Kvasnikov, Volodymyr; Ornatskyi, Dmytro; Dostavalov, Valerii

Article

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Volodymyr Kvasnikov,
Dmytro Ornatskyi,
Valerii Dostavalov

DEVELOPMENT OF A METHOD FOR IMPROVING THE ACCURACY OF MEASUREMENT OF LINEAR MEASURES OF 3D MODELS VIA SCANNING

The object of research is to refine the linear sizes of the obtained 3D models via scanning, and reducing the numbers of errors when obtaining the model. For now, there is no accuracy method for transferring the actual sizes of an object to a 3D model. One of the most problematic places in the existing methods of transferring sizes from the object to the model is the error in the placement of dimensional markers due to inaccuracy, or poor quality of the received surface via scanning.

A model of the instrument complex is used to implement an improved method of 3D scanning, based on the photogrammetric method. The advanced technology of construction and measurement of 3D models on the basis of photos on the principle of stereo pairs in combination with image projection is based on a combination of existing scanning methods. As well as the introduction of new functionalities, such as maintaining the actual sizes of an object, its textures, color and light characteristics, as well as improving the accuracy of linear sizes.

As a result of the use of a standard, reference projections, and a new method of comparing photographs to build a 3D model, a 60 % increase in the accuracy of linear dimensions was achieved. This is due to the fact that the proposed new combined method incorporates all the existing most important aspects of scanning. And also has a number of features, such as the definition of boundary surfaces, automatic sizing, detection, and processing of glass and mirror surfaces. Due to this, this method eliminates the main disadvantages of the usual photogrammetric method – inaccuracies in the surface quality of the models, and inaccuracies in the transfer of linear dimensions. It is estimated that the combined method will allow to transfer the real size of simple objects in 3D with an accuracy of 99.97 % of the actual size of the object. It will also improve the quality of complex surfaces (boundary, glass, mirror) by at least 40–60 %, compared to other existing methods.

Keywords: *3D scanning, subjective error, instrumental error, linear dimensions, image projection, photogrammetry.*

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1. Introduction

Over the last years, the use of 3D scanning has become an integral part of development in almost every technical field. The main field of usage – 3D engineering [1], because this field needs accurate linear measures the most as well as accurate scanning of carcass objects.

Currently, there are many different scanning methods for forming 3D models. The most common methods are next:
- usage of laser rangefinders;
- usage of laser 3D scanners;
- usage of X-rays;
- usage of ultrasound scanners;
- usage of triangulation scanners;
- usage of contact 3D scanners;
- usage of 3D scanners with LED backlight;
- usage of photogrammetric scanners [2, 3].

Despite the variety of scanners and methods, each of the existing methods and algorithms of 3D scanning has its drawbacks. For now, there is no method that could build 3D model of an object that have mirror, glossy surface or have carcass parts, and in the same time preserving their textures and actual dimensions (Fig. 1).

In [4, 5] the photogrammetric method of scanning objects is analyzed in detail, its advantages and disadvantages are described, the principle of its correct use is described, its work is analyzed.

A new technique for constructing 3D objects has been develop via adoption the strengths of the conventional photogrammetric method and using the latest technology. As well as elimination of its shortcomings by changing the principles of operation, construction of the technical part, and changes in processing and information processing algorithms. The process of selecting an object in an image is shown in [6, 7], which presents algorithms for image processing and selection of moving objects on them.

This work presents improved technology for building 3D models based on photographs on the principle of stereo pair in combination with image projection, and combination and refinement of existing scanning methods. As well as the introduction of new features, such as maintaining the actual size of the object, its textures, as well as color and light characteristics.

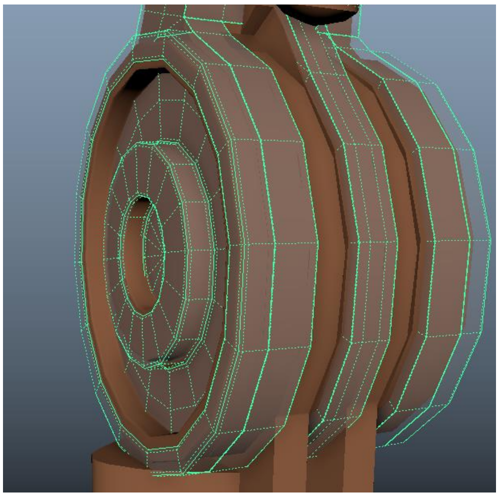

Fig. 1. A clear example of errors in the application of two scans of the body and frame models of the same object

When talking about the accuracy of the 3D scanner, usually mean the level of conformity of the obtained 3D model to the real characteristics of the sample. This parameter determines the error of the 3D scanner or the interval within which the comparison results may vary.

