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Use of reverse engineering methods in the process of restoration of machine parts

Yevhen Mishchuk[1], *Andriy Sorochenko*[2], *Yevhen Berezovsky*[3]

[1]Kyiv National University of Construction and Architecture,
31, Povitroflotskyi Avenue, Kyiv, Ukraine, 03037,
[2] Separate structural unit "Kyiv Professional College of Computer Technologies and Economics of the National Aviation University",
St. Boryspilska, 5, Kyiv, 02099
[3] Separate structural unit "Professional College of Engineering, Management and Land Management of the National Aviation University",
St. Metrobudivska, 5-a, Kyiv, 03065
[1]mischuk.ieo@knuba.edu.ua, https://orcid.org/0000-0002-7850-0975,
[2]Andru69@ukr.net,
[3]rezottissimo@gmail.com

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Abstract. The paper considers the peculiarities of creating digital copies of objects using reverse engineering technology. The main process used in reverse engineering is the processing of digital copies of objects, which is called photogrammetry. The reverse engineering process consists of the following stages. First, a 3D scan of the product and scan data processing is performed. The received digital data (polygonal mesh) is converted into a CAD file, which can be used to change the shape and topology of the model in accordance with the project. Based on this, an analysis of the two main technologies on which photogrammetry is based was performed: 1) laser triangulation method (laser scanners are used), 2) structured light method (optical scanners are used). The main disadvantages of using laser triangulation when scanning machine parts and methods of reducing their negative impact on the final result are given. The process of determining the position of a point when scanning parts by the laser triangulation method is considered in detail. Equations for normalizing the position of the point and equations that remove the distortion of the point due to the aberration of the camera lens are given. An equation for determining the width of a laser beam is presented, on the basis of which its main geometric characteristics are determined. A general diagram of the influence of the main factors on the quality of the process of scanning parts by the method of laser triangulation is constructed. One of the varieties of scanning objects using structured light is the range imaging (SfM) technique. The SfM technique is a process of estimating a three-dimensional structure from a sequence of two-dimensional images that can be associated with local traffic signals. The position of the camera in space is used to find the x,y,z coordinates of each pixel. An overview of the main software for creating and editing a structured polygonal mesh based on scan data is carried out. As a study of the process of reverse engineering technology, a connecting rod of a car engine was scanned by the SfM method and its digital model was created.

Keywords: reverse engineering, photogrammetry, scanner, laser, parts repair, mechanical engineering.

INTRODUCTION

The technology of reverse engineering is essentially the reverse of the classical technology of development and creation of industrial objects [1], [2]. The main process used in reverse engineering is the processing of digital copies of objects, which is called photogrammetry. Photogrammetry is the process of creating 3D models from photographs. Today, photogrammetry is widely used to solve applied problems in construction, architecture, industrial modeling, and art [3]. The reverse engineering process consists of the following stages. First, a 3D scan of the product and scan data processing is performed. The received digital data (polygonal mesh) is converted into a CAD file, which can be used to change the shape and topology of the model in accordance with the project. Creation of a solid-state CAD model that will meet the customer's requirements (will be compatible with his software). Creation of working documentation for a detail [4].

OBJECTIVE OF WORK

Analysis of the technology of manufacturing and repairing machine parts by the method of reverse engineering.

PURPOSE OF THE PAPER

Photogrammetry technology is based on several different methods: 1) laser triangulation method (laser scanners are used), 2) structured light method (optical scanners are used).

Laser triangulation is a machine vision technique used to obtain three-dimensional data by combining a laser light source with a camera. The laser beam and the camera are aimed at the control point, knowing the known angular displacement (α) between the laser source and the camera sensor, it is possible to measure the depth difference using trigonometric calculations [5].

High detection speed allows you to track the position of a moving or vibrating part of any machine. The resulting accuracy can reach one thousandth of the distance. For diffuse reflection, the distance may be limited by the requirement to obtain a certain reflected optical power; with mirroring, much greater distances can be measured, but angular alignment in the direction of measurement is required. Of course, the reasons for using a laser beam when scanning objects should be noted here.

