Review of Photogrammetry Techniques for 3D Scanning Tasks of Buildings

Maxim Kovynev, Mark Zaslavsky
Saint-Petersburg Electrotechnical University "LETI"
Saint-Petersburg, Russia
kovinevmv@gmail.com, mark.zaslavskiy@gmail.com

***Abstract*—The purpose of this work is a comparative analysis of photogrammetry methods for three-dimensional scanning of buildings. This work contains a description of the photogrammetric techniques and their comparison. The paper identifies the features that arise during the three-dimensional reconstruction of buildings. In this work, also, a comparison of photogrammetric programs was made. The paper contains research on the influence of the identified features on the quality of the resulting model. Synthetic test data were created for research based on generating a sequence of images of an existing three-dimensional object. The benchmark was developed to automate calculating model quality metrics: Hausdorff distance, mean error, and root mean square error. The program accepts two models as input, calculates the given metrics, and builds a similarity color map.**

I. Introduction

Photogrammetry is a scientific and technical discipline that allows using photographic images of the object to restore its size, shape, position in a given coordinate system, or other object characteristics. There are two main types of photogrammetry: Close-range (Terrestrial) Photogrammetry and Aerial Photogrammetry. Only terrestrial methods are investigated in this work, that is, methods without usage photos from cameras of aircraft (UAV, spacecraft) [1].

Photogrammetry uses methods and techniques from optics and projective geometry.

In the simplest case, to restore the spatial object point coordinates, the object's position can be determined by measurements made from two or more photos and taken from different positions. Simultaneously, it is necessary to determine common points (features) on each image, that is, points that characterize the same detail of an object in different images. After that, a beam is drawn from the camera's location to a point on the object. The intersection of these rays determines the location of the point in space.

Photogrammetry is used in various fields of human activity: the creation of three-dimensional models of a human face [2], tracking the life cycle of plants [3], creating a game map based on real images.

Photogrammetry allows automating some of the processes. In this case, it appears to perform digitalization of buildings, that is, you can view the state of the object from anywhere, regardless of where the building is now.

Moreover, for example, photogrammetry can be used to carry out the construction control of objects. Having created a three-dimensional model of a building object allows calculating the amount of work done, which will automate this process. Alternatively, in general, assess the degree of readiness of the building.

This article *does not contain a description of the process of object reconstruction*. It is aimed at comparison of photogrammetric approaches and programs for the problem of three-dimensional reconstruction of buildings based on metrics.

II. Features of Building Reconstruction

A. Inaccessibility of shooting individual building parts

To create a complete model, capturing the building from all sides, including facades, roof. It turns out that the operator needs to go around the object from all sides. Some details (points) of the building can be captured closer than others due to their inaccessibility. The distance from the camera to the object is an important point when creating a three-dimensional model.

However, in some cases, without special equipment, it is almost impossible to capture every section of the building. For example, take shots of the roof of a 12-story building while standing on the ground. To take pictures, the operator can use a particular unmanned aerial vehicle (UAV) flying around the building from all sides, which will speed up the process and make it possible to photograph high-lying or hard-to-reach parts [4].

B. Data volumes and time

It should be noted that buildings or building ensembles are large objects. An object's size can be more than 400 m2 [5], which entails a larger number of images and, accordingly, a larger volume of memory for storing images and larger processing time. For example, the total time to create a three-dimensional model can be more than 200 hours [5].

C. Weather conditions

Another essential feature of the building reconstruction process is that the buildings are located outdoors in an open space. The influence of weather conditions when creating images can affect the resulting model.

1) Precipitation.

Precipitation, such as rain or snow, degrades the quality of the resulting model. The images can show precipitation, overlapping the building's details, and can also lead to incorrect operation of photogrammetric programs, which leads to incorrect creation of a 3D model.

2) *Lighting.*

Lack of light can affect the resulting model. The presence of shadows or unlit parts leads to the lack of distinction of building details, which, like precipitation, can lead to incorrect creation of a three-dimensional model [6].

Based on the features described above, it is necessary to determine the influence of each of these features on the resulting three-dimensional model when comparing photogrammetric programs' work, namely, on its quality. During work, it is required to compare the resulting model with models with "roughness": the presence of weather precipitation, reduced lighting, reduced resolution of images, and increased distance to the object. This comparison will reveal the significance of each problem. In comparison, we primarily focus on the preservation of the geometric characteristics of the object in the resulting model.

III. Photogrammetry techniques description

To select photogrammetric methods, a search was made for articles in the scholar.google.com service using the following keywords: “photogrammetry”, “photogrammetry techniques”, “photogrammetry classification”. The selection of the methods described in the found articles was made according to the following criterion — articles have more than 1000 citations.

A. Structure from Motion (SfM)

Structure from Motion (SfM) is a technique that utilizes a series of 2-dimensional images to reconstruct the 3-dimensional structure of an object. SfM can produce point cloud-based 3D models. The camera does not need to be specialized; common low-cost cameras work well for SfM methods. In essence, multiple views of an object are captured with a digital camera from a range of different positions. A scale-invariant feature transform (SIFT) then identifies common feature points across the image set, sufficient to establish the spatial relationships between the original image locations in an arbitrary 3D coordinate system. A sparse bundle adjustment, needed to transform measured image coordinates into 3D points covering the area of interest, is used in this process. The result is three-dimensional locations of the feature points in the form of a sparse point cloud in the same local 3D coordinate system. An example of the SfM method is shown in Fig. 1.

