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CONCEPTUAL FOUNDATIONS OF APPLYING INNOVATIVE 3D SCANNING TECHNOLOGIES IN THE CONTEXT OF MAINTAINING AIRWORTHINESS OF STATE AVIATION EQUIPMENT

The goal of this article is to analyze the use of modern 3D scanning technologies and additive manufacturing in addressing practical needs to maintain airworthiness of state aviation equipment. The unified algorithm for 3D scanning of complex technical objects which is independent of specific methods and equipment types has been developed as well as the detailed description of each step of the algorithm. Innovative optical methods of 3D scanning technologies are explored, and a comprehensive methodology that utilizes these optical 3D scanning methods for determining the potential improvement of identified resource indicators of aviation equipment is proposed.

***Keywords:** airworthiness maintenance, resource indicator, 3D scanning technologies, digital 3D model, CAD/CAE, 3D scanner, structured light, laser.*

Introduction

Problem statement. Modern warfare foresees the achievement of air superiority for successful large-scale ground operations. Aviation, as an integral part of the armed forces, stands as a key enabler of their combat capabilities. It represents a complex system where the reliable functioning and guaranteed achievement of assigned targets demand a high level of readiness and support from each of its elements [1; 3; 4, p. 18…28].

Under wartime conditions the service maintenance of the Ukrainian Armed Forces' aviation equipment has become highly complicated due to numerous combat damages, shortages of specific spare parts, constant threat of shelling and limited time [1; 2].

Hence, in the face of large-scale military aggression, various measures are undertaken to restore the functionality of aircraft and their engines that got combat damage [5, p. 1…10]. One of these measures foresees the implementation of modern innovative 3D scanning technologies for evaluation of respective aviation equipment in order to assess in a qualitative and quantitative manner the extent of damage to the components which are critical for flight safety; development of corresponding repair techniques [6…11].

Analysis of recent research and publications. Review of publications [6…11], which describe the methodology of maintenance of complex technical objects with 3D scanning technologies, demonstrates an absence of comprehensive and systematic approaches in implementing 3D scanning technologies for the repair of aviation equipment.

The aim of the article is to explore the incorporation of modern 3D scanning methods as a mean to maintain airworthiness and perform repair of aviation equipment as well as analyzing the future potential.

Presentation of the core material

3D scanning [12, p. 108…255; 15, p. 82…92; 17, p. 280…286] is a process of capturing geometric parameters of a real-world object and their structured storage in a specific format using specialized technologies and equipment - 3D scanners.

As part of the research of the possibility to restore the functionality of aircraft and their engines, 3D scanning technologies may be proposed to address certain phases of the renewal process as described in Figure 1.

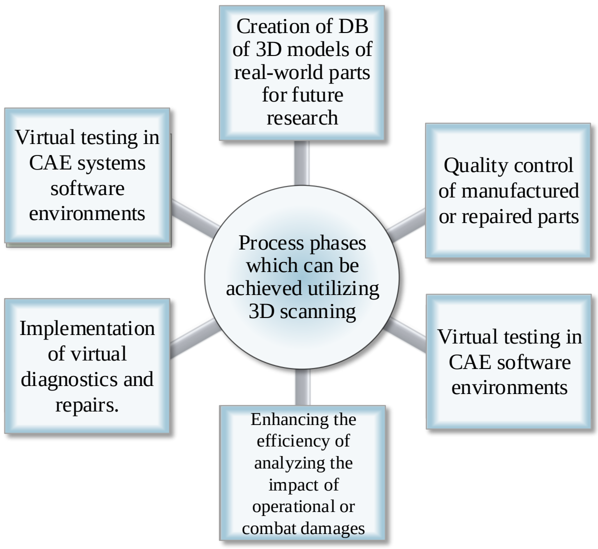

Fig. 1. Relevant phases of the process which can be achieved with the application of 3D scanning technologies. Source: developed by the authors.