The advantages of a laser beam over other light sources lie in its wave properties, namely coherence, the ability to emit light of the same color and the same orientation. However, the laser beam also has disadvantages, which are manifested due to the illumination of surfaces with high roughness with a highly coherent beam. As a result, we can see the optical phenomenon shown in fig. 1. Such a chaotic pattern is created by the interference of waves that scatter on the microscopic unevenness of the illuminated surface and is called the speckle effect [6].

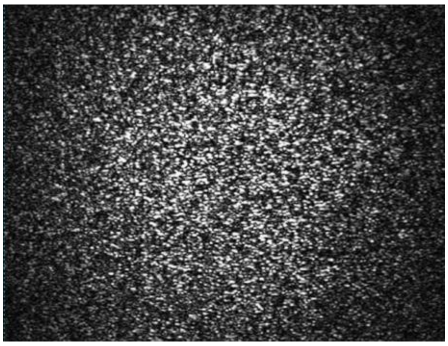
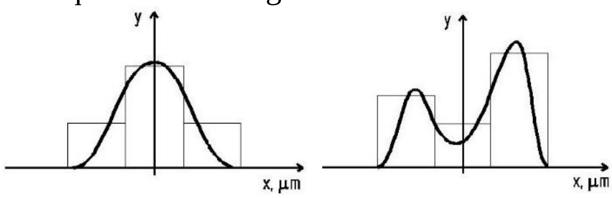


Fig. 1. An example of the speckle effect when emitting a laser beam. Source – LibreTest Chemistry (https://t.ly/ZUKsD)

Laser speckle is a useful phenomenon for determining surface roughness, but for optical triangulation it is a negative factor as it increases signal noise and random error. The essence of the problem is that laser triangulation uses rays with a Gaussian profile, the position of the points is also calculated based on the assumption of a Gaussian distribution of the intensity of light that is reflected from the scanning surface. Due to the speckle effect, the light reflected from the scanning surface no longer has a Gaussian profile. In fig. 2 shows for comparison the beam of the Gaussian profile and the distortion of the profile due to the speckle effect. To reduce the influence of the speckle effect, there are several methods [7]: 1) speckle reduction; 2) use of a less coherent light source, which at the same time should be monochromatic; 3) scanning of the object from several different points with subsequent combining of the obtained results.



a *b*

Fig. 2. Examples of a Gaussian beam during laser triangulation:
a – a normally reflected beam with a Gaussian profile;
b – the profile of the Gaussian beam under the conditions of the speckle effect

Let's consider in more detail the process of laser triangulation when determining the position of a point, Fig. 3.

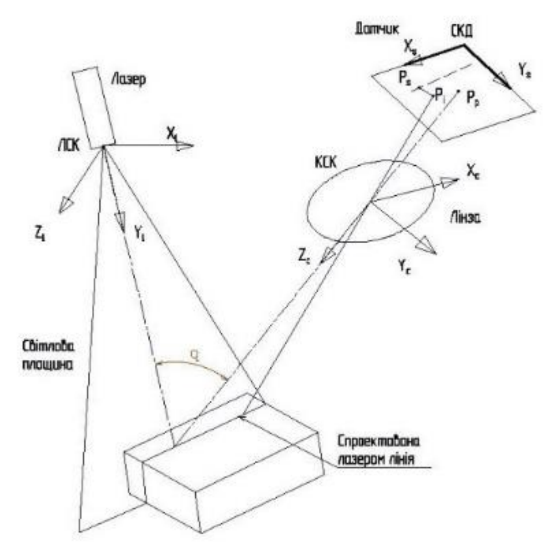


Fig. 3. Scheme to describe the method of laser triangulation

The Ps point is a reflection of the P point that is projected by the laser onto the measured surface of the part. The position of point P in the video camera coordinate system (CCS) can be described by the vector $R_C=(X_C,Y_C,Z_C)^T$. In the laser coordinate system (LSC), the point is described by the vector $R_l=(X_l,Y_l,Z_l)^T$. These two vectors can be mutually expressed by the following equation [8]:

$$R_C=R_{CP}R_P+T_{CP} \qquad (1)$$

where:
R_{CP} – the rotation matrix, which defines the rotation of the laser coordinate system relative to the video camera coordinate system, i.e. axis rotations X_l,Y_l,Z_l to the corresponding corners α,β and γ.

