UDC 629.73.002
DOI: 10.15587/1729-4061.2024.311478

IMPLEMENTATION OF REENGINEERING TECHNOLOGY IN THE TECHNOLOGICAL PREPARATION FOR GENERAL AVIATION AIRPLANE WING TIP MANUFACTURING BASED ON THE CONSTRUCTION OF A DIGITAL MOCK-UP

Kateryna Maiorova
Corresponding author
PhD, Head of Department*
E-mail: k.majorova@khai.edu
Viacheslav Nikichanov
PhD, Associate Professor*
Ihor Lysochenko
PhD Student*
Svitlana Myronova
Senior Lecturer*
*Department of Technology of Aircraft Manufacturing
National Aerospace University "Kharkiv Aviation Institute"
Vadyma Manka str., 17, Kharkiv, Ukraine, 61070

The object of this study is the technological preparation of the production of a light aircraft wing using reverse engineering technology. The subject of research is a quality indicator – the geometric accuracy of manufacturing the convex-concave parts of aerospace technology. Calculations of geometric accuracy were performed for the program-instrumental method of co-ordination. As the experimental part it was taken the worn out wing tip of a light aircraft. The following results were obtained. An approach for specifying the aerodynamic airfoil and cross sections of the wing tip when constructing its digital model has been proposed. A 3D scanning of the wing tip with the formation of a digital portrait in STL format, as well as its refinement into a STEP format, using organic and mechanical methods, was accomplished. A digital mock-up of the wing tip was built taking into account the geometry of the aerodynamic airfoil in cross sections as well as a digital mock-up of the form (mould) for its manufacture according to the polygonal model, which was created by the organic method due to it had the highest dimensional accuracy. It was determined that the maximum deviation of the actual wing contour from the theoretical one was as follows: the upper deviation was 0.84 mm, the lower deviation was –0.65 mm. The maximum deviation of the actual wing contour from the theoretical one was ±0.3 mm. The expected (calculated) errors did not exceed the specified value of the tolerance on the wing outer contour that equal to ±1.0 mm, thus, the adopted method of assembling the wing under the conditions of co-ordination by the program-instrumental method ensured the specified geometric accuracy. The results of experimental studies confirmed the adequacy of the proposed approach for determining the aerodynamic airfoil of the cross-sections of the digital mock-up of convex-concave parts for aerospace technology during their technological preparation for production with the use of reverse engineering

Keywords: technological preparation of production, reverse engineering, digital mock-up, 3D scanning, geometric accuracy, aerodynamic airfoil

Received date 11.07.2024
Accepted date 13.09.2024
Published date 25.10.2024

***How to Cite:** Maiorova, K., Nikichanov, V., Lysochenko, I., Myronova, S. (2024). Implementation of reengineering technology in the technological preparation for general aviation airplane wing tip manufacturing based on the construction of a digital mock-up. Eastern-European Journal of Enterprise Technologies, 5 (1 (131)), 43–53. https://doi.org/10.15587/1729-4061.2024.311478*

1. Introduction

The manufacturing of aerospace technology (AT) is the field of implementation of various advanced design and technological solutions in engineering, production, and operation. The studies of optimal strategies for improving the AT quality and optimizing the technological processes stride to developing and refining the technical performances of the tooling and equipment being used. That is why in the aerospace industry, coordinate measuring machines (CMMs), CNC machinery, robots and robotic complexes, 3D printers, laser trackers and 3D-scanners were and remain the most relevant and promising for highly effective technological preparation of production (TPP) [1, 2]. The latter allows to digitize a physical sample that actually exists and create its digital mock-up (DMU), which becomes the primary source of information in CAD/CAM/CAE systems. This technology is known as reverse engineering or backwards engineering; it is also used at the stages of product technical inspection by comparing the "portrait" obtained by 3D scanning with the geometry of the existing DMU [3]. That is, reverse engineering solves the two most important problems of production. The first one is a direct task, when a DMU is first created, which is used for post-operational inspection and manufacturing an AT sample. The second one is the inverse problem, when a DMU is created by a physical sample of an existing AT [4]. It should be noted that the implementation of both of these tasks is based on a single source of information – DMU. This is especially relevant if it is necessary to prototype a part during repair, modernization, re-motorisation of an already operated AT in order to extend its life cycle (LC). In this case, the implementing of reverse engineering becomes not only a way to improve quality but also a decisive factor in ensuring the competitiveness in the market of goods and services for both the manufacturer and commercial airlines.

It should be noted as well, that the implementation of reverse engineering in the established production that already exists at the enterprise is difficult. It's explained by the manufacturer desire to minimize the costs while changing production process, with simultaneous improving the quality of products. Therefore, now, when prototyping the AT assembly components, which can be produced by additive (in particular, extractive) technologies, provided that the specified quality is ensured, they try to use not a DMU, but a digital portrait obtained by 3D scanning (file of STL format) [5]. However, the convex-concave parts of the AT, such as the wing tips and fairings of the aircraft, which are made of polymer composite materials, require high manufacturing accuracy (less than 1.5 mm). The latter is also affected by the manufacturing accuracy of technological tooling (TT) [6, 7]. In this case, it will be mandatory to create a DMU both for the prototype and for the forming tooling as well. The problem is the determination of the aerodynamic airfoil geometry in cross sections, which in turn affects the accuracy of the DMU creating. Therefore, the development of TPP for the convex-concave parts of AT and especially those that are worn or damaged, with the determination of their aerodynamic airfoil in cross-sections during the reconstruction of the DMU using reverse engineering, is an urgent task.

2. Literature review and problem statement

Reverse engineering is widely used for the need for rapid prototyping of parts using additive technologies. Thus, paper [8] reports the manufacturing by reverse engineering and additive technology (extrusion of material) of an outdated part – a template for sand casting. However, the positivity of the results is questionable since there is no inspection and comparison of the DMU with a digital portrait of the new template. In [9], a complete cycle of prototyping for cylindrical part is given, where the key whether to let it into production is the inspection of the finished printed part by the DMU geometry. The authors focused specifically on the parameters of the roundness and cylindricity of the surface of the part and indicated the obtained deviations. However, there are no conclusions regarding the passing this part into production as well as finite element method (FEM) analysis regarding the adequacy of the material replacement – from metal to plastic. The results reported in [10] are a continuation of work [9] on a convex-concave part, where aerodynamic and strength calculations were performed for the wheel cover of the Cessna182 Skylane light aircraft in the ANSYS program. The obtained experimental data demonstrated the positivity of the theoretical principles, but need confirmation by field experiments, since the wheel cover during the aircraft landing perceives the maximum shock loads, which was not taken into account by FEM analysis. Work [11] demonstrates the reproduction of the propeller blade DMU, using the photogrammetric method and reconstruction in Geomatic Studio with additional data correction by artificial intelligence and inspection of reconstruction based on the data of CMM measurements on parts. Note that the proposed there re-engineering algorithm is time-consuming and requires special software for data correction of images obtained from a digital camera. In addition, the obtained geometry deviations are more than 5 %, which can be used for prototyping the parts of "non-demandive" quality, that is, accuracy of 14th quality grade and worse. An alternative is the work [12], where the part DMU reconstruction is performed by sequential construction of geometric primitives – such as vertices, edges, loops, and faces, which includes the approach of the "automatic" height determination mechanism. However, the only condition for such successful results is an experimental part digital portrait without "gaps". Thus, paper [13] shows the difficulties of obtaining such portraits for mating surfaces: holes, edges, and sharp corners with a radius of less than 5 mm. Therefore, they are created directly during the DMU construction at the stage of 3D modeling. Work [14] demonstrates the analysis of the total time, cost, and quality (comes about geometric data) of prototyping a complex airfoil part of automobile under the conditions of its manufacturing by 3D printing. The authors opted for laser 3D scanning over photogrammetry, but the highest accuracy remains with the reproduced DMU. Study [15] reports an approach to building a 3D model in CAD system from 2D orthographic drawings in the case when there is no real physical part, but there are drawings for it. Such research correlates with work [11] and allows to appoint geometry parameters and material properties directly during the DMU construction. That is resulted by the DMU high cost as well as the high labor intensity of this work, especially for parts larger than 150×150×150 mm. An alternative is the proposed reverse engineering methodology in [16], using the example of a pumped hydroelectric power plant blade, in which the authors suggested testing on scaled samples (of reduced size) made by 3D printing. A peculiarity is in using a finished portrait in STL format instead of DMU. However, it is not shown how the construction of the aerodynamic airfoil geometry in cross-section was performed, which would add to the reliability of the results. Work [17] proposes to use the digital twins by attaching specific functions or technological processes to them. Thus, in [18] their use in additive manufacturing of parts is given. But the predecessors of the digital twin are DMUs, that is, such a solution does not reduce the labor intensity of work and the amount of stages for reverse engineering, so remains "in prospects" both for mass production and at the stages of product inspection while maintenance. The authors of study [5] claim sufficient geometric accuracy of the finished portrait in the STL format for manufacturing the part using additive technologies. In turn, work [13] refutes these provisions, proving that the functions of existing engineering programs are not sufficient for the correction of a digital portrait to ensure the requirements of geometric accuracy up to ±0.5 mm per manufactured part. Also, such an approach raises doubts about ensuring the geometric accuracy of convex-concave aircraft parts, which aerodynamic airfoils should be inspected in cross-sections, so that is the relevance of the research. The latter affects the accuracy of creating the technological tooling for the manufacture of such convex-concave parts made of polymer composite materials (PCM). Therefore, there is a need to ensure the geometric accuracy while production the convex-concave parts of AT and their technological tooling on the base of the full cycle of DMU creation when using reverse engineering.