One of the primary objectives is control of quality and part's geometry while manufacturing is in progress and after it is completed [14, p. 114…122; 16, p. 1069…1090; 19, p. 281…291; 21, p. 255…268]. Upon completion of the manufacturing process the scanned 3D model of the part's geometry is verified against specifications through comparison to the values of the reference CAD model. The verification results are presented as 3D image with color highlights of the areas with deviation, permit filtering based on selected parameters, and also support generation of statistics for detected deviations.

The 3D scanning technologies can also be utilized to create a digital CAD 3D-model of a specific part for further testing purposes to determine its functional compliance with initially set criteria. For instance, physical modeling with software for automation of engineering analysis can be performed [29, p. 143…153]. Generation of the CAD model based on a real-world part ensures that highly accurate data is available for analysis. Additionally, the availability of digital CAD models of similar parts from different manufacturers permits to perform comparative tests in the virtual environment of a CAE system to identify the most optimal design.

An essential aspect here is the capability for reverse engineering of parts and assemblies, namely: generating 2D/3D drawings based on their scanned 3D model and the ability to integrate scanning results into a wide range of automated CAD/CAE systems used in manufacturing process. Reverse engineering [23, p. 204…213] is the process of re-designing a product for which there are no drawings or documentation or they have been lost. The objective of reverse engineering is to recreate a physical part without using design documentation. Accurate 3D scanners are utilized for reverse engineering to collect data from the surface of the real-world part producing its digital 3D replica as a result, which can be replicated, enhanced and stored in a digital archive.

At present there is a need to renew the aircraft components and their engines that have suffered operational and combat damage. 3D scanning allows relatively quick and straightforward acquisition of geometric parameters of the incurred damage to objectively assess the technical condition of the object. For instance, 3D scanning can be used to detect the minor defects in the external surface of the aircraft engine's nacelle at the earliest stage to prevent further destruction.

Another important goal that can be achieved with the 3D scanning technologies is the creation of the electronic database of 3D models of components with combat and operational damage. Such database can be further utilized in the scientific research, particularly in the development of the information system, which permits mathematical modeling of the interrelation and the impact of resource-limiting components and assemblies on the technical integrity of an aircraft.

In order to achieve the described goals, a unified algorithm for 3D scanning has been developed. It can be utilized for any physical object and irrespective of the specific method or equipment used (see Fig. 2).

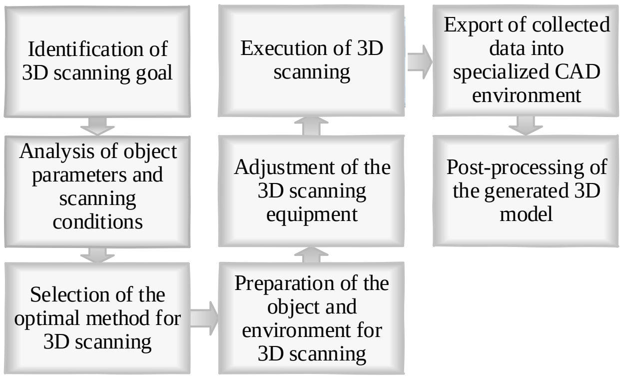

Fig. 2. Unified algorithm for 3D scanning.
Source: developed by the authors.

The respective 3D scanning algorithm was developed based on the following technological processes [12, p. 391…501; 13, p. 565…694; 13; 22, p. 43…53; 25, p. 295…305; 27, p. 153…205].

Calibration of Equipment. Prior to starting the 3D scanning process it is necessary to calibrate the 3D cameras used for image capture. Camera calibration involves determining various parameters such as focal length, lens distortion and camera positioning.

Image Acquisition. This step involves capturing a series of static 3D frames of the scanned object using a single camera or a set of cameras. These 3D frames should depict the object from various angles. Ensuring sufficient overlap between adjacent 3D frames is essential to partially represent the same scanned surface area.

Feature Detection. The software performs analysis of the acquired 3D frames to identify unique features on the scanned object's surface according to a specific algorithm. The software stores the findings of the analysis for the use in the next step of the process.