Vector $T_{CP} = (T_X,T_y,T_z)^T$ is a translation vector between coordinate systems.

The point projected by the laser line passes through the lenses and falls on the sensor with a charge connection. Due to the aberration of the video camera lens, the point is recorded in the coordinate system of the sensor with coordinates $P_s=(X_s,Y_s)$. Since the units of measurement in the coordinate system of the sensor are expressed in pixels, and in the coordinate system of the video camera in millimeters, it is necessary to perform normalization, at the same time it is necessary to shift the coordinate system to the optical axis of the camera (point P_0) [9].

To carry out the above operation, the equation is used:

$$\left(X_{sn},Y_{sn}\right)=\left(\frac{X_s\text{-}C_x}{f_x}\text{-}\frac{Y_s\text{-}C_y}{f_y}\right), \qquad (2)$$

To obtain an ideal geometric transformation of a point, it is necessary to remove the distortion of the position of the point due to the aberration of the camera lens [10]. For this purpose, the following equation is used:

$$\left(X_n,Y_n\right)=\begin{pmatrix}\dfrac{X_{sn}\text{-}2p_1X_{sn}Y_{sn}\text{-}p_2\left(r^2+2X_{sn}^2\right)}{1+K_1R^2+K_2R^4}, \\ \dfrac{Y_{sn}\text{-}2p_2X_{sn}Y_{sn}\text{-}p_2\left(r^2+2Y_{sn}^2\right)}{1+K_1R^2+K_2R^4}\end{pmatrix}, \qquad (3)$$

where:
$R=\sqrt{X_{sn}^2+Y_{sn}^2}$, K_i and p_i – radial distortion coefficients, which are determined by calibration.

The same transformations apply to parameters C_x and C_y, which represent the coordinates of the intersection of the optical axis and the axis of the sensor (point P_0) in the coordinate system of the charge coupling sensor. And also to the parameters f_x and f_y, which represent the focal length between the video camera lens coordinate system and the point P_0. The resulting equations are solved numerically.

Another factor that affects the error when scanning objects is the geometry of the laser beam itself [11], [12]. Conventionally, two areas can be distinguished in the laser beam. In the first section, the beam is parallel and does not change in diameter along the entire length of the section. In the second section, the beam gradually expands in diameter. The first section is short in length and is called the collimated section of the laser beam. To reduce the measurement error, it is necessary that the optical system was configured in such a way that only the collimated part of the laser beam will enter the field of view of the sensor with charge coupling [12].

The width of the laser beam can be calculated according to the following relationship:

$$R(z) = r_0 \sqrt{1+\left(\frac{X}{X_r}\right)^2} \quad , \tag{4}$$

where:
r_0 – the radius of the laser beam on the calibrated area;
X – distance from the center of the calibrated area along the X axis;
X_r – the Rayleigh length or the distance from the center of the collimated section to the point where the radius of the beam increases by 1.41 compared to the radius of the beam in the collimated section.

When scanning objects of a complex shape, the effect of reflection of the laser beam on another surface of one part, then and further hitting the camera sensor, may occur. This effect is called higher-order reflection. Such an effect should be excluded from the scanning process, as it affects obtaining a realistic model of the part. One of the solutions is the use of polarized laser light [10], [12]. However, practice shows that this method is well suited for scanning parts with simple geometry.