3. The Purpose and Objectives of the Study

The purpose of the study is to develop an approach to determining the aerodynamic airfoil in the cross-sections of

DMU for the AT convex-concave parts during their technological preparation for production using reverse engineering with the selecting the methods for assembling and co-ordination. This allows to implement engineering solutions of reverse engineering into the existing established technological systems of the enterprise, which help to solve both the problems of production updating and maintenance with extended life cycle of AT.

To achieve the purpose, the following scientific tasks have been stated:

– to create a digital portrait of the light aircraft wing tip and a DMU on its basis, taking into account the aerodynamic airfoil geometry in cross sections and the DMU of a form (a tooling) for the wing tip manufacturing;

– to calculate the expected accuracy of the geometric parameters of the light aircraft wing tip contour under the conditions of using the DMU as the primary source of information for co-ordination the tooling for the wing tip manufacturing and the wing assembly *jig*.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of the study is the technological preparation of the light aircraft wing production using reverse engineering. The research is based on the general principles of technology of AT production. During the accomplishing the work, the methods of general scientific and empirical research on analysis and synthesis were applied – for the preliminary statement of the problem, determining the direction and assumptions of the search area, as well as field experiments and inspection.

The research was carried out in the following steps:

1) design and technological analysis of the convex-concave experimental part;

2) selection of the necessary scanning device;

3) preparation for 3D scanning and placement of markers on the surface of the convex-concave experimental part;

4) 3D scanning;

5) processing of the received scanned surfaces and creating the experimental part digital portrait (hereinafter, the portrait) – file in STL format;

6) constructing the DMU from the geometry data of the obtained portrait of the convex-concave experimental part;

7) constructing the DMU of convex-concave technological tooling for the manufacture of a test part;

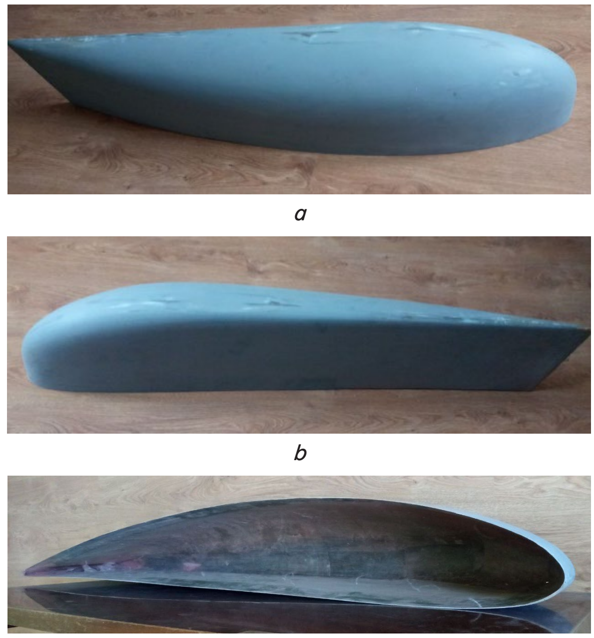
8) calculating the expected accuracy of the geometric parameters of the experimental convex-concave part and its TT for selecting the co-ordination method, under the conditions of using a certain method of the wing assembling;

9) analysis of the results and making conclusions.

4. 2. The study subject

The subject of the study is the geometric accuracy of a convex-concave part and patterns of the geometric accuracy forming during the technological preparation of production as well as during production immediately. The light aircraft wing tip made of PCM was chosen for the experiments. According to the results of the design and technological analysis of the experimental part, the ARTEC Leo 3D scanner (Luxembourg) with the characteristics given in [19] was selected for scanning its surface. Such a scanner has a 3D scanning accuracy of 0.1 mm and a resolution of up to 0.2 mm, which satisfies the field of tolerances for the size of the light aircraft wing tip, which is ±1.0 mm.

Fig. 1 shows an experimental part – the tip (in the form of a fairing) of a light aircraft wing made of PCM.



a

b

c

Fig. 1. Tip of the light aircraft wing: *a* — outer upper surface; *b* — outer lower surface; *c* — airfoil

Scanning and processing of the portrait of the light aircraft wing tip was performed in the Artek Studio program, which is the built-in software for the chosen 3D scanner ARTEC Leo (Luxembourg).

In order to build a portrait quickly and with ease, as well as to obtain accurate and mathematically defined models, it was used modeling by simple geometric figures – primitives [20].

3D models refer to digital objects that use a set of points in 3D space connected to each other by various geometric objects such as triangles, lines, etc. [21].

The term "digital model" means a 3D model, which is developed by means and tools of CAD systems using spline geometry [15].

A portrait is a set of point data in the form of a data file – point cloud, obtained as a result of 3D surface scanning [22]. A point cloud is a set of vertices in a three-dimensional coordinate system defined by X, Y, and Z coordinates. A point cloud gives the surface geometry and representation of the object’s outer surface, i.e., its shape.

The methodology for creating and refinement the DMU of a convex-concave part was based on the example of the geometry of the light aircraft wing tip; the DMU geometry was created in the SOLID Works software by the function of an arbitrary shape and Boolean operations of adding and subtracting the volumes [23].

The "deviation of the shape from the given airfoil" according to the definitions given in [24] was taken as the parameter of inspection and comparison of the obtained portraits. The values of such deviations are the largest deviations of the real airfoil points from the corresponding points of the nominal airfoil, which are determined by the normal to it within the normalized zone.

The portrait measurement data did not have topological information and therefore were converted into files of mesh structures with triangular shaped elements – file of STL (stereolithography) format [25, 26].

Portrait processing consisted of refinement and cleaning of the obtained portrait of the scanned light aircraft wing tip in Geomagic Design X software, and inspection – in Geomagic Control X (USA) [27]. The construction of DMU of the wing tip was performed according to the geometry of the processed portrait and the selected aerodynamic airfoil in cross-sections by mechanical selection of compliance with the obtained airfoil polygonal model geometry (in STEP format).