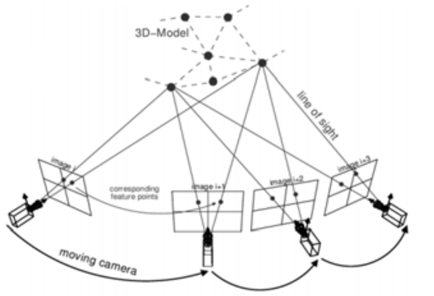

Fig. 1. An example of the Structure from Motion method working for four shots from different positions

B. Stereophotogrammetry

Similar to the SfM method, stereophotogrammetry tries to capture the detail of an object from different angles. In this case, stereophotogrammetry implies creating a stereopair - a pair of flat images (left and right) of the same object, with differences between the images, designed to create a volume effect. According to the stereographic principle, a stereo pair can be viewed together, which creates spatial (stereoscopic) vision. This effect can be used to achieve 3D reconstruction performance. The principle of creating a three-dimensional model is similar to the SfM method and is shown in Fig. 2.

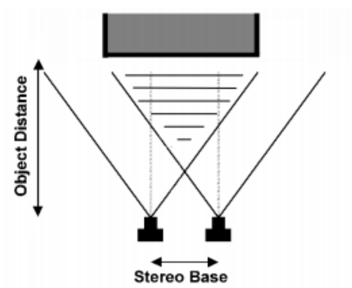

Fig. 2. Schematic representation of a stereophotogrammetric system of two cameras

This method is considered as the use of special equipment - a pair of cameras. There are several approaches to using this method - take pictures from predefined angles and positions, or take pictures similar to the previous method as the camera moves (or video [22]). However, the second approach will be no different from SFM, only in that the amount of data will double. On the other hand, given our limitations on the task for the reconstruction of buildings, it is rather difficult to describe the camera positions, given that these are large objects and the process of selecting these positions is also an independent task to solve. Based on this fact, we will consider only the second approach.

A similar method is the reconstruction of an object based on images from given angles – multi-camera photogrammetry [18]. An example of use is the creation of a three-dimensional model of a person using several cameras fixed around a person on a special structure. Thus, we have prepared the cameras in advance and can calculate the model, however, for buildings, this is not an easy approach, since each building has its own architecture and it is necessary to calculate the positions of the cameras again.

Therefore, we will be looking at a narrower approach to creating models through 2 cameras. By using a stereo pair, we ensure that there is a matching pair for each photo.

C. Terrestrial laser scanning (TLS)

Terrestrial laser scanning (TLS) is a terrestrial way of using the LIDAR scanner, based on obtaining and processing information about distant objects using active optical systems [19]. Compared to TLS, the photogrammetric solution is inexpensive since such a system requires only any photographing device, unlike TLS with more expensive laser scanners, for example, the cost of the Intel® RealSense ™

LIDAR Camera L515 is $349 [7]. In contrast, a regular camera can be purchased within $50- $100 [8]. The vital step of the process is 3D point clouds aligning. Because after each shot, the camera performs translation/rotation in space, it is necessary to align the point clouds, each made in its coordinate system relative to the camera [23].

D. Hybrid SfM/TLS

TLS methods can create dense point clouds attached to the surface of an object with high accuracy. However, TLS systems also have disadvantages, such as the high cost of equipment, the complexity of calculations, and post-processing data. The limitations of TLS systems can be overcome by using a photogrammetric approach such as SfM [20].

Combining the SfM photogrammetric method with TLS allows more accurate models to be created [9]. Before moving to the process of three-dimensional modeling, it is necessary to combine both point clouds obtained by the photogrammetric method and from the data of a three-dimensional camera into one system using Helmet (7-parameter) transformation and the Iterative Closest Point (ICP) algorithm, after which use the combined point cloud for the reconstruction of the object. One of this method's main advantages is a high point density due to TLS and more complete raster information about points due to photogrammetry [10].

E. Ortho-projection

The simplest way to reconstruct buildings, in particular, to create a simplified building model, is to generate ortho-projection of building facades (SVR - Single View Reconstruction). To create such a model, only one photograph of each facade (side) of the building is needed. After creating orthoprojections (orthophoto), these images are combined per the building's geometry [11].

However, this method is becoming less popular due to the presence of analogs that can create three-dimensional, more detailed models (for example, SfM). An example of creating an orthophoto of a building is shown in Fig.3.

Fig. 3 An example of creating an orthophoto of a building. On the left — the original image of the building, on the right — an orthophoto

IV. Comparison of photogrammetric techniques for 3D scanning building tasks

A. Required equipment

To create a three-dimensional model, each method specifies its necessary equipment — the type and number of cameras. This criterion is directly related to equipment costs; the more cameras are required, the higher the price. The same for the type of cameras: the use of unique LIDAR increases the price. TLS-based methods require 3D cameras, stereophotogrammetry, as the name suggests, requires two cameras, the rest of the considered methods - one.

B. The volume of input data

Define M as the size of the resulting image in bytes, K - the number of images.