In this way, it is possible to build a general diagram of the influence of the main factors on the quality of the process of scanning parts by the method of laser triangulation, Fig. 4 [10].

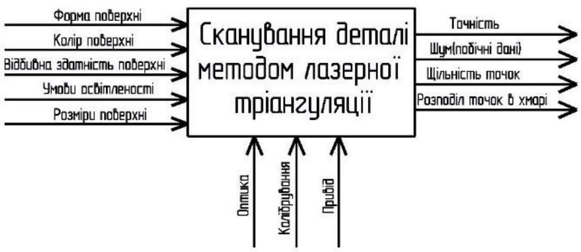


Fig. 4. Scheme of factors affecting the result of the laser triangulation scanning process

In the structured light method, an ordinary light source is used. When using this method, a certain number of light patterns are projected onto the target object. The displayed image is captured by the cameras and the position of each point on the surface of the object is calculated based on the obtained distortions of the pattern. After repeatedly scanning each element of the surface of the target object, these discrete structures are combined into a single model, which is then cleaned (filled holes, unnecessary artifacts) and exported to an editable format.

Structured light scanners are quite fast, as they receive information from several points in the field of view. Structured light scans weakly curved surfaces and detailed surfaces of organic nature very quickly and efficiently. One of the types of object scanning using structured light is the range imaging (SfM) technique, Fig. 5. The SfM technique is a process of evaluating a three-dimensional structure from a sequence of two-dimensional images that can be combined with local traffic signals [6]. The position of the camera in space is used to find the *x*, *y*, *z* coordinates of each pixel.

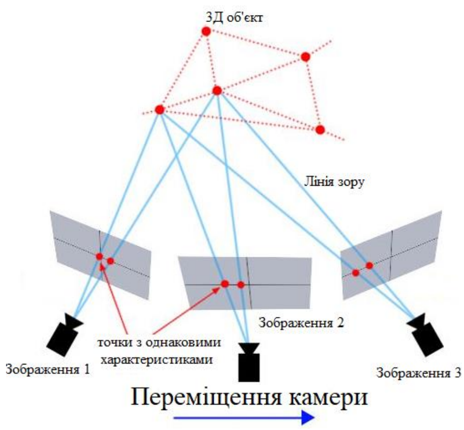


Fig. 5. Object scanning using range imaging technique (SfM)

Today, most digital means of photography and video recording store additional information. It can be the coordinates of the place of photography, the type of digital device, etc. The program for 3d models extracts this information and writes it into a special file where the following is indicated: height, camera rotation angle, longitude and latitude data. The program uses machine vision and photogrammetry technologies to find similar points in the photo. Thus, for each pixel in one photo there is a corresponding pixel in other photos. Next, if a point is found in three or more photos, the program calculates the coordinates of this point in space and stores them. The more matches in different photos, the more accurate the model will be. A 60% to 80% image overlap is optimal.

In the process of photo processing, a cloud of points is created, which are used to generate a polygonal grid. A polygonal grid is a collection of points and lines that define the shape of a multifaceted object.

When choosing equipment for scanning objects, you can use the diagram shown in Fig. 6.

When scanning objects using the SfM method, special attention should be paid to the illumination of the room, the uniformity of the movement of the camera and the quality of the camera itself. The total number of images was 48.