The selection of the aerodynamic airfoil was performed in a "semi-automated" mode with taking into account data from [28] by comparing the polygonal model with all airfoils and searching for the smallest deviations of the geometry in cross sections.

Determining the appropriate airfoil in terms of geometry took place in the SolidWorks program by combining airfoil curves. The parameter value of the maximum and average deviations, as well as the percentage of the curve length that falls within the tolerance field of ±1.0 mm, were chosen as the criteria for determining the airfoil that closest in terms of geometry.

The calculation of the expected geometric parameters of the shape of the manufactured wing tip of a light aircraft was performed for the program-instrumental method (PrIM) of co-ordination under the conditions of a certain method of wing assembling [29].

The term "co-ordination" refers to the process of mating the geometric parameters of parts, assembly units, elements of technological tooling for the manufacturing the individual parts or their assembling [30].

The calculation of the geometric parameters of the light aircraft wing tip is based on the analysis of technological dimensional chains, which reflect the transfer of size during the technological preparation of production and production itself from the primary source of information to the finished part or assembly tooling.

A technological dimensional chain is a set of dimensions that form a closed circuit and directly participate in the formation of the final size of a part or assembly unit [31]; there are two main types of technological dimension chains. While calculating the expected accuracy, the errors of transferring the primary size, which is equal to the nominal one by the DMU, were used as components of the technological dimensional chain, i.e., the technological dimensional chain reflects the changes in this dimension at all stages of its transferring during both TPP and the manufacture of light aircraft wing tip. This set of dimensions directly participates in ensuring the accuracy of the geometric parameters of the wing tip of a light aircraft.

In order to assess the applicability of the chosen co-ordination method (PrIM) for the technological preparation of the wing tip manufacturing and its further assembling with the wing, the error of the wing manufacturing was compared with the tolerance for this unit, that is, it was compared with the value of ±1.0 mm.

The value of error while assembling the wing by contour $E_{as}^{contour}$, that is, the deviation of the real wing contour from the theoretical wing contour, was determined under the conditions of the accepted method for co-ordination – the PrIM – and the assembly method ("from the surface of the airframe") according to the following formula [32]:

$$E_{as}^{contour} = E_{jig}^{contour} + k_{f_{rib}} C_{jig-rib}^{contour} + + k_{f_{tip}} C_{rib-tip}^{contour} + E_{tip}^{thickness} + E_{others}, \quad (1)$$

where $E_{jig}^{contour}$ is the error of the contour locator ("fixing arm") of the wing airframe assembly *jig* relative to the theoretical contour; $C_{jig-rib}^{contour}$ – error of co-ordination of the *jig* contour locator and the rib (airframe element, immediately located to a *jig*), which can be reduced by using clamps that taken into account by coefficient of fixation $k_{f_{rib}}$; $C_{rib-tip}^{contour}$ – error of co-ordination of the contours of the airframe (rib) and the wing tip; which can be reduced by using clamps – taken into account by the appropriate coefficient of fixation $k_{f_{tip}}$; $k_{f_{rib}}$ and $k_{f_{tip}}$ – fixation coefficients during assembly in the *jig* for the rib and wing tip, respectively; $E_{tip}^{thickness}$ – the wing tip thickness error, the thickness of the wing tip at the surface of mating to the wing is 1.5±0.2 mm, i.e., $E_{tip}^{thickness} = 0.2$ mm; E_{others} – errors of the wing contour caused by the deformation after joining, which during assembling of the wing (assembly unit of classification group IX) is $E_{others} = 0.15 E_{as}^{contour}$ [29].

The coefficient of fixation during assembling in the *jig* is calculated according to the formula:

$$k_f = 1.5 \left(\frac{L}{L_f} \right)^{-1.05}, \quad (2)$$

where L is the maximum overall size of the assembly unit; L_f is the distance between clamps.

The main error parameters in (1) are the width of the dispersion field δ and the coordinate of the field middle Δ_0.

The calculation of the accuracy of the assembling – practically, the mounting of the wing tip on the wing – was carried out by the probabilistic method [32]:

$$\delta_\Sigma = \sqrt{\sum_{i=1}^{m-1} \xi_i^2 k_i^2 \delta_i^2}, \quad (3)$$

$$\Delta_{0_\Sigma} = \sum_{i=1}^{m-1} \xi_i \left(\Delta_{0_i} + \alpha_i \frac{\delta_i}{2} \right), \quad (4)$$

where k_i is the coefficient of relative dispersion of errors; α_i is the coefficient of relative asymmetry of the dispersion curve, which is equal to 0 for the normal law; δ_Σ and Δ_{0_Σ}, δ_i and Δ_{0_i} – parameters of errors of the closing and component links of the dimensional chain, respectively; $m-1$ – the number of component links; ξ_i is the transmission ratio of the component link of the dimensional chain – size error or tolerance, which characterizes the influence of this stage of size transfer on the final value of the size, where the links that increase or decrease the closing link are distinguished. According to the latter, ξ_i is equal to 1 or –1.

Limit deviations of the size were calculated according to the formulas:

$$\Delta_{up} = \Delta_{0_\Sigma} + \frac{\delta_\Sigma}{2}, \quad (5)$$

$$\Delta_{low} = \Delta_{0_\Sigma} - \frac{\delta_\Sigma}{2}, \quad (6)$$

where Δ_{up} and Δ_{low} are the upper and lower size deviation, respectively.

5. Results of research of the technological preparation for the aircraft wing tip production

5. 1. Results of studies on the construction of a wing tip DMU

5. 1. 1. Creating a portrait of the wing tip in the STL format

The design and technological analysis revealed that the tip (Fig. 3):

– has a convex-concave shape with a variable airfoil, i.e., double curvature;

– at the place of joining to the wing, it has an aerodynamic airfoil and a uniform skin thickness (1.5 mm);

– does not have holes and sharp corners on the surface;

– has overall dimensions of 1375×300×170 mm and its surface is formed by upper and lower parts glued together, which preliminary made of PCM separately;

– made of three-layer fiberglass and polyurethane foam filler, manufactured by the method of vacuum forming into a matrix;

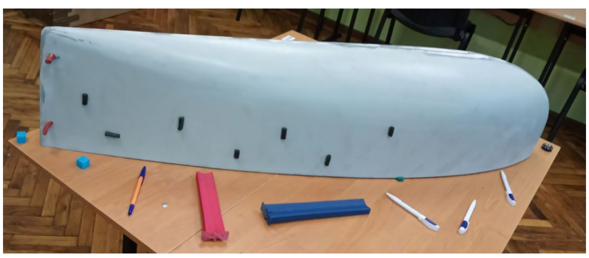
– joined to the wing by blind rivets.

To obtain a closed scanned surface of the light aircraft wing tip, markers were first applied over the entire surface. Fig. 2 shows two options for placing the markers:

– the first: with a distance of 50 mm from each other evenly over the entire surface in a chess-board pattern;

– the second: at a distance of 70 mm in a staggered order in two rows only near the edge of the airfoil.