The accuracy of the 3D scanner depends not only on the hardware – on the own characteristics of the device, but also on a number of other factors, in particular the accuracy is affected by:

– object size: 3D scanning of large objects is performed in parts, and stitching increases the error;
– the right choice of lenses;
– scanner settings;
– correct preparation of the object for scanning;
– subjective factors during scanning: surface oscillations, lighting.

The same scanner can give different values of accuracy depending on the subject of scanning and qualification of the executor, for these reasons and there are subjective on instrumental errors.

Considering the standard photogrammetric method, in Table 1 highlighted the problems that need to be solve.

Scans combining accuracy.

When scanning occur from different angles, there is a difficulty in processing further results, because there are errors in combining different fragments. Several matching technologies are used:

1. Combination via surface geometric features. The accuracy of this technology is the highest, but only if the object has a sufficient number of particular qualities. If the object is completely in the scan area, the drop in accuracy is insignificant. If geometric particular qualities are few (scanning large smooth objects), other alignment technologies are used.

2. Combination via markers. Before the scanning process, the model is prepared for work – in an arbitrary chaotic order, markers of contrasting color (relative to the object) are glued evenly on the surface. The scanner automatically reads the coordinates of the markers and combines the fragments.

3. Combination of markers using a photogrammetric system. For large objects, the technology is used when the coordinates of the markers are estimated in advance using a photogrammetric system that provides high accuracy.

To sum up, it is possible to see that there is no perfect method for scanning all types of objects. Therefore, it is necessary to develop a method to improve the accuracy of measuring the linear measures of 3D models.

Therefore, *the object of the study* is to refine the linear measures of the obtained 3D models via scanning, and reduce errors when obtaining the model.

The aim of this research is to modernize the system of building 3D models, which could quickly make 3D models of any surface with high accuracy. At the same time, minimize human intervention in the scanning process to eliminate subjective error and exclude human work from data processing from the algorithm after processing the information to get the final result.

Table 1

Causes of loss of accuracy in 3D scanning

Ideal conditions	Conditions that cause difficulties	The result of work in not ideal conditions
Hard object	Deforming object	Scanned parts of the object that are distorted from different angles. There are problems when combining parts into a single model
Static object	Move the object relative to the scanner during scanning	Any movement distorts the result and worsens the model
Light object	Dark object	Most scanners do not scan black surfaces, in the 3D model there will be holes in these places
Matt object	Shiny or translucent object	There will be holes in these places
Object without holes	Product with edges of sheet material	The edge of a thin sheet on 3D always breaks off, without reaching the real border of the object
Geometric features of the object	Degeneracy along one or more axes	Individual fragments can't be qualitatively combined, accuracy without the use of markers becomes uncontrolled
The object is completely in the scan area	A large or long object that needs to be scanned into fragments	When combining fragments, errors appear
The object is scanned perpendicular to the surface	Scanned «at an angle»	Decrease in values of accuracy and detailing
Cameras located on recommended distances	The cameras are shifted to scan deepening	Increased noise in the data

2. Methods of research

After analyzing existing scanning systems and methods, attention was drawn to several major shortcomings. A common and main disadvantage for all these systems is the inability to make an accurate 3D scan while maintaining the actual size, as well as textures and colors. Also, the inability to make an acceptable scan of mirror, glass, or glossy surfaces. In addition, most scanners are not suitable for creating accurate models of large complex objects, such as cars, production equipment, aircraft parts, and so on. The third – most 3D scans do not have the correct measures after scanning, only in the end people manually set the desired measures of the model, which also makes large errors in the linear measures. The main task was to create and improve a new photogrammetric method that can build the textures of the object, its raster image, image texture, texture coordinates, and the basic 3D model while maintaining linear measures.