Matching of the Elements. The software compares identified elements across different 3D frames and determines their relative positions. This matching process is performed by analyzing the similarity and positioning of elements in the images.

Triangulation. This step involves computing the 3D coordinates of matched objects by intersecting various viewpoints. With the help of the triangulation the software reconstructs the object's 3D geometry.

Point Cloud Generation. Triangulation results in a 3D point cloud representing the object's surface geometry. The 3D point cloud can be visualized as a collection of individual 3D points in 3D space. A polygonal mesh is generated from the 3D point cloud.

Texture Application. Texture refers to the external appearance or surface characteristics of the object. To enhance the reconstructed 3D model's appearance software can influence the polygonal mesh by effectively incorporating information about the object's texture and color.

Post-processing and Refinement. During the initial reconstruction of the polygonal mesh post-processing methods can be applied to refine the 3D model. This might involve removal of noise or outliers from the point cloud, mesh topology optimization or data interpolation techniques to fill in missing data.

Possible example of effective application of 3D scanning is the reconstruction of a 3D model of a high-pressure turbine rotor blade of an aircraft engine, which can be used for remote assessment of its technical condition by experts without physical presence at the military facility or transporting the engine to a repair site.

The most advanced methods of 3D scanning technologies are structured light scanning (optical method) and laser scanning [20, p. 89…92; 26, p. 1565…1572; 28, p. 1237…1239]. Their primary advantages are contactless data acquisition of the object's geometry, significantly higher scanning speed and accuracy of scanning. Contactless 3D scanners are portable, versatile and relatively easy to use.

Structured light 3D scanning is a method that uses a projector and a camera to reconstruct the geometry of the object surface. It operates by illuminating the object surface with a calibrated geometric pattern of white or blue light. This pattern consists of a series of parallel lines, or a grid structured in a particular way. The illumination process is captured by two special 3D scanner cameras recording any deviations or deformations of the light pattern on the object's surface. An increase in the distance between the light lines of the pattern indicates that object's surface is closer to the cameras and vice versa. Based on these established patterns through sequential triangulation of different images of the light structure the geometric shape and dimensions of the object are determined. The 3D scanner software consolidates the obtained results and generates a unified polygonal mesh of the 3D model. Modern structured light 3D scanners also include an additional camera that captures the object surface texture.

The high accuracy and speed allow the structured light 3D scanner to be applied to digitize objects of various sizes and geometries making it a versatile instrument for a wide range of tasks. With a structured light 3D scanner one can monitor the manufacturing quality of critical aircraft engine parts such as working blades or high-pressure turbine discs. After the production process is completed, it is necessary to scan the produced part and analyze its 3D model for potential discrepancies in external geometry compared to design parameters. In specialized software the 3D quality control function visually displays all detected deviations using a chromatography method. Consequently, any error in the manufacturing process of the blades can be identified determining the reasons behind, and necessary adjustments can be made based on the obtained results.

The laser 3D scanning method, similar to structured light, starts with projecting a laser line or point onto the object surface. Two special sensors of the laser 3D scanner continuously capture the laser emission reflected from the object. The distances and angles between the laser source and the camera are determined with high precision. By utilizing algorithms, which are based on triangulation and trigonometric formulas, the 3D scanner determines at which angle the laser emission returns to the sensor and the distance to the object surface. The obtained data is used to generate a polygonal mesh representing the geometry of the scanned object.

Unlike structured light the laser is less sensitive to external lighting conditions. Laser scanners are more effective in capturing poorly prepared parts, with glossy or dark surfaces. The laser method of obtaining 3D data is highly optimized for calculations, so using a regular laptop is often sufficient for operating laser 3D scanners. There are models of laser 3D scanners that are entirely autonomous in terms of power supply, and the software of the 3D scanner generates preliminary view of the 3D model in real-time.