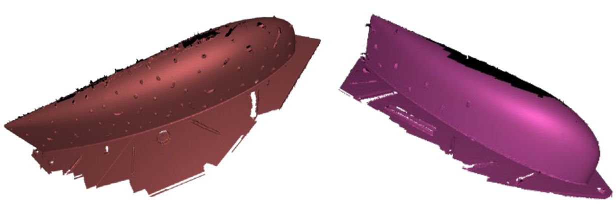
a



b

Fig. 2. Location of the markers on the wing tip experimental sample according to two options: *a* — evenly over the entire surface in a chess-board pattern; *b* — only near the edge of the tip

Fig. 3 shows the resulting scanned surfaces for both options.



a *b*

Fig. 3. Scanned surfaces, obtained according to two options of markers location: *a* — evenly across the entire surface in a chess-board pattern; *b* — only near the tip edge

The next step was to clean up unnecessary surfaces (markers) and create a single portrait of the surface of the light aircraft wing tip in the following sequence:

1. Cleaning. Rough cleaning of scanned surfaces using the Eraser tool. Removal of support and unnecessary objects.

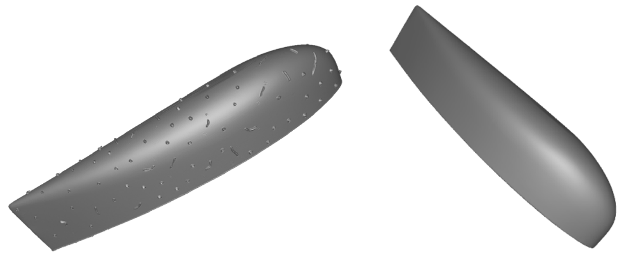
2. Alignment. Alignment of several (groups) of scans into the one object.

3. Registration. Optimizing the frames location within one or more scanned surfaces.

4. Gluing. "Assembling" of scans and combining them into a single portrait.

5. Post-processing. Polygonal structure simplification, portrait smoothing, and other optional steps to refine the portrait geometry.

Fig. 4 shows the resulting portrait (point cloud in STL format) of the experimental wing tip of a light aircraft.



a *b*

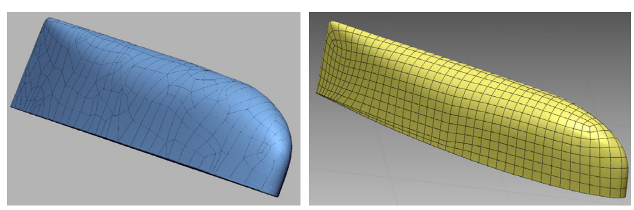
Fig. 4. Portrait of the wing tip in STL format: *a* — with markers; *b* — without markers

Next it was performed alignment of the scanned surfaces, referring to the markers and the obtained geometry of the point cloud, and a portrait of the wing tip was created in STL format. Difficulties with scanning were detected only for the edge of the airfoil, so these surfaces were refined at the next stage – during the processing of the portrait geometry.

The processing of the portrait of the light aircraft wing tip and the creation of a polygonal model was performed in the Geomagic Design X program using the following functions:

1. Automated checking and correction of various defects.
2. Smoothing.
3. Grid optimization.
4. Automated surface creation.

Fig. 5 shows two polygonal models (in STEP format) of the light aircraft wing tip, which were obtained by processing the portrait using two methods: organic and mechanical.



a *b*

Fig. 5. Polygonal models of the wing tip obtained using two methods: *a* — organic; *b* — mechanical

To determine which of the polygonal models has a higher accuracy of geometry, a comparison of the obtained geometry of the models with the light aircraft wing tip portrait was performed in the Geomagic Control-X program.

The deviations for a polygonal model in the STEP format, built according to the organic method, ranged from +0.23 to –0.22 mm. The deviations for the polygonal model built by the mechanical method ranged from +1.05 to –0.42 mm.

5. 1. 2. Construction of a digital mock-up of the wing tip taking into account the geometry of the aerodynamic airfoil in cross sections

For the construction of the wing tip DMU, it was chosen a polygonal model that built according to the organic method, as it had the smallest deviations of the geometry.

The geometrical data analysis on the polygonal model of the wing tip has shown the following parameters: chord length is 1379 mm; the maximum thickness is 169 mm, the relative thickness is 12 %, and the relative curvature of the airfoil is 4 %. Under an automated mode and taking into account data from [28], several airfoils were selected: NACA4412, GOE 623 AIRFOIL, GOE 593 AIRFOIL, N-22 AIRFOIL. A comparison of the polygonal model with all the airfoils revealed that the smallest deviations of the cross-sectional geometry were for the NACA4412 airfoil.

Fig. 6 shows a visualization of the comparison of the NACA4412 airfoil and the polygonal model of the light aircraft wing tip in one of the cross-sections, which had the closest match in terms of airfoil geometry.

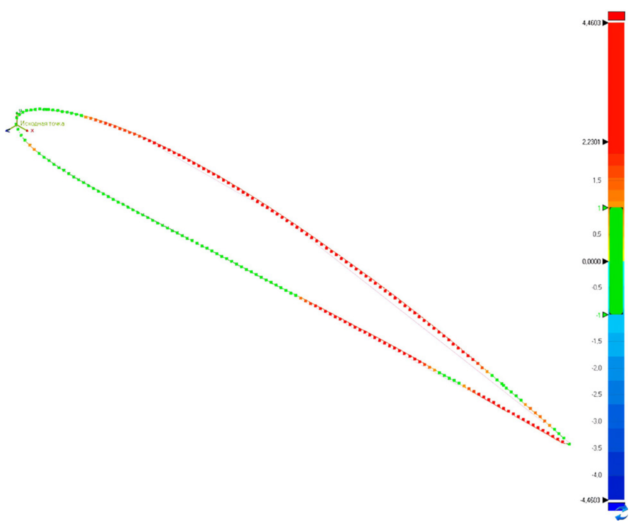


Fig. 6. Visualization of the comparison of NACA4412 airfoils and a polygon model of a light aircraft wing tip

The values that within the tolerance field are marked in green, and those that outside the tolerance field – marked in red.

Selection of curves for cross sections in the longitudinal direction of the wing tip was performed in the same way (Fig. 7).

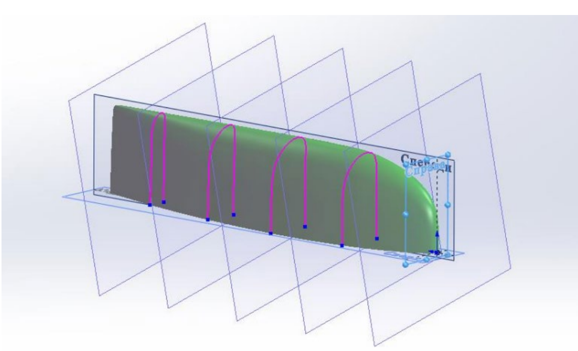


Fig. 7. Selection of curves in cross sections along the wing tip

Cross sections were selected at a distance of 20 %, 40 %, 60 %, and 80 % of the airfoil chord from the airfoil toe.

Fig. 8 shows the DMU of the light aircraft wing tip, and Fig. 9 – tooling (form) for its manufacturing.

During the construction of the DMU of the light aircraft wing tip and the DMU of tooling for its manufacturing, their shapes, geometric dimensions were finally adjusted, and the properties of material, they should be made of, were described.