And reduction of possible errors at all stages of scanning – receiving photos, their stitching, and construction of the model.

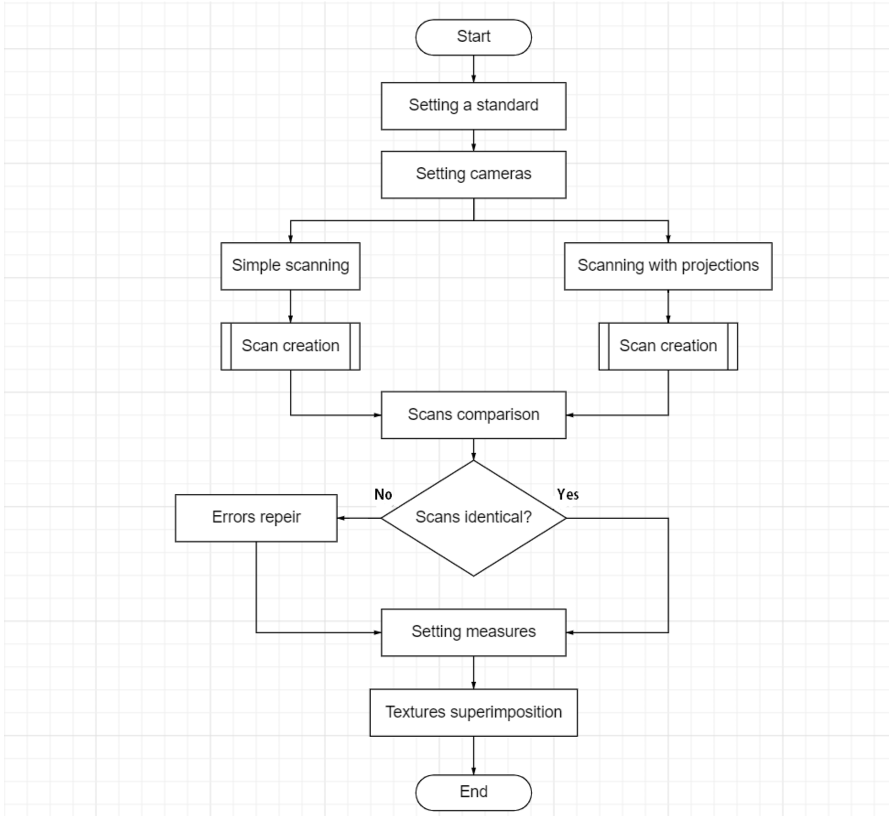

Fig. 2. Algorithm of operation of the complex

2.1. Development of the instrument complex. The following instrument complex has been developed to improve the method of constructing 3D objects. The system must be of the closed type, so it must be inside the room to prevent sunlight from entering, the room type must be cubic (this is necessary to avoid angular distortion when shooting). On each side of the complex, a projector is placed parallel to the walls. It will project pre-prepared, calculated images on the scanned object. Lighting should be based on the lightbox principle, as it's unacceptable for direct light to fall on scanned objects during scanning. Computer-controlled sliders are located around the perimeter of the room (except for the floor) on the walls and ceiling to move cameras, projectors, and in some cases, lightbox-based light sources. The equipment is attached to the rails, which move them across the area to the specified points on the X and Y axes, relative to the planes in which they are located. The exact position of the cameras is fixed and immediately transmitted to the computer. Each slider has its own article in the control program. Thus, get the necessary coordinates of the cameras, which will be used to stitch the resulting images without processing a large amount of information, speeding up the system.

This method is very different from the main principle of stitching photos by photogrammetric method (Fig. 2) and has an incomparable advantage over it. After all, in the photogrammetric method, cameras are set based on triangulation, by finding key points with computer vision.

2.2. Modernization of the method of exposing cameras for further stitching of photos. Consider in more detail the process of obtaining a 3D model. The scanning program implements the Structure from motion (SFM) [8, 9]. This is a technology for determining the distance to the subject with several flat images.

The scan program automatically checks for the presence and comparison of connecting points on several overlapping images and determines the position and orientation of the cameras, lens distortion parameters and 3D coordinates of the points.