- **SfM** — requires K images with size M, that is, proportionally to KxM bytes Information about authors
- **Stereophotogrammetry** — considering our approach, it creates stereopairs, so there is an additional factor x2: 2xKxM
- **TLS** — creates three-dimensional images, that is, a depth map is created for each image (image with the size D). Also, during the shooting process, additional information from the sensor data is cached at each time (we denote it as S bytes), so that Kx(M+D) + S. This metadata appears during shooting and is associated with each shot, while for classic approaches with conventional cameras, the data is not recorded, since there is no IMU [21].
- **Hybrid SfM/TLS** — similar to TLS, uses snapshots for photogrammetry and depth maps for TLS, so Kx(M+D) + S
- **Ortho-projection** — similar to SfM

Let V = KxM be the size in bytes for K pictures, E = KxD be the size in bytes for K depth-map pictures [12].

C. Method popularity

Considering that we are interested in the applicability of these methods, we must look for real applications of these methods on the application. One of the ways for assessing popularity is Google Trends.

To assess the popularity, let us use the Google Trends service and examine the frequency of web searches for these methods' information from 2004 to the present. Results are shown in Fig.4.

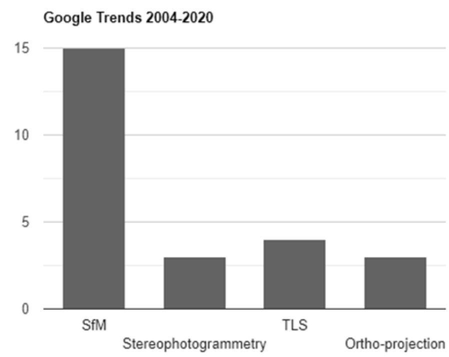

Fig. 4 Popularity of the method based on Google Trends service

C. Model Level of Detail Method popularity

- **Low** — minimal detail of the object; only the main distinctive curves and shapes of the building are present, the texture of the building is set.
- **High** — the resulting model retains the object's shape, all details (patterns, texture, color) of the facades are present.
- **Very high** — more model points, more correct color rendering.

The comparison results are presented in the Table I.

TABLE I. TEQCHIQUES COMPARISON

Photogrammetry techniques	Required equipment	Volume of input data	Method popularity	Model Level of Detail
SfM	x1 Camera	V	15	High
Stereo photogrammetry	x2 Camera	2xV	3	High
TLS	x1 LiDAR (x1 RGB-D)	V + E + S	4	High
Hybrid SfM/TLS	x1 LiDAR (x1 RGB-D)	V + E + S	3	Very high
Ortho-projection	x1 Camera	V	0	Low

As shown in Table 1, the SfM method is the best in terms of price and popularity. This method works with fewer data and provides models with a high degree of detail.

The worst method, according to the same criteria is the method of ortho-projection. This method works with the same dataset as SfM, but provides a lower result in terms of granularity.

SfM and the stereophotogrammetric methods are very similar since they have the same algorithm for creating a model; however, stereophotogrammetry requires two times more equipment costs and a larger amount of data than SfM; therefore this method is inferior to SfM, although it gives approximately the same degree of model detail.

After analyzing the table, we can conclude that it is necessary to *compare the work of methods on real data with buildings* to determine the best building reconstruction approach.

Given that we are examining the quality of the resulting models, we want to compare the methods from this perspective. For this, we need some test data.

V. TEST DATA

Test datasets are needed to compare photogrammetric programs and investigate the impact of 3D building reconstruction features.

First of all, a "reference" three-dimensional model is required; comparison of three-dimensional models obtained from photogrammetric programs with it will be performed.

It should be noted that many additional factors can affect the quality of the resulting models, such as handshake when shooting, which leads to blurring in the photo, different distances and heights between shots, the presence of foreign objects.

Moreover, for the comparison to be objective, it is necessary to have a "reference model" and images of the same object. The "reference model" should not be obtained from the same images; that is, a photogrammetric program was not used. However, nowadays, photogrammetry is widely used; therefore it is difficult to find a three-dimensional model of a building obtained differently. The found models are either simplified and created manually through special 3D-modeling programs or are qualitatively detailed and not distributed free of charge.

Based on these difficulties, it was decided to use synthetic data. Having chosen the "reference model," we will take pictures from different angles in the modeling 3D-scene program, the resulting set of photos will be sent to photogrammetric programs as input data, and the resulting model will be compared with the "reference model".

The next step is to set the criteria for choosing a “reference model”.

1) The central object in the model should be the building without foreign objects.

2) The 3D model must be created manually, without using photogrammetric software, and detailed.

3) The 3D model must be free to use.

A "reference model” of the building was selected based on the set criteria, shown in Fig. 2. The model is taken from the site to find free 3D models free3d.com [13] and shown in Fig. 5.

Fig. 5 “Reference model”.

The Blender program was used to create a sequence of images. The animation of object rotation along one of the axes is set, the animation duration is set - 50 frames. The image quality is 1440x1080. The result of starting the animation creation process is a video file in the .avi format. The video rendering process took approximately 3 hours. All 50 frames were extracted from the resulting video file, saved in .jpg format. The camera positions are shown in Fig. 6. This dataset is called “Original”.

Based on the features identified in part II, it was decided to make the input data "coarse": the presence of weather precipitation, reduced lighting, reduced image resolution, and increased distance to the object. Coarse datasets have been created for the current model.

