WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.141898
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVIII ISSUE 3 2022

pp. 481 –500

Research paper

3D modelling with the use of photogrammetric methods

Izabela Piech[1], Tomasz Adam[2], Paulina Dudas[3]

Abstract: Extremely intensive development of technology has resulted in many innovations. There are new methods of acquiring spatial data, such as laser scanning, unmanned aerial vehicles or digital non-metric cameras, which are the subject of this study. Integration of this data has become a new tool that has expanded existing measurement capabilities, finding applications in 3D modelling, archaeology and monument conservation. Owing to scanning, we can get the coordinates of almost every point of the scanned surface, obtaining full and detailed information about the object dimensions. The level of technical advancement of digital cameras allows them to be successfully used in short-range photogrammetry [27], and recently also in low-altitude aerial photogrammetry (unmanned aerial vehicles). Two different test objects were selected to achieve the intended purpose. The monument located on the 14-meter-high top of the Wanda Mound was adopted as the first object. It consists of a simple rectangular plinth made of brown marble. On its top there is a figure of an eagle with a crown of white marble. On the west wall of the plinth there is an inscription “Wanda” and a drawing showing a sword crossed with a distaff. The following features supported the choice of the monument: interesting shape of the object, which includes both simple geometric forms with large and flat surfaces (plinth), and more detailed surfaces (figure of an eagle); detailed texture of the object (complicated marble veins, wing details). The second object under study was The Helena Modrzejewska National Stary Theatre. The building was rebuilt in the style of Viennese Art Nouveau, so that it fully incorporates into the rest of buildings. Measurements included data obtained from a non-metric camera, Leica ScanStation scanner and DJI S 1000 multi-rotor.

Keywords: 3D modelling, visualization, terrestrial laser scanning, unmanned aerial vehicles, non-metric cameras

[1]PhD., Krakow University of Agriculture, Faculty of Environmental Engineering and Land Surveying, Al. Mickiewicza 24/28, 30-059 Krakow, Poland, e-mail: izabela.piech@urk.edu.pl, ORCID: 0000-0002- 6710-4387
[2]Eng., Graduate of the University of Agriculture in Krakow, Faculty of Environmental Engineering and Land Surveying, Al.Mickiewicza 24/28, 30-059 Krakow, Poland, e-mail: tomasz.adam@urk.edu.pl
[3]Eng., Graduate of the University of Agriculture in Krakow, Faculty of Environmental Engineering and Land Surveying, Al.Mickiewicza 24/28, 30-059 Krakow, Poland, e-mail: paulina.dudas@urk.edu.pl