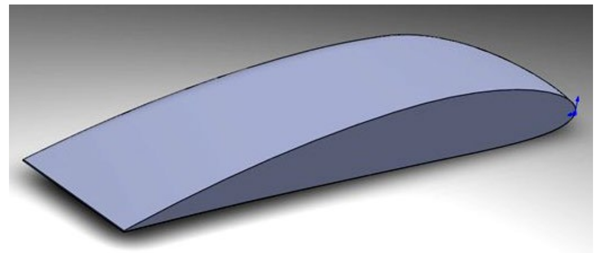
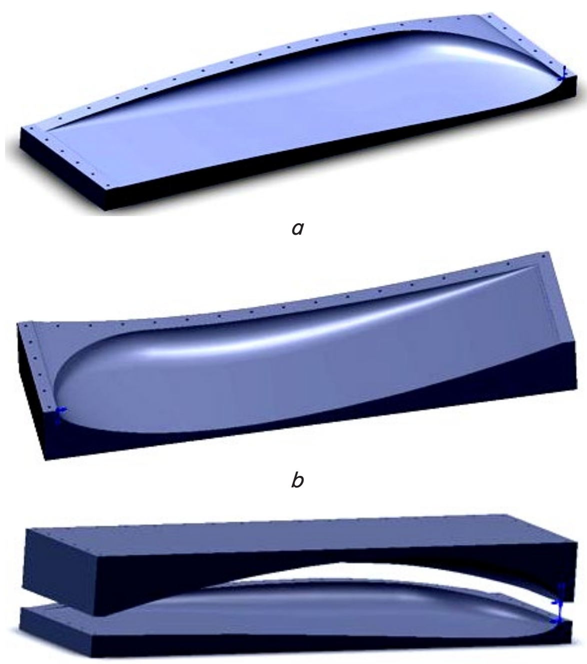


Fig. 8. DMU of the wing tip of a light aircraft



a

b

c

Fig. 9. DMU of technological tooling (form) for the light aircraft wing tip manufacturing: *a* – the lower part; *b* – upper part; *c* – in assembly

5. 2. Calculating the geometric accuracy parameters of the wing tip outline

In the technical specification for the aircraft assembly, the deviations of the actual values of the outlines and contours from their theoretical values are provided only for aggregates and are limited by various tolerances: ±1 mm, ±1.5 mm, and ±2.0 mm [30]. For the calculations, the value ±1.0 mm was chosen, which was previously selected by results of the design and technological analysis of the light aircraft wing tip.

The coefficient of fixation (clamping) while assembling in the *jig* is found by (2):

$$k_{f_{rib}} = 1.5\left(\frac{1{,}300}{300}\right)^{-1.05} = 0.32;$$

$$k_{f_{tip}} = 1.5\left(\frac{1{,}300}{150}\right)^{-1.05} = 0.19.$$

For $E_{jig}^{contour}$, $C_{jig-rib}^{contour}$, $C_{rib-tip}^{contour}$ calculation, the dimensional chains shown in Fig. 10 were built.

Table 1 gives data for calculating the manufacturing error of the *jig* $E_{jig}^{contour}$, where λ_i is the coefficient of relative dispersion of the dimensional chain component link values – the size error or tolerance, which for the Gauss dispersion law (the so-called normal law) is equal to 1 [33].

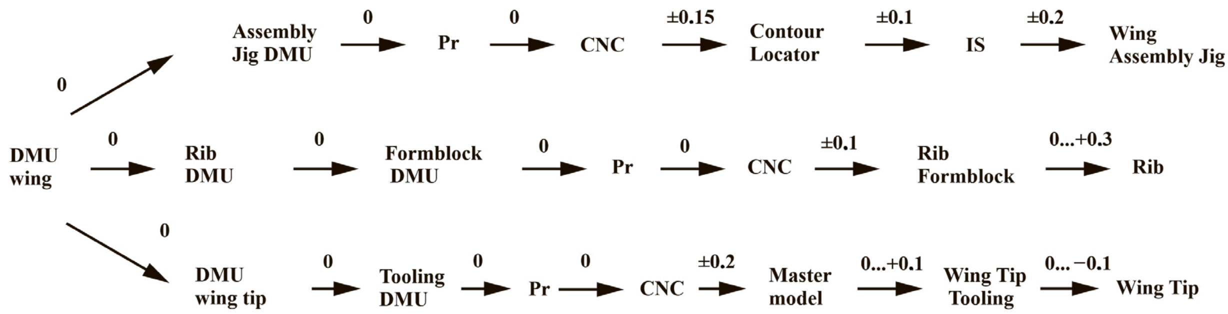


Fig. 10. Technological dimensional chains for calculating the errors of manufacturing and co-ordination: DMU — digital mock-up; Pr — program; CNC — machine with computer numerical control; IS — instrument stand; Master Model — a master model of tooling for manufacturing the working copies of the wing tip technological tooling

Table 1

Data for calculating the limit deviations of assembly *jig* mounting $E^{contour}_{jig}$

Dimensional chain link	Δ_{up_i}	Δ_{low_i}	Δ_{0_i}	$\frac{\delta_i}{2}$	$\left(\frac{\delta_i}{2}\right)^2$	ξ_i	α_i	λ_i	λ_i^2	$\lambda_i \cdot \frac{\delta_i}{2}$	$\xi_i^2 \cdot \lambda_i^2 \cdot \left(\frac{\delta_i}{2}\right)^2$
Wing DMU – Assembly *jig* DMU	0	0	0	0	0	+1	0	1.0	1.0	0	0
Assembly *jig* DMU – Pr	0	0	0	0	0	+1	0	1.0	1.0	0	0
Pr – CNC	0	0	0	0	0	+1	0	1.0	1.0	0	0
CNC – Contour locator	+0.15	–0.15	0	0.15	0.022	+1	0	1.0	1.0	0.15	0. 0225
Contour locator – IS	+0.1	–0.1	0	0.1	0.01	+1	0	1.0	1.0	0.1	0.01
IS – Wing assembly *jig*	+0.2	–0.2	0	0.2	0.04	+1	0	1.0	1.0	0.2	0.04
$E^{contour}_{jig}$	–	–	0	–	–	–	–	–	–	–	0.27

The limit deviations of the *jig* manufacturing error are determined by formulas (5), (6):

$$\Delta_{up\ jig} = \Delta_{0_{jig}} + \frac{\delta_{jig}}{2} = 0.27 \text{ mm;}$$

$$\Delta_{low\ jig} = \Delta_{0_{jig}} - \frac{\delta_{jig}}{2} = -0.27 \text{ mm.}$$

Table 2 provides data for calculating the error of co-ordination for contours of rib and the assembly *jig* locator $C^{contour}_{jig-rib}$.

The limit deviations of the error of co-ordination for contours the assembly *jig* locator and the element of airframe (rib) were calculated by formulas (3), (4), and values are follows:

$$\Delta_{up_{jig-rib}} = \Delta_{0_{jig-rib}} + \frac{\delta_{jig-rib}}{2} = 0.47 \text{ mm;}$$

$$\Delta_{low_{jig-rib}} = \Delta_{0_{jig-rib}} - \frac{\delta_{jig-rib}}{2} = -0.17 \text{ mm.}$$

Table 3 gives data for calculating the error of co-ordination for contours of rib and wing tip, respectively, $C^{contour}_{rib-tip}$.

Table 2

Data for calculating the error of co-ordination for contours of rib and the assembly *jig* locator $C^{contour}_{jig-rib}$

Dimensional chain link	Δ_{up_i}	Δ_{low_i}	Δ_{0_i}	$\frac{\delta_i}{2}$	$\left(\frac{\delta_i}{2}\right)^2$	ξ_i	α_i	λ_i	λ_i^2	$\lambda_i \cdot \frac{\delta_i}{2}$	$\xi_i^2 \cdot \lambda_i^2 \cdot \left(\frac{\delta_i}{2}\right)^2$
Wing DMU – Assembly *jig* DMU	0	0	0	0	0	+1	0	1.0	1.0	0	0
Assembly *jig* DMU – Pr	0	0	0	0	0	+1	0	1.0	1.0	0	0
Pr – CNC	0	0	0	0	0	+1	0	1.0	1.0	0	0
CNC – Contour locator	+0.15	–0.15	0	0.15	0.022	+1	0	1.0	1.0	0.15	0.0225
Contour locator – IS	+0.1	–0.1	0	0.1	0.01	+1	0	1.0	1.0	0.1	0.01
IS – Wing assembly *jig*	+0.2	–0.2	0	0.2	0.04	+1	0	1.0	1.0	0.2	0.04
Wing DMU – Rib DMU	0	0	0	0	0	+1	0	1.0	1.0	0	0
Rib DMU –Formblock DMU	0	0	0	0	0	+1	0	1.0	1.0	0	0
Formblock DMU – Pr	0	0	0	0	0	+1	0	1.0	1.0	0	0
Pr – CNC	0	0	0	0	0	+1	0	1.0	1.0	0	0
CNC – Rib Formblock	+0.1	–0.1	0	0.1	0.01	+1	0	1.0	1.0	0.1	0.01
Rib formblock –Rib	+0.3	0	0.15	0.15	0.022	+1	0	1.0	1.0	0.15	0.0225
$C^{contour}_{jig-rib}$	–	–	0.15	–	–	–	–	–	–	–	0.32