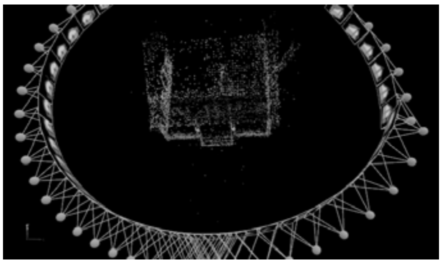

Fig. 6 Arrangement of cameras. Points are the cameras' position in space; the corresponding rectangle is the image in the camera lens

A. Weather conditions. Precipitation.

The snow was selected as weather precipitation. Snowflakes have a simple spherical shape of white. In theory, the white spheres that look like dots in the photo should be recognized as key, and given that the snow is chaotic and even, then the quality of the resulting model should be lower. Generated 10,000 and 100,000 spheres for the model. Added even distribution of snow throughout the visible space of the camera. The sets of images with 10,000 and 100,000 spheres will be named "Medium Snow" and "Extra Snow", respectively.

B. Weather conditions. Lighting.

To change the lighting, the Ambient parameter was reduced from 1 to 0.5 and 0.25. Let us call the sets of images "Medium Dark" and "Extra Dark". As can be seen from the figures, there is more shadow on the building's porch, which should reduce the number of key points to be found.

C. Data volumes and time.

The resolution of images has been reduced from 1440x1080 to 720x540 and 320x240, that is, approximately two times each. The sets of images will be called "720x540" and "320x240".

D. Inaccessibility of shooting individual building parts

The distance from the center of the model to the camera has been increased from 20 to 30 and 40, respectively. Let us call the sets of images "Medium Distance" and "Far Distance".

Examples of the obtained data sets are shown in Fig. 7. From each set, one picture of the same camera position was selected.

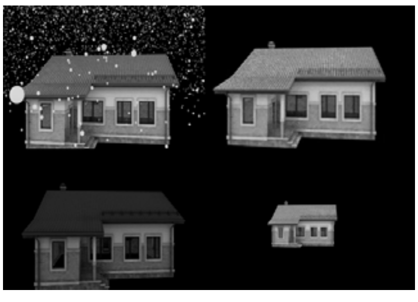

Fig. 7 Examples from the dataset. Starting from the upper left corner clockwise – “Extra snow”, “320x240”, “Extra dark”, “Far Distance”

Data sets have been received, on which the comparison of photogrammetric programs will be made. In theory, each of the "coarse" models should degrade the quality of the resulting model.

VI. Comparison of photogrammetric software

At the moment, there is a wide variety of photogrammetric programs. Based on the Geo-matching website [14], a list of photogrammetric programs was obtained. The main criterion for the selection of programs are:

1) Type of photogrammetry — the presence of Close-range photogrammetry in the supported list since we are considering a three-dimensional ground reconstruction of a building

2) Price — the presence of a trial/demo/free version of the application for comparing programs is required.

3) Popularity dynamics is a metric based on the number of requests for a given program based on the Google Trends service.

Based on these criteria, four photogrammetric programs were selected: 3DF Zephyr, Pix4Dmapper, Agisoft MetaShape, Meshroom.

1) *3DF Zephyr* is commercial photogrammetry and 3D modeling software. The photogrammetric method used is SfM. The free version has a 50 input photos limit.

2) *Pix4Dmapper* is commercial photogrammetry and 3D modeling software for objects and terrain plans. The photogrammetric method used – SfM

3) *Agisoft Metashape* is professional commercial photogrammetry and 3D modeling software from the Russian company Agisoft LLC. The photogrammetric method used – SfM

4) *Meshroom* is open-source photogrammetry and 3D modeling software. The photogrammetric method used – SfM.

A. Description of the program comparison process

The task is to restore a three-dimensional model of a building based on the transferred set of images. The selected set of photographs is "Original" since it does not contain "roughness". The resulting three-dimensional models are converted into the same for all .ply format, which contains information about the texture, position of points in space, and their color. Considering that each obtained three-dimensional model is in its coordinate system, it is necessary to bring each model's coordinate system to a single one. The selected coordinate system is the coordinate system of the "reference model”. To translate, it is needed to perform a rotation, translation, and scaling transformation. This operation was performed in the Meshlab program using the "Point-Based Glueing" function.

To measure the quality of the obtained models with the "reference model”, it is necessary to set metrics.

B. Model comparison metrics

1) Hausdorff metrics

Let us denote as by *d(p,V')* the distance from point *p* belonging to the three-dimensional object *V* to the object *V'*, where *V* , *V'* are *finite* set (collection) of points in a real 3D vector space [17]. Then:

$$d(p, V') = min_{p' \in V'} \; || \; p - p' \; ||$$

Where || . || is the Euclidean distance. By the definition of Hausdorff distance, the distance between objects *V* and *V'* denoted as *d(V,V')* will be equal to:

$$d_{\mathrm{m}}(V, V') = \max_{p \in V} d(p, V') \qquad (1)$$

The distance between two objects can be defined as the distance between the corresponding sections of the object [15]. It is important to note that the distance is not symmetric, that is, $d(V,V') \neq d(V', V)$ [15].

The symmetric Hausdorff distance is then defined as follows:

$$d_{\mathrm{m\_sym}}(V, V') = \max \{ \, d_{\mathrm{m}}(V, V'), \; d_{\mathrm{m}}(V', V)\}$$

The mean error d_{me} (Mean Error) between two 3D objects is defined as:

$$d_{me}(V,V') = \frac{1}{|V|} \iiint_{p \in V} d(p,V')dV \qquad (2)$$

The d_{rmse} mean square error (RMS Error) between two 3D objects is defined as:

$$d_{rmse}(V,V') = \sqrt{\frac{1}{|V|} \iiint_{p \in V} d(p,V')^2 dV} \qquad (3)$$

In our experiments we used the symmetric Hausdorff distance calculated with the developed benchmark based on Meshlab Server Software

2) Number of walls

In the "reference model", there are 4 sides: front-side, right-side, back-side, left-side. Looking at the model, it is possible to assess whether a given side has recovered or not, knowing what the "reference model" looks like. Let us set the criteria:

- The wall is completely restored to its appearance - 1 point.
- The wall is partially restored, cavities or holes are visible - 0.5 points.
- The wall is missing or not restored - 0 points.