1. Introduction

Development of IT techniques, including image information systems combined with the Internet, as means of communication and information is constantly increasing, and the latest methods break the views that have so far been difficult to accept by some researchers. Suitability of the non-metric cameras, that have until recently been considered controversial in photogrammetric applications, is also growing, and constantly being improved, in some cases, they can replace expensive, more professional devices. Bearing this in mind, it is possible to obtain easy-to-process, visually attractive models of selected objects, or entire areas in 3D. For larger objects, the image data can come from both terrestrial and above-ground positions, where a special role can be assigned to the so-called low-altitude photos from unmanned aerial platforms (UAVs) [20]. Methods of digital short-range photogrammetry get more and more applicable in various types of measurements. In recent years, modern photogrammetric technologies are widely used in reconstruction of 3D models of any objects. The resulting 3D models can be a source of information useful for measurement, inventory and visual purposes [5,8,14,18]. A 3D model is a mathematical representation of an object in three dimensions. Objects are represented using a collection of points in three-dimensional space, connected by various geometric entities such as triangles, lines, curved surfaces, etc. After creating a model, textures are often applied to define details of the surface or its colour [1,26]. The method of obtaining 3D models from the computing cloud is used to create three-dimensional models using flat digital photos, even those taken with an ordinary camera. The software can be used to model spaces or objects, based on the SFM technique [11, 12, 21]. This technique is based on tracking position of many feature points, depicted on a sequence of photos taken with a camera moving in the environment of the recorded scene. Movement of the camera makes an object visible in each photo from a slightly different angle [2]. Process of reproducing information concerning depth of the scene from a series of flat pictures taken with a non-metric camera, such as a conventional digital camera, in most cases of the applied software, is carried out in a similar manner. The following stages of the reconstruction can be distinguished and described in more detail [9], quality assessment of the acquired images, search for and correlation of details in the photos. Developing a model from a series of photos of appropriate quality begins with finding these details in all the images. Characteristic points are such elements as edges, corners, or other fragments of the image that stand out in contrast to their surroundings [16, 17]. An example of an algorithm that correlates details is the Multicore Bundle Adjustment (MBA) algorithm used by the VisualSFM software, and developed in 2011. Operation of the algorithm is based on linking key points recognized as corresponding to mathematical equations describing the inverse projection of these points from the image plane into space (photogrammetric backward indentation) with the use of a seven-parameter camera [6]. Due to dynamic development of terrestrial laser scanning technology and speed and accuracy of obtaining large amounts of data in a short time, laser scanners are gaining popularity. These devices are widely used in topography, research on the natural environment, research on deformation of engineering structures, and increasingly in research on historic buildings, especially in their inventory. The laser scanning technology allows to quickly obtain a large, multimillion cloud of points with known coordinates. This provides accurate picture of the tested surface. The function of assigning shades of grey or colours with RGB code is also very useful to illustrate the model [3, 19, 28]. Point cloud registered with the use of a terrestrial laser scanner is itself a good reflection of the building model due to its high scanning resolution. However, size of the data sets makes such a model not very practical for use there is also a need to create a geometric 3D model. In the case of terrestrial scanning data, it is referred to as automatic modelling of building façades [4, 22, 23]. Modelling advanced buildings, in particular historical objects, in three dimensions, is an extremely tedious and labour-intensive task. The complexity of this form of object's representation often comes from the architectural elements themselves. Often, each component is a different type of architecture. Apart from the walls, there are openings, irregular roofs, balconies, cornices, pediments, pillars, vaults, domes and hand-carved elements. Therefore, creating models of monuments is time consuming, and the time itself is not related to the chosen method [7]. UAV technology is used in many fields of science, including creating thematic maps of small areas, inventory of existing buildings using 3D models, research on shape, deformation and displacement, creating architectural documentation of monuments, monitoring of land use and cover, cadastral measurements, inspections of tall buildings (chimneys, masts) and other aims for which we can use photos taken with an unmanned aerial vehicle [24]. Drones can be used for photogrammetric tests of buildings, which allow reconstruction of the shape, size and mutual position of objects in the field on the basis of the photos taken [13]. Smaller range drones can also be used for smaller objects, such as archaeological sites or buildings and their entire complexes [15]. Use of drones and advanced technology enables us to use a large number of photos from the air, create a dense, three-dimensional point cloud, and on its basis obtain very accurate models and 3D reconstructions of indicated objects [30]. Non-metric photos obtained from the raid allow to obtain a three-dimensional model by recognizing the same points from many camera positions. Next, the 3D model can be presented in the form of a dense point cloud and then subjected to further spatial analysis and calculations [29].

2. Area of research

This study aims to present the possibility of using data from a digital non-metric camera, terrestrial laser scanning and unmanned aerial vehicles as tools for obtaining high-resolution photogrammetric material in order to develop colourful 3D models of selected objects. The subject of the study was the monument at the top of the Wanda Mound in Krakow and the Helena Modrzejewska National Stary Theatre. Creating 3D objects is a process that requires appropriate software and preparation of the starting material. The measurement work of the monument was made with a Canon EOS 6D camera. The first object of the study on the basis of ground photographs was the monument at the top of the Wanda Mound in Kraków (Fig. 1a). The second object was the National Stary Theatre (Fig. 1b), developed on the basis of data obtained from terrestrial laser scanning and photos from an unmanned aerial vehicle.

(a) (b)

Fig. 1. Monument located on the Wanda Mound (a),
Helena Modrzejewska National Stary Theatre (b)

3. Methods

Field works on the first object started with taking four groups of photos. The first series (63 photos) was taken with the camera placed on a tripod in the lowest possible position, at a height of about 0.8 meters. The second series (72 photos) was taken with the tripod extended to the maximum possible height of about 1.9 meters. The third one (also 72 photos) was taken in an intermediate position, at a height of about 1.5 meters. These series were made at a distance of 3.5 to 5 meters from the monument, so as the entire body of the object is in the frame. Additionally, 99 photos were taken from a shorter distance (about 1.3 meters) in order to capture the finer details of the monument's surface, in particular the details of the marble finish of the eagle at the top of the monument. A total of 306 photos were taken. All the photos were taken with a lens with a fixed focal length of 24 mm. Lock of the focal length and focus made it possible to keep the elements of internal orientation constant. The non-metric camera in photogrammetric studies can be used in three ways: either calibrate the photos during calculations of the coordinates of the points of the photographed object (self-calibration) or determine the elements of internal orientation and distortion for the camera, and then take the determined values as known and proceed in the same way as when processing metric photos, or use uncalibrated images and DLT function [3]. In this publication, a non-metric camera was applied using the first method, i.e. self-calibration.