The high-end technical specifications of laser 3D scanners permit to address quite complex tasks diagnosing critical components of aircraft engines, for example, when evaluating the condition of fuel nozzles for measuring such parameters as nozzle diameter and swirl channel sizes. The obtained results can be used to assess the nozzles performance and detect deviations. Laser 3D scanning can detect the slightest deformations or the appearance of micro-cracks on the nozzle surface, which are invisible during regular inspection. The collected data can be used to decide whether to replace or repair respective components.

As per the described, a comprehensive methodology has been developed. It utilizes 3D scanning technologies to determine the technical condition of critical elements of aircraft engines and evaluate the potential improvement of their identified resource indicators (Fig. 3). This methodology consists of the following stages (Figure 3).

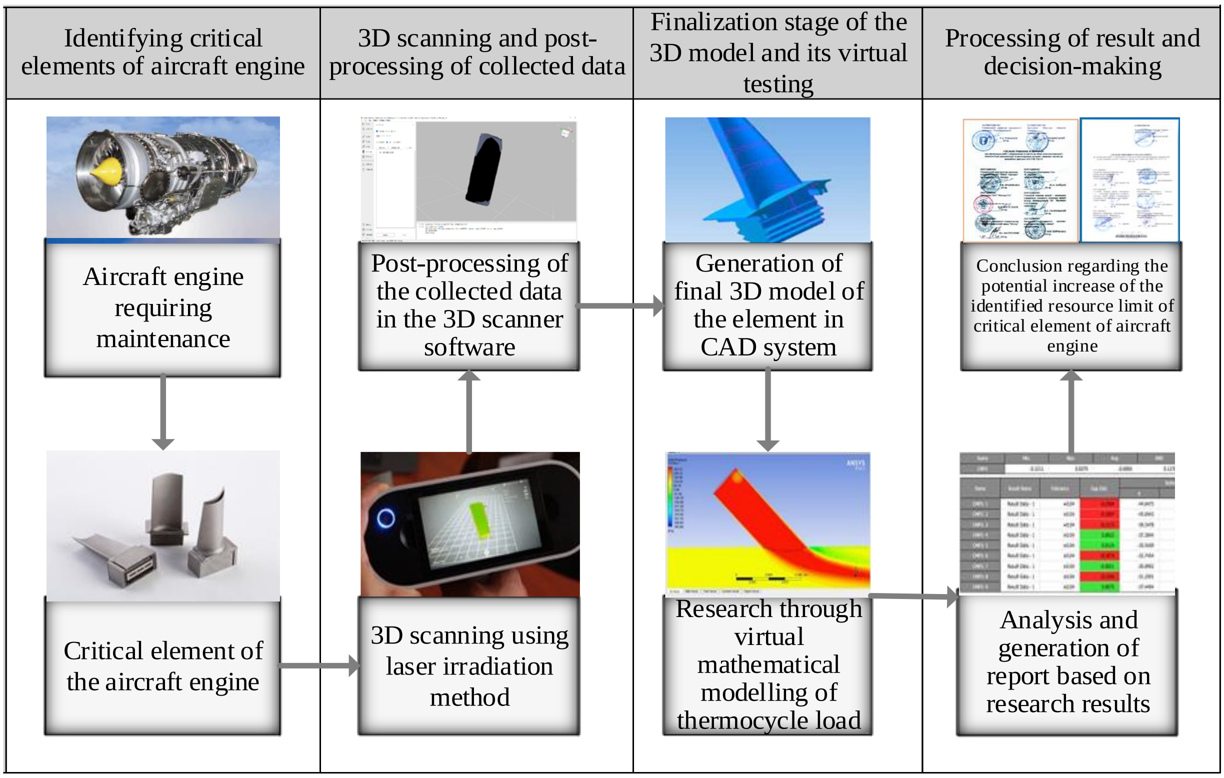

Fig. 3. General methodology that utilizes innovative 3D scanning technologies in order to determine the potential improvement of identified resource indicators of aviation equipment illustrated by aircraft engine example.
Source: developed by the authors.

Firstly, the identification of critical elements of the aviation engine is carried out through decomposition into nodes and systems that limit its resource. Following the decomposition, an individual analysis of each component is conducted concerning the specificities of their structural design, operating conditions, and impact on the engine's performance in case of failure.