Table 3

Data for calculating the error of co-ordination for contours of rib and wing tip $C^{contour}_{rib-tip}$

Dimensional chain link	Δ_{up_i}	Δ_{low_i}	Δ_{0_i}	$\frac{\delta_i}{2}$	$\left(\frac{\delta_i}{2}\right)^2$	ξ_i	α_i	λ_i	λ_i^2	$\lambda_i \cdot \frac{\delta_i}{2}$	$\xi_i^2 \cdot \lambda_i^2 \cdot \left(\frac{\delta_i}{2}\right)^2$
Wing DMU – Rib DMU	0	0	0	0	0	+1	0	1.0	1.0	0	0
Rib DMU – Formblock DMU	0	0	0	0	0	+1	0	1.0	1.0	0	0
Formblock DMU – Pr	0	0	0	0	0	+1	0	1.0	1.0	0	0
Pr – CNC	0	0	0	0	0	+1	0	1.0	1.0	0	0
CNC – Rib formblock	+0.1	–0.1	0	0.1	0.01	+1	0	1.0	1.0	0.1	0.01
Rib formblock – Rib	+0.3	0	0.15	0.15	0.022	+1	0	1.0	1.0	0.15	0.0225
Wing DMU – Wing tip DMU	0	0	0	0	0	+1	0	1.0	1.0	0	0
Wing tip DMU – Tooling DMU	0	0	0	0	0	+1	0	1.0	1.0	0	0
Tooling DMU – Pr	0	0	0	0	0	+1	0	1.0	1.0	0	0
Pr – CNC	0	0	0	0	0	+1	0	1.0	1.0	0	0
cnc – master model	+0.2	–0.2	0	0.2	0.04	+1	0	1.0	1.0	0.2	0.04
Master model – Wing tip tooling	+0.1	0	0.05	0.05	0.0025	+1	0	1.0	1.0	0.05	0.0025
Wing tip tooling – Wing tip	0	–0.1	–0.05	0.05	0.0025	–1	0	1.0	1.0	0.05	0.0025
$C^{contour}_{rib-tip}$	–	0.15		–	–	–	–	–	–	–	0.35

The limit deviations of the error of co-ordination for contours of rib and wing tip take the following values:

$$\Delta_{up_{rib-tip}} = \Delta_{0_{rib-tip}} + \frac{\delta_{rib-tip}}{2} = 0.5 \text{ mm};$$

$$\Delta_{low_{rib-tip}} = \Delta_{0_{rib-tip}} - \frac{\delta_{rib-tip}}{2} = -0.17 \text{ mm}.$$

The values of the maximum deviation of the actual wing contour from the theoretical one are:

$$\Delta_{up_{as}} = \Delta_{0_{as}} + \frac{\delta_{as}}{2} = 0.84 \text{ mm};$$

$$\Delta_{low_{as}} = \Delta_{0_{as}} - \frac{\delta_{as}}{2} = -0.65 \text{ mm}.$$

The values the obtained expected (calculated) error do not exceed the tolerance of the wing outer contour that equal to ±1.0 mm.

The forming of the wing tip outer contour is implemented in the forming tooling for moulding, which is a sort of assembly *jig* for two halves of the wing tip.

According to (1), the value of deviation of the wing tip actual contour from the theoretical one is defined as:

$$E^{contour}_{\Sigma tip} = E^{contour}_{tip} + E_{others}, \quad (7)$$

where $E^{contour}_{tip}$ is the manufacturing error in the outer contour of the wing tip, which is determined by the dimensional chain in Fig. 11; E_{others} – error of the outer contour of the wing tip, which occurs as a result of deformation after moulding and usually is around 30 % of $E^{contour}_{\Sigma tip}$, that is, $E_{others} = 0.3E^{contour}_{\Sigma tip}$.

The results of the calculation of the manufacturing error in the wing tip outer contour $E^{contour}_{tip}$ are given in Table 4.

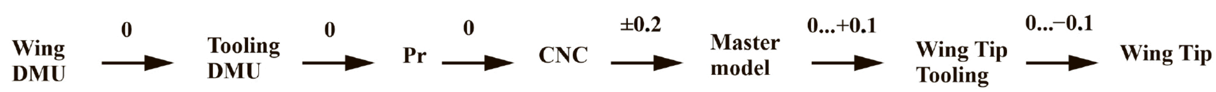


Fig. 11. Dimensional chain for calculation of manufacturing errors and co-ordination of the wing tip: Tooling DMU – primary source of information for tooling; Pr – program; CNC – machine with computer numerical control; Master Model – a master model of tooling for manufacturing the working copies of the wing tip technological tooling

Table 4

Results of calculating the manufacturing error of the wing tip outer contour $E^{contour}_{tip}$

Dimensional chain link	Δ_{up_i}	Δ_{low_i}	Δ_{0_i}	$\frac{\delta_i}{2}$	$\left(\frac{\delta_i}{2}\right)^2$	ξ_i	α_i	λ_i	λ_i^2	$\lambda_i \cdot \frac{\delta_i}{2}$
Wing DMU – Tooling DMU	0	0	0	0	0	+1	0	1.0	1.0	0
Tooling DMU – Pr	0	0	0	0	0	+1	0	1.0	1.0	0
Pr – CNC	0	0	0	0	0	+1	0	1.0	1.0	0
CNC – Master мodel	+0.2	–0.2	0	0.2	0.04	+1	0	1.0	1.0	0.04
Master мodel – Wing tip tooling	+0.1	0	0.05	0.05	0.0025	+1	0	1.0	1.0	0.0025
Wing tip tooling – Wing tip	0	–0.1	–0.05	0.05	0.0025	–1	0	1.0	1.0	0.0025
$E^{contour}_{tip}$	–	–	0	–	–	–	–	–	–	0.21

Then the values of the maximum deviation are:

$$\Delta_{up_{\Sigma tip}} = \Delta_{0_{\Sigma tip}} + \frac{\delta_{\Sigma tip}}{2} = 0.3 \text{ mm};$$

$$\Delta_{low_{\Sigma tip}} = \Delta_{0_{\Sigma tip}} + \frac{\delta_{\Sigma tip}}{2} = -0.3 \text{ mm}.$$

The values of the obtained expected (calculated) error for the manufacturing the light aircraft wing tip do not exceed the tolerance value for the outer contour of the wing ±1.0 mm.

6. Discussion of results of research as to the development of technological preparation for the wing tip production

In this studies, a portrait of the light aircraft wing tip in STL format, for wing tip that actually physically exists, was built, taking into account the accuracy provided by the selected scanner. The ARTEC Leo scanner allows to obtain geometry with an accuracy of ±0.1 mm. It should be noted that the transformation of the portrait in the STL format (Fig. 4) into the polygonal model in the STEP format (Fig. 5) did not result in a loss of geometry, contrary to the data reported in [11].

The construction of two variants of portraits for the wing tip showed that increasing the number of markers (Fig. 2, *a*) does not increase the accuracy of the obtained portrait geometry but increase the labor input of the works related to its processing. Thus, 8 hours were spent on cleaning the portrait from markers by the first version, while for the second it takes only 4 hours. However, in both versions, there were no gaps during the assembly of the obtained scanned surfaces, which was not taken into account in work [12]. In turn, the use of markers did not increase the accuracy of geometric data for complex-shaped parts in work [13], in which the correct selection of scanning equipment becomes important.