$[XC, YC, ZC, 1]T$ – generalized coordinates of a point in the coordinate system of the camera; $[X, Y, Z, 1]T$ – generalized coordinates of a point in the world coordinate system. This ratio can be written as follows:

$$\begin{bmatrix} Xc \\ Yc \\ Zc \\ Zc \end{bmatrix} \sim \begin{bmatrix} RT \\ 01 \end{bmatrix} \sim \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}, \qquad (1)$$

where R – the rotation matrix, which represents the orientation of the camera in world coordinates, and T – the coordinates of the center of world coordinates in the camera system. These settings are called external camera settings.

Processing. The main stages of processing to prepare a dense cloud of points for export are:

1. Import pictures.
2. Applying masks.
3. Search for common points, align and create a sparse cloud of points.
4. Create a dense cloud of points.
5. Placement of markers and scale bars.
6. Export point clouds.

In our case, let's compare the images on the already obtained exact coordinates of the cameras without the slightest error. Snapping photos is a set points, because the devices that take photos are always at known, fixed coordinates. Stitching photos occur not by the markers on the object, but by the coordinates x, y at the planes where the cameras are located. As it is well-known step of the cameras moving, it is possible to develop an incredibly accurate photo stitching algorithm. This makes stitching photos incredibly accurate, and avoids stitching errors due to glare or loss of markers for any reason, and also, it allows to completely get rid of unnecessary points on the end result.

Shooting process. It is recommended to shoot at least 3 rows in height with an overlap of 70 % or more, all rows must be shot with the same angle for optimal stitching of photos and accurate construction of points. From each point, it is possible to take pictures perpendicular to the surface, as well as tilting the camera in both directions horizontally and vertically. It is necessary to exclude from the view of the camera all surfaces that are homogeneous with the object (ceiling, walls, if they are similar to the object in color). It is necessary to shoot so that in a frame there were the characteristic points present on the next pictures. Try to avoid shots that have nothing but a smooth solid color surface.

3. Research results and discussion

3.1. Combined photogrammetric method. Let's move on to a new combined scanning method, based on the developed complex, that consisting of two consecutive scans, which in the future will also help to calculate the absolute error:

$$\Delta a = |a - a_0|, \quad (2)$$

where a_0 – measured value; a – measurement result; Δa – measurement error.

The first scan is performed in the usual photogrammetric way with the adjustments described above. It is necessary to do two scans not only to improve accuracy, but also to obtain textures and UV mapping, because the second scan receives only the exact model. Let's consider this point in more detail:

$$g(\xi,\eta) = Af(x,y) + n(\xi,\eta), \quad (3)$$

where ξ,η – spatial coordinates in the indicator; A – conversion operator; $n(\xi,\eta)$ – errors [10].

The photogrammetric method when constructing a 3D model always has a texture UV map of the object [11, 12], i. e. a texture of its 3D image in 2D (Fig. 3).

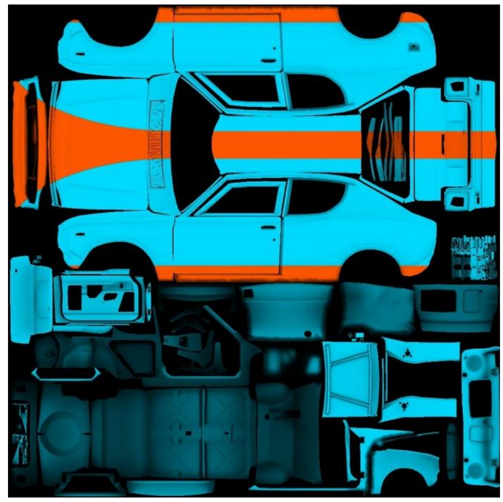

Fig. 3. Simple UV mapping example

The second scan is also performed via photogrammetry, but now projectors are connected to the scanning process, which, in dim light, project a special, previously described image on the scanned model.

This is a necessary step due to the fact that the photogrammetric method has gaps in the grid in places of solid surfaces [13]. Even ignoring glossy, mirrored, and glass surfaces, photogrammetry can cause grid problems when constructing fuzzy objects. Even a large number of photos can't cope with this problem (Fig. 4).