C. Benchmark

To automate the process of comparing three-dimensional models based on the metrics presented in section 2, a program is required that will calculate these metrics using two models as an input.

1) *Functional requirements*

- The program should automatically calculate metrics and display the result on the user's screen.
- The program should demonstrate which models were loaded as input.
- The program must be able to view three-dimensional models from all sides, that is, have controls for the model's view.

2) *Technology stack used* – Python / Panda3D / PyQt / Meshlab

3) *Process of calculation*: To calculate metrics and build a color map of the model, Meshlab is used, which has MeshlabServer with CLI. This benchmark directly sends commands through the MeshlabServer CLI, specifying as input the models selected by the user and a pre-formed list of tasks that must be applied to the models, namely calculating the Hausdorff metrics, a color map is calculated based on the metrics for the "reference".

The user interface is developed in the Qt Designer program. An example of the developed interface of the main window for displaying selected models is shown in Fig. 8. An example of the developed interface for displaying the results of comparing models is shown in Fig. 9.

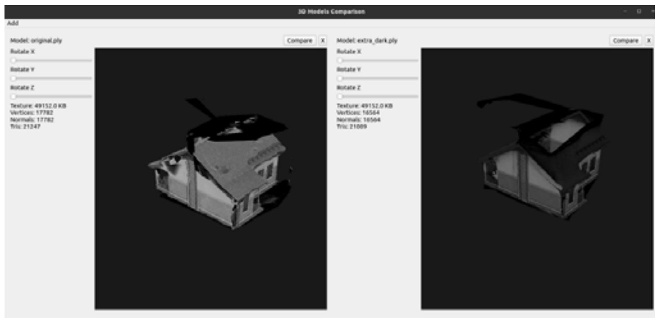

Fig. 8 Interface of the main window

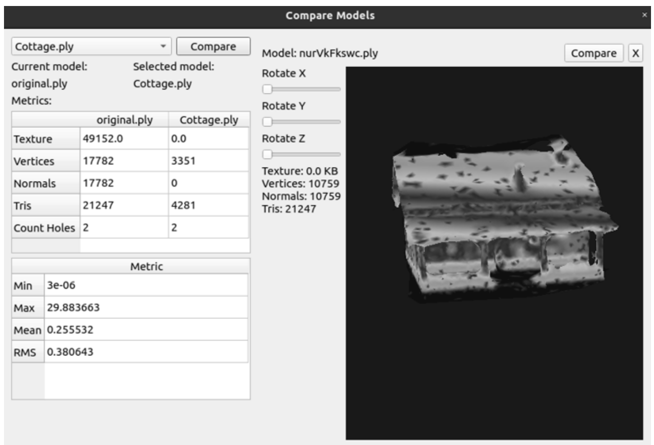

Fig. 9 Interface for displaying the results of comparing models

D. Description of the model comparison process

Based on the described three Hausdorff metrics (1), (2), (3) and the presence of walls, the models were compared. The calculation of the metrics was performed in the developed benchmark. The comparison results are presented in the Table II. In parentheses are the relative Hausdorff metrics, that is, divided by the length of the circumscribing parallelepiped, in percent.

Let us set the quality of the models equal to the metric d_rmse. The model recovered qualitatively (high quality) if this parameter is not more than 5%. Medium quality model if the metric is 5-10%. Poor quality model: more than 10%.

TABLE II. COMPARISON OF PHOTOGRAMMETRIC PROGRAMS ON THE "ORIGINAL" DATASET

Program	d_m	d_{me}	d_{rmse}	Walls
3DF Zephyr	5,041015 (24,35%)	0,255532 (1,2%)	0,380643 (1,8%)	4
Agisoft MetaShape	4,571903 (22,08%)	0,685344 (3,3%)	1,190965 (5,7%)	3
Meshroom	3,942915 (19,04%)	0,374198 (1,8%)	0,571769 (2,7%)	4
Pix4Dmapper	2,335918 (11,28%)	0,618741 (2,9%)	0,728786 (3,5%)	2,5

After analyzing the Table II, we can conclude that the metric d_m for the presence of noise and extraneous points. As can be seen from the table, Pix4Dmapper has minimal noise compared to other programs.

We can also say that the 3DF Zephyr program recovered better, judging by the metrics and the number of walls.

The second in quality is Meshroom, which also raised all four walls.

Pix4Dmapper is also of high quality but was unable to restore all four walls. The Hausdorff metrics could not identify this problem since the model contains more gross blunders in the form of noise.

Agisoft MetaShape did the worst in terms of quality, as it has an average quality model and only restored 2 walls

VII. RESEARCH THE INFLUENCE OF FEATURES ARISING DURING THE RECONSTRUCTION OF BUILDINGS

A. Formulation of the problem

Based on the features identified in part II and the generated dataset in part V, it is necessary to research the influence of the features that arise during the reconstruction of buildings. Feature list:

- The presence of weather precipitation
- Reduction of lighting
- Reducing the resolution of images
- Increasing the distance to the object

B. Input data

The measurement will be carried out on the generated datasets: "Original", "720x540", "320x240", "Medium Dark", "Extra Dark", "Medium Distance", "Far Distance", "Medium Snow", "Extra Snow".