Inspection in the Geomagic Control-X program of two variants of polygonal models of the wing tip (in STER format), which were obtained by organic and mechanical methods, showed a lower accuracy for the latter. That is, the deviations for the polygonal model built according to the organic method ranged from +0.23 to –0.22 mm, and according to the mechanical method – from +1.05 to –0.42 mm. This allows to choose a polygonal model that built according to the organic method as the one that had the greatest geometric accuracy and would reduce the deviations of the geometry of the polygonal model of the wing tip from the aerodynamic airfoil. Such an intermediate stage for defining a polygonal model complements the work [14].

A peculiarity of the approach proposed in this study is the refinement of the aerodynamic airfoil and cross sections of the wing tip according to the defined polygonal model, which narrows down the search for airfoils and reduce the time for comparison and determination of the most acceptable geometry.

The introduction of such an approach also allows to combine a number of decisions based on it, namely:

– to determine with high accuracy the geometry of the DMU of convex-concave parts during their prototyping by reverse engineering, which is proposed in paper [16];

– to use the polygonal model as an "ideal portrait" in the system of rapid production with additive (in particular, extractive) technologies, as indicated in studies [5, 13].

Determining of the aerodynamic airfoil and cross sections of the wing tip by this approach used for elaboration of its DMU geometry, which became the only primary source of information for constructing the DMU of technological tooling – the form (mould) for the manufacture of the wing tip. The simplicity of the approach is in the fact that when creating a DMUs of an experimental convex-concave part and tooling for its manufacture, it was used software of ARTEC Studio, Geomagic Design X, Geomagic Control X and SolidWorks. Such software is quite widespread and can be matched and implemented with ease into existing CAD/CAM/CAE production systems. Note that the use of geometry from a single mathematical source guarantees the co-ordination of tooling with high accuracy, which is determined by the accuracy of the equipment used for the manufacture of geometric elements of the tooling. Therefore, the use of DMU creates an opportunity to solve a large number of tasks as to operating and maintenance of metal-forming systems, as well as the PCM production systems, development of material and labor standards of TPP, implementation of technological processes, normalization and unification of technological tooling, modernization of equipment. This especially applies to the use of digital twins in production, which is shown in detail in work [17].

The choice of PrIM as a method of co-ordination for the wing of a light aircraft and its tip is due to the availability of the wing tip DMU and the DMU of its tooling, which are built by to reverse engineering. The DMU availability means its using for inspection of geometry at all stages of the part production, which is shown in detail in [29, 30]. Thus, calculations of the accuracy of the geometric parameters of the wing tip contour according to the developed technological dimensional chains (Fig. 10, 11) demonstrated the following. The maximum deviation of the actual wing contour from the theoretical one was as follows: upper deviation is +0.84 mm, lower deviation is –0.65 mm. The maximum deviation of the actual wing tip contour from the theoretical one was ±0.3 mm. The expected (calculated) errors did not exceed the specified value of the tolerance on the outer contour of the wing (equal to ±1.0 mm), that is, the adopted method of assembling with the method of co-ordination PrIM ensured the specified geometric accuracy.

It should be noted that by the calculation of technological dimensional chains it was solved the problem of ensuring the dimensional accuracy of the closing link of the chain, and the analysis of the expected accuracy of the dimensions of the wing tip and the wing as a whole was performed, taking into account the technological processes of their manufacturing according to the chosen method of co-ordination, the PrIM. Errors in the transfer of the primary size, i.e., the nominal size of DMU, were used as components of the technological dimensional chain; thus, the technological dimensional chain reflects the size changes at all stages of its transfer during both TPP and manufacturing of the wing tip of a light aircraft. The set of dimensions considered in the calculations directly participates in ensuring the accuracy of the geometric parameters of the light aircraft wing tip.

This study results allows to estimate and predict the expected "dispersion" of deviations of the actually manufactured wing tips contours from the theoretical contour, the requirements for which are usually set by designers.

The disadvantage of using the proposed approach to TPP is the need to determine an acceptable co-ordination method, which increases the labor input of the work due to the calculation and comparison of results by several methods.

However, in turn, this allows to determine the expediency of using one or another method by criteria of "price-quality". Thus, the use of PrIM allows to reduce significantly the time spent on TPP, provided that highly qualified specialists, modern inspection tools and equipment are available. For example, the labor input of the work when using PrIM with the construction of DMU by reverse engineering compared to the loft-template method of co-ordination is 1.5 times less [33]. It should be noted that DMU is the primary source of information not only for the parts manufacture but also for co-ordination of technological tooling for assembling the product as a whole. It should be noted that the use of reverse engineering becomes appropriate not only during the TPP of parts which documentation for was lost or they were manufactured using outdated methods and there is a need to renew the production. It becomes indispensable at the stages of inspection of the parts manufacturing and assembling of the product as a whole. The implementing of reverse engineering technology into the existing system of the enterprise can be time-consuming but over time – justified by indicators of economic efficiency. Therefore, this study could be used to improve and update the existing technologies for the AT production and may be used as the basis for further research of another mechanical engineering objects.

7. Conclusions

1. A portrait (in STL format) of the wing tip of a light aircraft has been created. An intermediate stage for converting the obtained STL portrait of the light aircraft wing tip into a polygonal model, a file in STEP format, has been proposed. The latter made allows to increase the accuracy of the geometry obtained by 3D scanning, which became the basis for the further construction of DMU. The refinement of the final geometry of the wing tip DMU was performed by selecting the aerodynamic airfoil and cross sections of the wing tip; the wing tip DMU became the only primary source of information for the construction of the DMU of TT, i.e., the mould for the manufacture of the wing tip. The software ARTEC Studio, Geomagic Design X, Geomagic Control X and SolidWorks being used for those work can be implemented with ease into existing CAD/CAM/CAE production systems, resulting in increase the efficiency of implementing the reverse engineering during TPP.

2. The accuracy of the geometric parameters of the light aircraft wing tip outline was calculated, using the probabilistic method, for co-ordination by PrIM. It was developed the dimensional technological chains of size transferring from DMU to the wing assembly components and to TT elements for selected methods of co-ordination and assembling. Using these technological chains, the problem of ensuring the accuracy of the closing link size was solved, and the analysis of the accuracy of the dimensions of the component links was performed, taking into account the technological processes of their manufacturing according to PrIM. As a component link of the technological dimensional chain it was taken the primary size – the nominal one according to DMU. It was found out that the expected (calculated) errors did not exceed the specified value of tolerance on the outer contour of the wing ±1.0 mm. The latter proved that the adopted method of co-ordination – PrIM – will theoretically ensure the specified geometric accuracy, which in turn confirms the correctness of using PrIM for the light aircraft wing tip TPP.

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.

Funding

The study was conducted without financial support.

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.