Fig. 4. Gaps on the grid of 3D model of the wing Ford Firebird 1998

Despite the large number of photos of the object from all sides (127 photos), program can still have problems with processing of certain areas of the object due to the similarity of points, smooth surface, and lack of transitions and contrasts.

There must be next step, to avoid any problems with the object grid due to homogeneity, specularity, or other negative properties, and to obtain an accurate 3D model of the object. Project on it a pre-calculated image at all points (x, y) of the coordinate lines relative to each camera.

3.2. Projecting a pre-calculated image. In total, the projection will be directed from five different sides, if to imagine the space where the scanned object is a 3-dimensional space XYZ, the projections will come from the extreme points of space on: X, Y, $-X$, $-Y$, $-Z$. The projectors are turned one after another for each direction, this is necessary to avoid overlapping the pattern on each other, as this will cause problems in calculating the curvature of the surface. Despite the fact that the projector works only on one side – the cameras work on all sides at the same time. This helps to detect glass and mirror surfaces and make the necessary masks in advance, which will facilitate the operation of the photo stitching algorithm by reducing the processing of the scanned surface.

The previously described image contains: different geometric figures of the correct shape, as well as splines of different levels of transparency, overlapping on each other. Such a complex image is necessary for further software determination of the curvatures of the figures on the uneven surface of the scanned object and the subsequent assembly of its model in accordance with these calculations. The projection goes not only to the object, but also to the flat control panel on the opposite side of the plane (if the projection is on the X side, the receiving panel is on the $-X$), the distance to which it is known at each step of the camera/projector. Knowing the exact dimensions of the image projected on the control receiving panel, using the prepared algorithm, it is possible to calculate the distance from the projector/camera to each point of the object, and thus make an accurate construction of the model in conventional units. Let's return to the question that all scans are not sized. In this case, due to the reference pattern, which is on the opposite side and is unchanged, the conversion of conventional units into the actual size of the object will not be difficult. This can be achieved by calculating the proportional size and distortion of the image. That is, the basic 3D model will also be built using the photogrammetric method, but the construction process will involve third-party algorithms, and set, pre-described images that are projected on the object to be scanned (Fig. 5). The projected image will be divided into layers. Each layer of the image will be described by a mathematical formula, so it is recommended to take as a basis for images such graphical functions as the Mandelbrot set, which is described by the formula:

$$f(z)=z^2+C, \quad (4)$$

where C is any complex number that includes real and imaginary parts, or is a function of bifurcation doubling of the period:

$$f(x,\lambda)=4\lambda x(1-x), \quad (5)$$

where λ – control parameter.

Mandelbrot set is difficult to describe, but it is best suited as a base layer. Due to its symmetry, it will be possible to use it in the future to adjust the obtained points on the 3D model, comparing the points of the additional and negative parts on the Y coordinate of the two-dimensional area.

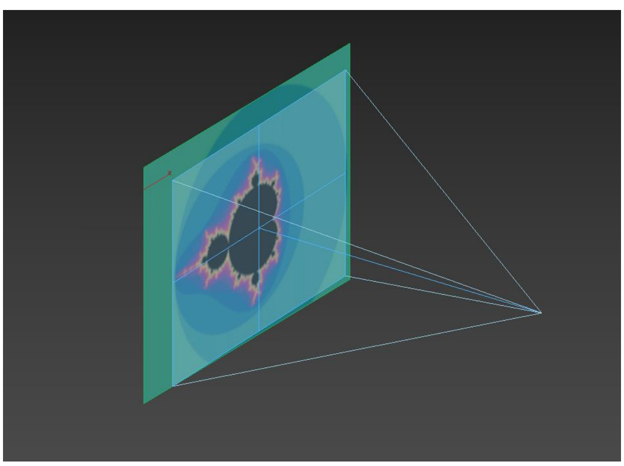

Fig. 5. Projection of the Mandelbrot set along the x, y axes relative to the camera

Subsequent layers of test images should contain different geometric shapes of the correct shape, as well as splines of different levels of transparency, superimposed on each other. The colors of the objects should never be the same, as the shape of the object will also be constructed with the considering of color. Such a complex image is necessary for further software determination of the curvatures of the figures on the uneven surface of the scanned object and the subsequent assembly of its model in accordance with these calculations. The splines must be described as part of the drawing along the entire length, so that there is an idea of how much each point has shifted. It is necessary because it have exceptional approximate properties, versatility and provide ease of implementation of computational algorithms derived from them. In this case, the algorithms for constructing splines coincide with the algorithm of the finite element method, which is the main industrial method of analysis of strength characteristics in computer-aided design systems.