C. Procedure

In each photogrammetric program selected in part VI, we will create three-dimensional models of buildings based on the generated datasets. This gives 9 x 4 = 36 building models. For each obtained model, we will compare the "reference model" and calculate the metrics described in sections VI.B. Based on the obtained models and calculated metrics. We will establish the dependence of the influence of each feature on the model.

D. Hypothesis

Each of the features should degrade the quality of the resulting model. Considering that each "coarse" dataset is based on a "reference model" with only one of the coarsening parameters changing (the rest of the data generation process is identical, left unchanged), changes in the resulting models will only be associated with changes in the data set.

E. Results

The resulting three-dimensional models are uploaded to the site for viewing 3D models sketchfab.com [16]. For each photogrammetric program, a summary table with metrics and names of datasets is compiled. Let us analyze the results further.

1) 3DF Zephyr

The research results are presented in Table III. The color marks models with a mean square error of more than 10% or models that could not be created by the program.

TABLE III. COMPARISON OF MODELS OBTAINED USING THE 3DF ZEPHYR PROGRAM

Program	Dataset	d_m	d_{me}	d_{rmse}
3DF Zephyr	Original	5,041015 (24,35%)	0,255532 (1,2%)	0,380643 (1,8%)
3DF Zephyr	720x540	3,654275 (17,65%)	0,721589 (3,4%)	0,91208 (4,4%)
3DF Zephyr	320x240	6,893617 (33,3%)	1,843136 (8,9%)	2,431263 (11,7%)
3DF Zephyr	Medium Dark	2,339342 (11,3%)	0,31501 (1,5%)	0,434793 (2,1%)
3DF Zephyr	Extra Dark	4,850242 (23,43%)	0,837354 (4%)	1,009879 (4,8%)
3DF Zephyr	Medium Distance	4,505886 (21,76%)	0,394112 (1,9%)	0,55938 (2,7%)
3DF Zephyr	Far Distance	4,479064 (21,63%)	0,424346 (2%)	0,616201 (2,9%)
3DF Zephyr	Medium Snow	3,932841 (18,99%)	0,709434 (3,4%)	0,868774 (4,1%)
3DF Zephyr	Exta Snow	5,569102 (26,9%)	0,784323 (3,7%)	1,006076 (4,8%)

Reducing the resolution of images from 1440x1080 to 720x540 and 320x240, that is, by 2 and 4.5 times, respectively (data sets "720x540", "320x240"), led to an increase in the root mean square error by 2.66 and 6.38 times. It can be concluded that the 3DF Zephyr program shows a direct proportional dependence of a decrease in the image resolution to a deterioration in the quality of the model.

Reducing the brightness by 2 times (data set "Medium Dark") did not lead to significant changes in the quality of the model. Reducing the brightness by 4 times ("Extra Dark" dataset), similar to decreasing the image resolution, degraded the quality of the model by 2.6 times.

Increasing the distance by 1.5 and 2 times (data sets "Medium Distance", "Far Distance") did not lead to significant changes in the quality of the model, an increase in the root mean square error by 1.5 times.

The presence of snow (datasets "Medium Snow", "Extra Snow") led to a deterioration of the model by 2.4 times on average

2) Pix4Dmapper

The research results are presented in Table IV.

TABLE IV. COMPARISON OF MODELS OBTAINED USING THE PIX4PMAPPER PROGRAM

Program	Dataset	d_m	d_{me}	d_{rmse}
Pix4Dmapper	Original	2,335918 (11,28%)	0,618741 (2,9%)	0,728786 (3,5%)
Pix4Dmapper	720x540	2,955821 (14,27%)	0,899285 (4,3%)	1,13757 (5,4%)
Pix4Dmapper	320x240	3,90482 (18,86%)	1,240908 (5,9%)	1,710691 (8,2%)
Pix4Dmapper	Medium Dark	1,569111 (7,58%)	0,472093 (2,2%)	0,723413 (3,4%)
Pix4Dmapper	Extra Dark	6,64249 (32,08%)	0,856278 (4,1%)	1,41657 (6,8%)
Pix4Dmapper	Medium Distance	2,207041 (10,66%)	0,585516 (2,8%)	0,880004 (4,2%)
Pix4Dmapper	Far Distance	2,520549 (12,17%)	0,719032 (3,4%)	0,925432 (4,4%)
Pix4Dmapper	Medium Snow	2,300998 (11,11%)	0,635846 (3,04%)	0,831456 (4,01%)
Pix4Dmapper	Extra Snow	1,490142 (7,19%)	1,253168 (6%)	1,716749 (8,2%)

Reducing the resolution of images from 1440x1080 to 720x540 and 320x240, that is, by 2 and 4.5 times, respectively (data sets "720x540", "320x240"), led to an increase in the root mean square error by 1.56 and 2.34 times. It can be concluded that the Pix4Dmapper program shows a directly proportional dependence of a decrease in the image resolution to a deterioration in the quality of the model.

Reducing the brightness by 2 times (data set "Medium Dark") did not change the quality of the model. Reducing the brightness by a factor of 4 ("Extra Dark" dataset), similar to decreasing the image resolution, degraded the quality of the model by 1.9 times.

Increasing the distance by 1.5 and 2 times (data sets "Medium Distance", "Far Distance") led to a deterioration in the quality of the model by 1.2 times on average.