References

1. Alcácer, V., Cruz-Machado, V. (2019). Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems. Engineering Science and Technology, an International Journal, 22 (3), 899–919. https://doi.org/10.1016/j.jestch.2019.01.006
2. Stojkic, Z., Culjak, E., Saravanja, L. (2020). 3D Measurement – Comparison of CMM and 3D Scanner. Proceedings of the 31st International DAAAM Symposium 2020, 0780–0787. https://doi.org/10.2507/31st.daaam.proceedings.108
3. Javaid, M., Haleem, A., Pratap Singh, R., Suman, R. (2021). Industrial perspectives of 3D scanning: Features, roles and it's analytical applications. Sensors International, 2, 100114. https://doi.org/10.1016/j.sintl.2021.100114
4. Buonamici, F., Carfagni, M., Furferi, R., Governi, L., Lapini, A., Volpe, Y. (2017). Reverse engineering modeling methods and tools: a survey. Computer-Aided Design and Applications, 15 (3), 443–464. https://doi.org/10.1080/16864360.2017.1397894
5. Saiga, K., Ullah, A. S., Kubo, A., Tashi. (2021). A Sustainable Reverse Engineering Process. Procedia CIRP, 98, 517–522. https://doi.org/10.1016/j.procir.2021.01.144
6. Onopchenko, A., Horbachov, O., Sorokin, V., Dudukalov, Y., Kurin, M. (2022). Optimal Conditions for Deformation of Stamping-Drawing Process from Aviation Materials. Advanced Manufacturing Processes IV, 109–118. https://doi.org/10.1007/978-3-031-16651-8_11
7. Onopchenko, A. V., Kurin, M. O., Shyrokyi, Yu. V. (2024). Ensuring Quality of Stamping Sheet Aviation Parts. Progress in Physics of Metals, 25 (2), 320–363. https://doi.org/10.15407/ufm.25.02.320

8. Subeshan, B., Abdulaziz, A., Khan, Z., Uddin, Md. N., Rahman, M. M., Asmatulu, E. (2022). Reverse Engineering of Aerospace Components Utilizing Additive Manufacturing Technology. TMS 2022 151st Annual Meeting & Exhibition Supplemental Proceedings, 238–246. https://doi.org/10.1007/978-3-030-92381-5_21
9. Helle, R. H., Lemu, H. G. (2021). A case study on use of 3D scanning for reverse engineering and quality control. Materials Today: Proceedings, 45, 5255–5262. https://doi.org/10.1016/j.matpr.2021.01.828
10. Andrei, I.-C., Stroe, G.-L., Berbente, S., Stoica, G. F., Crisan, N., Prisecaru, D. et al. (2023). Applications of design and reverse engineering for the development of digital and smart tools for composite additive manufacturing. INCAS BULLETIN, 15 (4), 19–34. https://doi.org/10.13111/2066-8201.2023.15.4.2
11. Faizin, M., Paryanto, P., Cahyo, N., Rusnaldy, R. (2024). Investigating the accuracy of boat propeller blade components with reverse engineering approach using photogrammetry method. Results in Engineering, 22, 102293. https://doi.org/10.1016/j.rineng.2024.102293
12. Zhang, Z., Zhao, M., Shen, Z., Wang, Y., Jia, X., Yan, D.-M. (2024). Interactive reverse engineering of CAD models. Computer Aided Geometric Design, 111, 102339. https://doi.org/10.1016/j.cagd.2024.102339
13. Maiorova, K., Kapinus, O., Skyba, O. (2024). Study of the features of permanent and usual reverse-engineering methods of details of complex shapes. Technology Audit and Production Reserves, 1 (1 (75)), 19–25. https://doi.org/10.15587/2706-5448.2024.297768
14. Kyaw, A. C., Nagengast, N., Usma-Mansfield, C., Fuss, F. K. (2023). A Combined Reverse Engineering and Multi-Criteria Decision-Making Approach for Remanufacturing a Classic Car Part. Procedia CIRP, 119, 222–228. https://doi.org/10.1016/j.procir.2023.02.133
15. Zhang, C., Pinquié, R., Polette, A., Carasi, G., De Charnace, H., Pernot, J.-P. (2023). Automatic 3D CAD models reconstruction from 2D orthographic drawings. Computers & Graphics, 114, 179–189. https://doi.org/10.1016/j.cag.2023.05.021
16. Maiorova, K., Kapinus, O., Nikichanov, V., Skyba, O., Suslov, A. (2024). Devising a methodology for prototyping convex-concave parts using reverse-engineering technology providing the predefined geometric accuracy of their manufacturing. Engineering Technological Systems, 4 (1 (130)), 112–120. https://doi.org/10.15587/1729-4061.2024.308047
17. Pliuhin, V., Zaklinskyy, S., Plankovskyy, S., Tsegelnyk, Y., Aksonov, O., Kombarov, V. (2023). A Digital Twin Design of Induction Motor with Squirrel-Cage Rotor for Insulation Condition Prediction. International Journal of Mechatronics and Applied Mechanics, 14, 185–191. https://doi.org/10.17683/ijomam/issue14.22
18. Phua, A., Davies, C. H. J., Delaney, G. W. (2022). A digital twin hierarchy for metal additive manufacturing. Computers in Industry, 140, 103667. https://doi.org/10.1016/j.compind.2022.103667
19. Technical specifications. Artec 3D. Available at: https://www.artec3d.com/portable-3d-scanners/artec-spider#specifications
20. Agoston, M. K. (2005). Computer Graphics and Geometric Modelling. Springer-Verlag London, 908. https://doi.org/10.1007/b138805
21. Langetepe, E., Zachmann, G. (2006). Geometric Data Structures for Computer Graphics. A K Peters/CRC Press. https://doi.org/10.1201/9780367803735
22. Agarwal, P. K., Arge, L., Danner, A. (2006). From Point Cloud to Grid DEM: A Scalable Approach. Progress in Spatial Data Handling, 771–788. https://doi.org/10.1007/3-540-35589-8_48
23. Aboshweita, I. M., Masood, M. A., Idris, A. A. M., Abotbina, W. (2024). Evaluation of the Freeform Feature of Solid works Parametric. International Journal of Latest Engineering and Management Research (IJLEMR), 9 (5), 35–44. https://doi.org/10.56581/ijlemr.9.05.35-44
24. Pajerová, N., Koptiš, M. (2024). Shape functions to scanner comparison. The International Journal of Advanced Manufacturing Technology, 132 (7-8), 3889–3902. https://doi.org/10.1007/s00170-024-13520-z
25. Sullivan, J. M. (2008). Curvatures of Smooth and Discrete Surfaces. Discrete Differential Geometry, 175–188. https://doi.org/10.1007/978-3-7643-8621-4_9
26. Burns, M. (1993). Automated Fabrication: Improving Productivity in Manufacturing. PTR Prentice Hall, 369.
27. Szilvśi-Nagy, M., Mátyási, Gy. (2003). Analysis of STL files. Mathematical and Computer Modelling, 38 (7-9), 945–960. https://doi.org/10.1016/s0895-7177(03)90079-3
28. Airfoil Tools. Available at: http://airfoiltools.com/
29. Krivov, G. A., Matvienko, V. A., Vorobev, Yu. A. (2007). Tehnologiya sborki uzlov i agregatov planera samoleta s ispolzovaniem otverstiy v kachestve sborochnyh baz: SOU MPP 49.035-90:2007. Kyiv, 156.
30. Sikulskiy, V., Boborykin, Yu., Vasilchenko, S., Pyankov, A., Demenko, V. (2006). Technology of airplane and helicopter manufacturing. Fundamentals of aircraft manufacturing. Kharkiv: National Aerospace University "Kharkiv Aviation Institute", 206.
31. Pekarsh, A. I., Tarasov, Yu. M., Krivov, G. A. et al. (2006). Sovremennye tehnologii agregatno-sborochnogo proizvodstva samoletov. Moscow: Agraf-press, 304.
32. Kryvtsov, V. S., Vorobiov, Yu. A., Bukin, Yu. M. et al. (2009). Tekhnolohiya vyrobnytstva litalnykh aparativ (skladalno-montazhni roboty). Kharkiv: Nats. aerokosm. un-t "Khark. aviats. in-t", 80.
33. Sikulskiy, V., Maiorova, K., Vorobiov, I., Boiko, M., Komisarov, O. (2022). Implementation of reengineering technology to reduce the terms of the technical preparation of manufacturing of aviation technology assemblies. Eastern-European Journal of Enterprise Technologies, 3 (1 (117)), 25–32. https://doi.org/10.15587/1729-4061.2022.258550