The method of inverse construction is based on the location of the cameras relative to the points, and not vice versa, so the camera $\delta(x-x_p)\delta(y-y_p)\delta(z-z_p)$ gives accordingly a three-dimensional image:

$$b_{p,\theta}\xi,\eta=\delta\xi-\xi_p, \quad (6)$$

where $\delta\xi$, ξ_p – projections on a straight line.

Or in the local coordinate system:

$$b_{p,\theta}(x,y,z)=$$
$$=\delta\left[(x-x_p)\cos\theta+(y-y_p)\cos\theta+(z-z_p)\sin\theta\right],$$

where $x{-}x_p\cos\theta$; $y{-}y_p\cos\theta$; $z{-}z_p\sin\theta$ – single points of reflection.

Thus, the pulse response (point image function) of the image system is defined as:

$$g_\theta(x,y,z)=\delta(x\cos\theta+y\cos\theta z\sin\theta). \quad (7)$$

It's important to use only vector images, not bitmaps, when constructing the image to be projected, because of the following reasons [14]:

1. A raster image consists of a huge number of pixels of a certain size, each of which consists of a combination of shades of different colors. In the reduced state, the set of pixels forms an image. The most striking example of a raster image is a digital photograph. Each bitmap has a certain resolution at which it looks acceptable. The higher the resolution of the image, the more space it takes up on any stock. The raster carries a larger amount of information. Each pixel located in a certain place has its own hue. This information is hidden in the graphic files of raster images. When the bitmap image is enlarged above the acceptable resolution, the pixels become visible to the naked eye and the image quality becomes worse.

2. The vector image consists of individual figures painted in certain colors, or gradation (gradation – a smooth transition from one color to another) from one color to another, created by lines and curves. In vector format, the amount of information is much smaller, and therefore, the vector image will load much faster than the register. The vector image can be stretched over a large area and the image quality will remain the same, unlike the raster.

In digital construction, there is the size of each image in certain conventional units (cm/px/em/rem, etc.). In order to convert them into real units, it is necessary a real standard with known measured parameters, placed perpendicular to the cameras. With its help, it is possible to to obtain data on the distance from $\bar{l}_0$ – the zero point of the camera – $\bar{l}_k$ – the end point bounded by the opposite wall, and what value will correspond to each object of the image. Next, the size of all figures of the obtained image is calculated relative to each point of each vector $\bar{l}$ of each chamber of the room.

3.3. Calculating proportional distortion to build a 3D model. The last step is to calculate via algorithm the proportional image distortion when projecting on the object that being scanned.

First of all, the algorithm creates an object mask based on the exclusion of areas with the same image sizes that matches the sizes of an image in an $\bar{l}_k$. In such cases, a mask is built along the contour of the object, which eliminates all parasitic points of the environment around the scan, which in the future leads to the elimination of instrumental error by reducing the information being processed. This also leads to faster file processing, to build a 3D model. This simple technique eliminates the subjective error in post-processing and eliminates the error along the contour of the object. With any other type of contactless scanning of the object, upon receipt of the model follows its manual processing, namely – a mask must be created on the right-left-front-back-top-bottom of the object. With the help of the mask, unwanted points of the obtained 3D model will be eliminated, such as: the floor of the wall, and other surroundings. This type of processing can only be done manually, which adds a lot of human factor errors, because a person can't select and delete the same points from different angles. Because of this, as a result, the 3D model has a large number of errors on the boundary line of the models and the background (Fig. 6).