The presence of snow (data set "Extra Snow") resulted in a 2.4-fold deterioration of the model.

3) Meshroom

The research results are presented in Table V.

TABLE V. COMPARISON OF MODELS OBTAINED USING THE MESHROOM PROGRAM

Program	Dataset	d_m	d_{me}	d_{rmse}
Meshroom	Original	3,942915 (19,04%)	0,374198 (1,8%)	0,571769 (2,7%)
Meshroom	720x540	4,849346 (23,42%)	1,203915 (5,8%)	1,734629 (8,3%)
Meshroom	320x240	-	-	-
Meshroom	Medium Dark	9,524522 (46,01%)	0,635837 (3%)	0,977292 (4,7%)
Meshroom	Extra Dark	10,311735 (49,81%)	0,905954 (4,3%)	1,224313 (5,9%)
Meshroom	Medium Distance	6,233581 (30,11%)	0,461862 (2,2%)	0,594002 (2,8%)
Meshroom	Far Distance	14,122382 (68,22%)	0,585682 (2,8%)	0,83157 (4%)
Meshroom	Medium Snow	24,258919 (117,19%)	0,701103 (3,3%)	0,924217 (4,4%)
Meshroom	Extra Snow	14,349888 (69,32%)	2,147317 (10,3%)	3,447384 (16,6%)

Reducing the resolution of images from 1440x1080 to 720x540, that is, 2 times (data set "720x540"), led to an increase in the mean square error by 3 times. When reducing the resolution of images from 1440x1080 to 320x240 Meshroom was unable to restore the 3D model of the building.

A decrease in brightness by 2 and 4 times (data sets "Medium Dark", "Extra Dark") led to an increase in the root mean square error by 1.7 and 2.14 times, respectively.

Increasing the distance by 1.5 (Medium Distance dataset) did not change the quality of the model. Increasing the distance by 2 times (dataset "Far Distance") led to a decrease in the quality of the model by 1.5 times.

The presence of snow (dataset "Extra Snow") led to a 6-fold deterioration of the model; the quality of the model is poor.

4) Agisoft Metashape

The research results are presented in Table VI.

TABLE VI. COMPARISON OF MODELS OBTAINED USING THE AGISOFT METASHAPE PROGRAM

Program	Dataset	d_m	d_{me}	d_{rmse}
Agisoft Metashape	Original	4,571903 (22,08%)	0,685344 (3,3%)	1,190965 (5,7%)
Agisoft Metashape	720x540	-	-	-
Agisoft Metashape	320x240	-	-	-
Agisoft Metashape	Medium Dark	3,949731 (19,08%)	1,224461 (5,9%)	1,974796 (9,5%)
Agisoft Metashape	Extra Dark	-	-	-
Agisoft Metashape	Medium Distance	3,344286 (16,15%)	1,438981 (6,9%)	2,351109 (11,3%)
Agisoft Metashape	Far Distance	-	-	-
Agisoft Metashape	Medium Snow	4,814337 (23,25%)	0,958315 (4,6%)	1,23351 (5,9%)
Agisoft Metashape	Extra Snow	2,842195 (13,73%)	1,96132 (9,4%)	3,20861 (15,5%)

Reducing the resolution of images from 1440x1080 to 720x540 and 320x240, that is, 2 and 4.5 times, respectively (data sets "720x540", "320x240"), made it impossible to restore the three-dimensional model of the building.

Reducing the brightness by 2 times (data set "Medium Dark") led to a decrease in the quality of the model by 1.7 times. Reducing the brightness by a factor of 4 ("Extra Dark" dataset) made it impossible to reconstruct the 3D model of the building.

A 1.5-fold increase in distance (Medium Distance dataset) resulted in a 1.97-fold decrease in model quality. Increasing the distance by 2 times (dataset "Far Distance") made it impossible to restore the three-dimensional model of the building.

The addition of snow (the "Medium Snow" dataset) did not result in significant quality changes. On the Extra Snow dataset, the quality degradation is 2.7 times. The quality of the model is poor.

5) Summary comparison

Based on the data in the Table III, IV, V, VI a summary table was created describing the change in the quality of the model depending on the data set and the photogrammetric program (see Table VII).

Table cells - a ratio of the root mean square error of the dataset to the root mean square error of the "Original" dataset

TABLE VII. COMPARISON OF THE INFLUENCE OF "COARSENING" ON THE RESULTING MODEL

Program	3DF Zephyr	Pix3D mapper	Meshroom	Agisoft Metashape	Aver.
Original	1,00	1,00	1,00	1,00	1,00
720x540	2,40	1,56	3,03	-	2,33
320x240	6,39	2,35	-	-	4,37
Medium Dark	1,14	1,00	1,71	1,66	1,38
Extra Dark	2,65	1,94	2,14	-	2,24
Medium Distance	1,47	1,21	1,04	1,97	1,42
Far Distance	1,62	1,27	1,45	-	1,45
Medium Snow	2,28	1,27	1,62	1,04	1,55
Extra Snow	2,64	2,36	6,03	2,69	3,43

As can be seen from the Table VII each method of "coarsening" the model leads to a deterioration in its quality.

The most significant impact on the model is the decrease in image resolution and the presence of snow. The quality of the model deteriorates by 4.37 times and 3.43 times, respectively.

The increase in the distance to the object is less significant. The quality of the model has deteriorated by no more than two times.