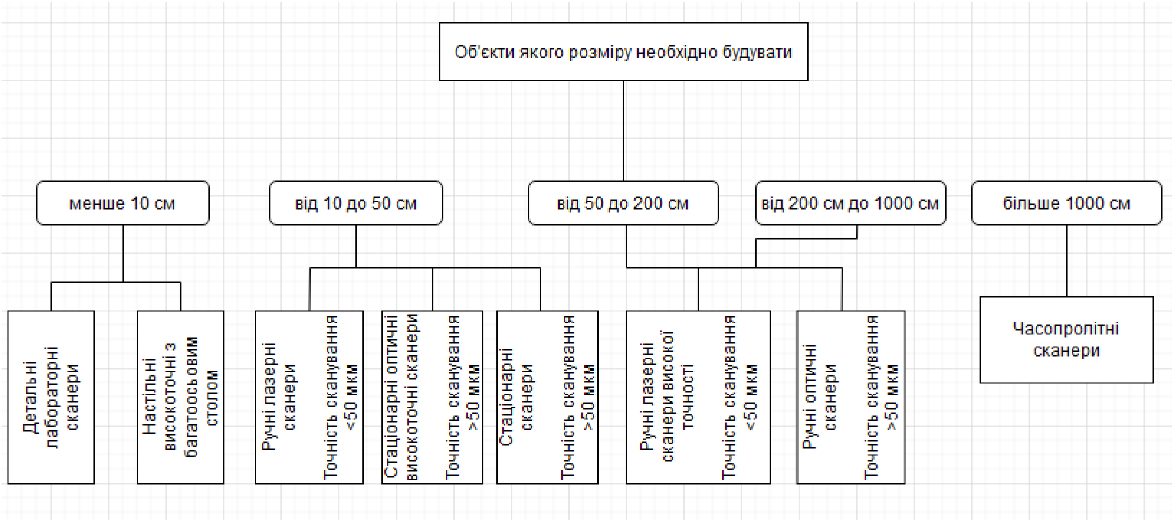


Fig. 6. Classification of scanners

Specialized software is used to process digital data. The most common software is: Geomagic Design X, Autodesk Remake, Agisoft Photoscan, Reality Capture, Pix4d.

The best open source photogrammetry software is: 3DF Zephyr, Colmap, MeshLab, Meshroom, MicMac, VisualSFM, OpenMVG.

Fig. 7. Car engine connecting rod

In this work, SfM technology was used to scan the object. The connecting rod of the crank-connecting mechanism of the car engine was taken as the object of scanning Fig. 7.

The generated textured polygonal mesh of the scanned connecting rod is presented in Fig. 8.

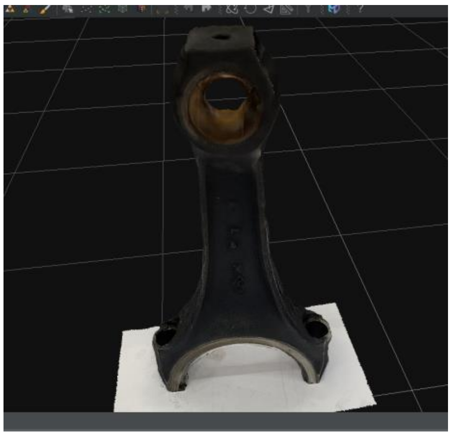
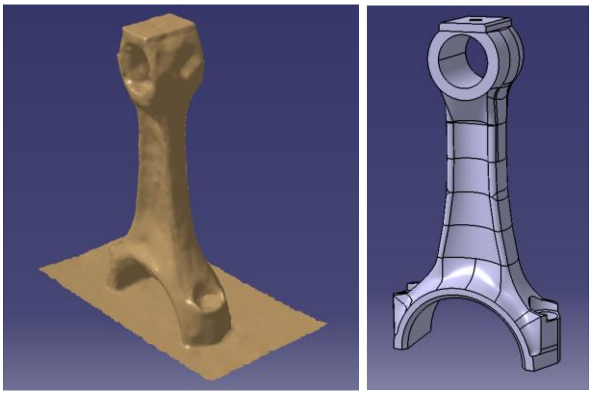


Fig. 8. Generated polygonal mesh of the connecting rod model

As can be seen from fig. 8 model of the connecting rod is not ideal as appropriate simplifications were adopted to speed up the process of creating a 3d model. The next step is to edit the connecting rod model in the appropriate CAD.

Today, most of the known CAD systems have all the necessary tools for processing the polygonal mesh of the part. CAD was used in this work - Catia V5 R2018.

