steering machine body was 5 hours, where the following was used for each stage (Fig. 13):

1 – scanning of the Part detail and processing of the portrait of the P_p detail – 2 hours;

2 – creation of an ideal portrait of a part of the «*.stl» format file for the production of the part by additive technologies or using CNC machines – 3 hours.

The time difference was 8 hours in favor of sustainable reverse engineering.

So, the conducted studies on the comparison of sustainable and conventional reverse engineering made it possible to establish their advantages and disadvantages over each other.

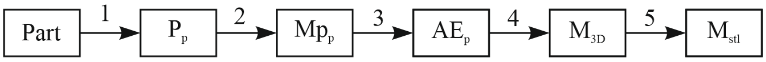

Fig. 12. Scheme of implementation stages of conventional reverse engineering

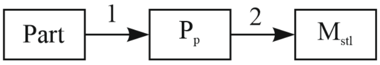

Fig. 13. Scheme of implementation stages of sustainable reverse engineering

The advantages of the reverse engineering method are:
- there is no need to refine the received portrait to the ideal (elimination of defects in corners, radii, etc.), because during the AS construction, these defects are eliminated automatically;
- the possibility of creating 3D models with AS in a format that can be recognized by most CNCs;
- the possibility of creating 3D models of equipment for the manufacture of parts of any size and complexity;
- the possibility of creating design, technological and operational documentation from AS data.

The disadvantages of the reverse engineering method are:
- the need to convert the finished AS back into a portrait of the «*.stl» file format when manufacturing the part using additive technologies or on CNC machines, which is dictated by the requirements of the equipment software.

The advantages of the sustainable reverse engineering method are:
- no need to create AS or separate 3D models, which significantly reduces the total time of work;
- speed of production with cost savings in the production of parts of simple shapes and geometry using additive technologies or on CNC machines.

The disadvantages of the sustainable reverse engineering method are:
- lack of guarantee of high accuracy (up to ±0.5 mm) of details of complex geometry;
- the need to create a 3D model from a portrait in the «*.stl» file format when manufacturing a part on CNC machines, which is dictated by the requirements of its software;
- impossibility of creating design, technological and operational documentation from portrait data.

There are a large number of methods and algorithms of reverse engineering based on reverse engineering, which are developed for the specific requirements of the researched tasks [17, 18]. This is the high accuracy of surface reproduction, or the reproduction of complex structures, or their many dimensions, or, conversely, the possibility of replacing them with geometric primitives [19]. However, similar problems have not been studied from the point of view of optimizing processes with a minimum of time and sufficient accuracy of obtaining results. This work investigates and compares the implementation of two methods of reverse engineering – sustainable and conventional – using the example of the AE steering machine box. The object of the study is the geometric accuracy of the extracted portrait in comparison with the AS of the AE steering machine body, as well as the time spent on each method. The results showed that the existing software today does not allow the refinement of the portrait in cities of complex surfaces and their intersections (radii, sharp corners, etc.) without losing the accuracy of the geometry. With high accuracy requirements, additional stages of AS construction cannot be dispensed with, which will also affect the production time. However, compared to conventional reverse engineering, permanent reverse engineering remains out of competition in solving the problems of rapid recovery and manufacturing [13], which is relevant for Ukraine as a country in a state of liberation war. However, the problem of restorative repair of parts and components of weapons, especially those manufactured outside of Ukraine, including trophy ones, is the lack of design and technological documentation for its parts and components, and obviously requires the AS construction. Therefore, the extracted AS as a digital primary source should be easily integrated into existing production systems and used in a single CAD/CAE/CAM information space [20, 21], which is timely for easy implementation in production practice and can become the topic of further research. The only limitation of the use of sustainable and/or conventional reverse engineering is the limits of accuracy requirements for the experimental part, which in turn requires additional scanning by other scanners of greater accuracy or the use of coordinate measuring machines in general. It should be noted that the error of the used scanning equipment should be an order of magnitude less than the tolerance on the part. To perform such work, there must be 2–3 highly qualified specialists in the production.

4. Conclusions

It has been proven that the use of modern sustainable and reverse engineering allows, in the first case, to quickly manufacture a part by 3D printing or milling on CNC machines, and in the second case, to create its AS. The existence of AS will make it possible to use the data for the production of the part according to any chosen technology.

A comparison of sustainable and conventional reverse engineering technologies on the example of the AE steering machine body showed the following. Sustainable reverse engineering allows to save both time and cost of work when implementing rapid production of parts using additive technologies, provided there are no strict requirements for geometric accuracy. The capabilities of the Geomagic Design X software to correct the obtained portrait into an ideal one do not currently guarantee the requirements of geometric accuracy (up to ±0.5 mm) for the manufacture of a part by 3D printing. Conventional reverse engineering allows to create AS parts of any complexity with the provision of specified requirements of geometric accuracy. Therefore, it is recommended to use a full cycle of work based on conventional reverse engineering for parts similar to the box of the AE steering machine, which have a complex geometry of rounding radii (up to 0.5 mm), corners, etc. The obtained portrait file in «*.stl» format can be used for the production of parts by milling on CNC machines, taking into account deviations at the stage of process model formation.

Research results can be the basis for the creation of technological systems built on a combination of reverse engineering processes, additive and extractive technologies using CNC machine tools, capable of realizing the idea of «quick repair» for the fastest return to combat condition of objects and components of military equipment, including aviation. This is especially relevant for the production or restorative repair of parts and components of weapons destroyed during hostilities, the design and technological documentation of which is either absent or lacking, including parts and components that were not manufactured in Ukraine.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

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

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