VII. CONCLUSION

In the course of this article, a comparative analysis of photogrammetry methods for the tasks of three-dimensional scanning of buildings was carried out.

The features that arise during the three-dimensional reconstruction of buildings were identified, namely weather precipitation, a decrease in lighting, a decrease in image resolution, and an increase in the distance to the object.

The following photogrammetric methods participated in the review: SfM, Stereophotogrammetry, TLS, SfM and TLS, Ortho-projection. The comparative analysis of the methods showed that the SfM method wins in terms of price and popularity among other methods; therefore, it has many implementations.

When comparing photogrammetric programs (3DF Zephyr, Agisoft Metashape, Meshroom, Pix4Dmapper), it was found that 3DF Zephyr recovers the model better among analogs (less than 2% in comparison with the original model).

Among the features that affect the quality of the resulting model, it was revealed that the greatest negative impact is exerted by a decrease in the resolution of images and the presence of precipitation (4.4 and 3.4 times the decrease in quality, respectively).

Further research includes comparing the texture restoration of the resulting model directions and experiments on different models.

REFERENCES

[1] Close-Range Photogrammetry and 3D Imaging / Luhmann, Thomas. — GermanyWalter de Gruyter, 2013.

[2] Galantucci, Luigi Maria, Ferrandes, R., Percoco, Gianluca, "New 3D digitizer for human faces based on digital close range photogrammetry: Application to face symmetry analysis," International Journal of Digital Content Technology and its Applications, Nov. 2012. — c. 390-396.

[3] Martinez-Guanter J. et al. Low-cost three-dimensional modeling of crop plants //Sensors. – 2019. – T. 19. – №. 13. – C. 2883.

[4] Remondino F. et al. UAV photogrammetry for mapping and 3d modeling–current status and future perspectives //International archives of the photogrammetry, remote sensing and spatial information sciences. – 2011. – T. 38. – №. 1. – C. C22.

[5] Fassi F. et al. Comparison between laser scanning and automated 3d modelling techniques to reconstruct complex and extensive cultural heritage areas //International archives of the photogrammetry, remote sensing and spatial information sciences. – 2013. – T. 5. – C. W1.

[6] Natour G. E. et al. Toward 3D reconstruction of outdoor scenes using an MMW radar and a monocular vision sensor //Sensors. – 2015. – T. 15. – №. 10. – C. 25937-25967.

[7] Intel website, "Intel® RealSense™ LiDAR Camera L515", Web: https://www.intelrealsense.com/lidar-camera-l515/. Accessed: Apr. 08, 2020

[8] Amazon website, "Amazon digital cameras cost", Web: https://www.amazon.com/Digital-Cameras/b?ie=UTF8&node=281052, Accessed: Apr. 08, 2020

[9] Grussenmeyer P. et al. Recording approach of heritage sites based on merging point clouds from high resolution photogrammetry and terrestrial laser scanning //International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. – 2012. – T. 39. – C. B5.

[10] Bethencourt A., Jaulin L. 3D reconstruction using interval methods on the kinect device coupled with an IMU //International Journal of Advanced Robotic Systems. – 2013. – T. 10. – №. 2. – C. 93.

[11] Toutin T. Geometric processing of remote sensing images: models, algorithms and methods //International journal of remote sensing. – 2004. – T. 25. – №. 10. – C. 1893-1924.

[12] Kovynev, M., "Review of photogrammetry methods for 3D scanning of buildings," Conference of the teaching staff of ETU, 2019.

[13] Free3d website, "GameReady Cottage 3D модель", Web: https://free3d.com/3d-model/gameready-cottage-free-163528.html, Accessed: Apr. 10, 2020

[14] Geo Matching website, "Photogrammetric Imagery Processing Software", Web: https://geo-matching.com/photogrammetric-imagery-processing-software, Accessed: Apr. 10, 2020

[15] Aspert N., Santa-Cruz D., Ebrahimi T. Mesh: Measuring errors between surfaces using the hausdorff distance //Proceedings. IEEE international conference on multimedia and expo. – IEEE, 2002. – T. 1. – C. 705-708.

[16] Sketchfab website: "The resulting three-dimensional models of the building", Web: https://sketchfab.com/kovinevmv/models, Accessed: Apr. 25, 2020

[17] Lavoué G., Corsini M. A comparison of perceptually-based metrics for objective evaluation of geometry processing //IEEE Transactions on Multimedia. – 2010. – T. 12. – №. 7. – C. 636-649.

[18] Russell, G. S., Tucker, D. M., Eriksen, K. J., & Olivieri, O. (2007). U.S. Patent No. 7,190,826. Washington, DC: U.S. Patent and Trademark Office.

[19] Baqersad J. et al. Photogrammetry and optical methods in structural dynamics–A review //Mechanical Systems and Signal Processing. – 2017. – T. 86. – C. 17-34.

[20] Julin A. et al. Automated multi-sensor 3D reconstruction for the web //ISPRS International Journal of Geo-Information. – 2019. – T. 8. – №. 5. – C. 221.

[21] Wilkinson M. W. et al. A comparison of terrestrial laser scanning and structure-from-motion photogrammetry as methods for digital outcrop acquisition //Geosphere. – 2016. – T. 12. – №. 6. – C. 1865-1880.

[22] Torresani A., Remondino F. Videogrammetry VS Photogrammetry for Heritage 3d Reconstruction. – 2019.

[23] Wang C. C. (ed.). Laser Scanning: Theory and Applications. – BoD–Books on Demand, 2011.