Subsequently, the identified critical element undergoes 3D scanning using structured light or laser technologies. During this stage, a primary point cloud of the 3D model geometry is generated, which, after processing in the integrated 3D scanner software environment, is converted into a polygonal mesh.

The finalization stage of the 3D model geometry of the critical element involves rectifying possible imperfections resulting from the 3D scanning and preparing it for virtual examinations, which conducting in CAD/CAE software environment (Ansys) using mathematical modeling [30].

The final stage involves compiling a report based on the research results and analyzing whether to increase the identified resource for the stand-alone elements or for the whole engine.

Conclusions

1. As a result of the conducted research, a unified algorithm for 3D scanning of aircraft components and a general methodology, that determines the potential improvement of identified resource indicators, have been developed. These can be implemented in addressing practical needs to maintain airworthiness of state aviation equipment.

2. It has been concluded that modern 3D scanning methods are effective and promising tool that helps to address a wide range of issues in the process of aintaining airworthiness of aircraft equipment of the Armed Forces of Ukraine.

The directions for further research. The future directions for research are to be as follows.

1. Adaptation followed by pilot implementation of the developed algorithms and methodologies in the real-life technological processes of maintaining airworthiness of aircraft equipment of the Armed Forces of Ukraine, specifically creating a database of 3D models of resource-limiting parts and assemblies with combat and operational damage. Evaluation of the effectiveness of the proposed methodologies based on the obtained results aiming to enhance its adequacy and reliability.

2. Further research of modern 3D scanning technologies and their potential implementation in order to improve the identified resource indicators of aviation equipment, in particular research of the effectiveness of such methods as coordinate-measuring (contact) and computer tomography.

3. Comparative analysis and experimental research of practical technical solutions and equipment used in 3D scanning technologies in order to determine the efficiency of their usage for restoring the functionality of aircrafts and their engine.

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КОНЦЕПТУАЛЬНІ ОСНОВИ ЗАСТОСУВАННЯ ІННОВАЦІЙНИХ ТЕХНОЛОГІЙ 3D-СКАНУВАННЯ В КОНТЕКСТІ ПІДТРИМАННЯ ЛЬОТНОЇ ПРИДАТНОСТІ АВІАЦІЙНОЇ ТЕХНІКИ ДЕРЖАВНОЇ АВІАЦІЇ

С.В. Пащенко, А.А. Шульгін, В.О. Харченко

У статті висвітлюється проблема підтримання справності та льотної придатності авіаційної техніки державної авіації в умовах протидії масштабній військовій агресії, важливість безперебійного функціонування авіаційних систем та обладнання для успішного проведення військових операцій. Зазначається, що в умовах інтенсивних військових дій значно ускладнюється підтримання справності авіаційної техніки через отримання численних пошкоджень, дефіциту запчастин та обмеженого часу. Як ефективна відповідь на визначені виклики розглядаються сучасні інноваційні технології 3D-сканування, як один із заходів для відновлення справності авіаційної техніки. З урахуванням спроможностей та поточного стану розвитку технологій 3D-сканування запропоновано перелік актуальних практичних завдань щодо підтримання льотної придатності авіаційної техніки державної авіації, які можуть бути вирішені з їх залученням. Розроблено єдиний уніфікований алгоритм 3D-сканування складних технічних об'єктів незалежно від конкретного методу та типу обладнання. Наведено детальний опис кожного з етапів розробленого алгоритму. У статті розглянуто такі інноваційні оптичні методи технології 3D-сканування, як структуроване світло та лазер. Виконано порівняльний аналіз їх ефективності. Представлено загальну методику визначення можливості збільшення встановлених ресурсних показників об'єктів авіаційної техніки із застосуванням зазначених оптичних методів 3D-сканування.

Ключові слова: підтримання справності, ресурсний показник, технології 3D-сканування, метод 3D-сканування, цифрова 3D-модель, CAD/CAE, оптичний 3D-сканер, структуроване світло, лазер.