Fig. 6. Visual display of the error in the construction of components on the boundary line of the model and the background

As mentioned earlier, knowing the size of the projection of the figure at each point in the room, it is possible to set the clipping of all unnecessary points via masks of an image. Assuming that the projection (or visible part of it) on the control panel is 100 cm by 100 cm. Then, if the algorithm captures the same image in the photo, or proportionally the corresponding part of the image with the same dimensions, it means that the picture was projected on the wall. This will mean that in the part where it is possible to see such an effect, there is no useful surface for us. In this way, it is possible to get rid not only of the points surrounding the object, but also of the points left in the through holes (if any).

Let's return to the question that all scans are not sized. In this case, due to the reference pattern, which is on the opposite side and is unchanged, the conversion of conventional units into the actual size of the object will not be difficult. This can be achieved by calculating the proportional size and distortion of the image by the formula:

$$\frac{a}{b}=\frac{c}{d}, \quad (8)$$

where a and b are called extreme members; c and d – average members of the proportion.

After the first two types of scanning and after processing the photos, there are scans combining. First, the mask obtained after scanning 2 overlapping over scanning 1 with subtracting the surroundings points and see-through points.

Then as the main model result of scan 1 is taken. Because it has fully preserves the visualization of the object. After that the scan points are correlated with the points of the result of the second scan, thus obtaining a finished model without distortion on glossy surfaces and with full visualization.

Using the combined method, the main attention should be paid to the technique used. Also, it should be noted that the entire complex might need to be redesigned for a certain size of the scanned object. The most important thing is to set the standard correctly, and not to make any mistakes in the initial stage of setting the measures. It is always possible to check the results of the second scan before comparing with the first. Also, it is possible to pay attention to the following restrictions. It is not possible to interrupt the scanning process, or to make significant pauses between scans.

Further development of the study may consist in constructing a topologically correct grid of the object, and reducing the number of polygons that will be needed to build the model. This may require the use of artificial intelligence based on the processing of existing similar models. It is also possible to further develop this study by redesigning the complex to scan objects of almost any size. In theory, it is possible to make a mobile complex and get rid of the burden of static.

4. Conclusions

A modern complex for 3D scanning has been developed. This complex is based on the usage of two independent scannings, unlike any other method of obtaining 3D models. The construction algorithm includes the obligatory verification comparison and, if necessary, correction of the model surface on the problem areas.

The accuracy of the proposed combination method increases due to a completely changed process of building the primary 3D model. A new method of photo stitching has been introduced, devoid of the old method of determining the coordinates of points by the triangulation method, and which builds a model using known camera coordinates, which allows to directly and without errors build an accurate 3D model of the object. Elimination of the outdated triangulation method, as well as stitching photos on the coordinates of the cameras allowed to increase the speed of photo processing.

An algorithm for saving linear measures by implementing projections on an existing object has been developed. With the help of reference images projected on the object and the standard screen, the proposed method got rid of the outdated method, which is present in all other photogrammetric scanning methods. The outdated method required human participation in setting markers and setting initial measures. The proposed method completely excluded the

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work and the subjective error allowed by humans from the algorithm for obtaining linear dimensions.

An algorithm for saving linear dimensions by implementing projections on an existing object has been developed. The speed of photo processing is increased due to the comparative analysis of projections, and automatic construction of masks on boundary points of the object on the basis of distortions of projections. The problem with scanning complex objects containing glass, glossy surfaces or wireframe, through objects has been solved. Focusing on the problems and demands of modern scanning, the solution of several problems was presented by a combination method and the implementation of technical solutions, namely – the construction of an instrumental complex for implementation, and a new method of processing photos to build models. Using the right technical equipment and methods, it is possible to implement the following steps in 3D scanning, both in terms of improving the quality of surfaces, and in terms of reducing errors and distortion of the resulting models.

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✉***Volodymyr Kvasnikov,*** *Doctor of Technical Sciences, Professor, Head of Department of Computerized Electrotechnical Systems and Technologies, National Aviation University, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-6525-9721, e-mail: kvp@nau.edu.ua*

Dmytro Ornatskyi, *Doctor of Technical Sciences, Professor, Department of Computerized Electrotechnical Systems and Technologies, National Aviation University, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-8005-824X*

Valerii Dostavalov, *Postgraduate Student, Department of Computerized Electrotechnical Systems and Technologies, National Aviation University, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-1822-4948*

✉*Corresponding author*