The polygonal mesh of the connecting rod and its reconstructed 3d model are presented in Fig. 9, *a*, *b*.



a *b*

Fig. 9. The model of the connecting rod during processing in Catia V5:
a – a polygonal model with an implicit surface; *b* – reconstructed 3d model

As can be seen from Fig. 9, and the polygon mesh has surface deflections that are associated with the scanning problems described above. Holes or tears on the surface of the part are also a common problem. Depending on production needs, there are several ways to solve such problems. If we need an exact copy of the original part, then we can build a frame based on the scanned polygon grid, the dimensions of which will correspond to the original part. Then, a 3D model is created from the frame using surface geometry. If there is no need to strictly adhere to the dimensions of the original part, the polygon mesh can be quickly edited in software designed for creating 3D computer graphics. One way or another, in both cases, the time for creating a 3D model of a part is significantly reduced compared to classical modeling. On the other hand, it should be remembered that reverse engineering technology does not solve the problem of creating a significantly new part and cannot fully replace classical modeling.

CONCLUSIONS

The main scientific problem in reverse engineering today is the improvement of algorithms and software, as well as the implementation of this technology in production. The use of digital methods of 3D scanning and information processing requires the use of new approaches and methods for solving photogrammetric tasks.

Machine vision technology is in demand in the conditions of creating or restoring parts and units of construction machines, determining the quality of the surface and the dimensions of the parts, when calculating the strength of the elements of constructions of machines and equipment.

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Використання методів реверсивного інжинірингу в процесі відновлення деталей машин

Євген Міщук[1], Андрій Сороченко[2], Євген Березовський[3]

[1]Київський національний університет будівництва і архітектури,
[2]Відокремлений структурний підрозділ "Київський фаховий коледж комп'ютерних технологій та економіки Національного авіаційного університету",
[3]Відокремлений структурний підрозділ "Фаховий коледж інженерії, управління та землевпорядкування Національного авіаційного університету"

Анотація. В роботі розглянуто особливості створення цифрових копій об’єктів з використанням технології реверс-інжинірингу. Основним процесом, який використовується при реверс-інжинірингу є обробка цифрових копій об’єктів, яка має назву фотограмметрія. Процес реверс-інжинірингу складається з наступних етапів. Спочатку виконується 3D сканування виробу та обробка даних сканування. Отримані цифрові данні (полігональна сітка) перетворюють в CAD-файл, за допомогою якого можна змінити форму і топологію моделі у відповідності до проекту. На основі цього був виконаний аналіз двох основних технологій на яких побудована фотограмметрія: 1) метод лазерної триангуляції (використовуються лазерні сканери), 2) метод структурованого світла (використовуються оптичні сканери). Наведено основні недоліки використання лазерної тріангуляції при скануванні деталей машин та методи зменшення їх негативного впливу на кінцевий результат. Детально розглянутий процес визначення положення точки при скануванні деталей методом лазерної тріангуляції. Наведені рівняння для нормалізації положення точки та рівняння, які прибирають викривлення точки внаслідок аберації лінзи камери. Представлено рівняння для визначення ширини лазерного променю на основі якого визначається його основні геометричні характеристики. Побудована загальна схему впливу основних факторів на якість процесу сканування деталей методом лазерної тріангуляції. Одним із різновидів сканування об’єктів за допомогою структурованого світла є техніка діапазонної візуалізації (SfM). Техніка SfM являє собою процес оцінювання тривимірної структури із послідовності двовимірних зображень, що можуть сполучатися із місцевими сигналами руху. Для знаходження координат x,y,z кожного пікселя використовується положення камери в просторі. Проведено огляд основного програмного забезпечення для створення та редагування структурованої полігональної сітки на основі даних сканування. В якості дослідження процесу технології реверс-інжинірингу було відскановано методом SfM шатун автомобільного двигуна та створена його цифрова модель.

Ключові слова: реверс-інжиніринг, фото-грамметрія, сканер, лазер, ремонт деталей, машинобудування.