The report below presents its results:

<chunk label="Chunk 1" enabled="true">
<sensors next_id="2">
<sensor id="0" label="Canon EOS 6D (24 mm)" type="frame">
<resolution width="3648" height="5472"/>
<property name="focal_length" value="24"/>
<property name="fixed" value="false"/>
<bands>

<band label="Red"/>
<band label="Green"/>
<band label="Blue"/>
</bands>
<calibration type="frame" class="adjusted">
<resolution width="3648" height="5472"/>
<fx>3733.3787535163005</fx>
<fy>3736.8261894803777</fy>
<cx>1822.4545044369968</cx>
<cy>2760.0579698299225</cy>
<skew>-1.0035747609890731</skew>
<k1>-0.11815683845047831</k1>
<k2>0.10249038689082111</k2>
<k3>-0.0099354673369588132</k3>
<p1>-0.00046610320051715875</p1>
<p2>0.00054428135544564566</p2>

In order to enable the evaluation of the geometrical quality of the obtained models, control measurements of the length were made directly on the monument. Time of taking the photos and measuring the reference lines took the authors of the study about 4 hours. Such a large number of photos was caused by the construction of the research object. The monument consists of four shapes of different sizes and contains small surface details. In order to obtain photos of the highest quality, both in terms of noise, dynamics (good reproduction of dark and bright parts of the image) and sharpness and lack of blur, the RAW format was used. Photo quality control was performed using Canon Digital Photo Professional software. All photos showed sufficient quality to create a model from them. RAW images were exported for further work to JPEG format with the lowest compression level. Unfortunately, the upper part of the object, due to its height, could not be measured. Therefore, only the characteristic edges of the pedestal were measured. To control the correctness of the measurement, each measurement was performed twice and the average of both measurements was taken. The locations of the control measures on the monument are shown in Fig. 2. The measure marked with letter "S" in Fig. 2 was used to give the models an appropriate scale, while the remaining measures marked with numbers 1–35 were used to assess the accuracy of the models.

The second object under study was The Helena Modrzejewska National Stary Theatre. It is the most magnificent tenement house located in the heart of the old town, next to the Main Square. The building has been rebuilt in the style of Viennese Art Nouveau, so that it fully incorporates into the other buildings. To achieve the intended goal for this facility, data obtained from the Leica ScanStation P40 terrestrial scanner and the DJI S 1000 multirotor were used. The measurement of the National Stary Theatre facility was preceded by a field interview, during which the possibilities of the raid were determined, choice of the place of take-off and landing of the drone and determination of its altitude. Before take-off, the compass was calibrated in accordance with the manufacturer's recommendations, as well as the vessel-controller connection and the GNSS signal quality were checked. During the

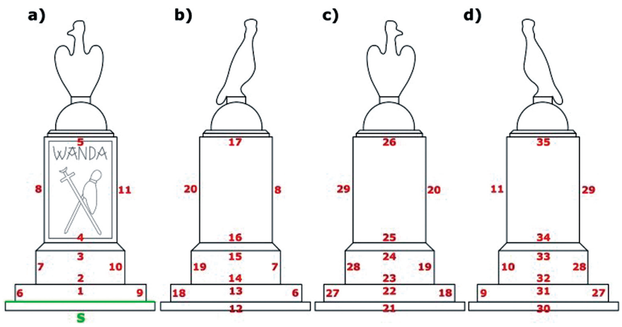

Fig. 2. Sketch of numbering of controls measured in the field.
View a) from the west, b) north, c) east and d) south

raid on the DJI S 1000 unmanned aerial vehicle, 86 photos were taken. The recommended coverage between photos is 70%, photos that differ slightly from each other have been omitted, and only those that guarantee this coverage have been uploaded to the program. Due to the historic nature of the building it was decided not to signal photo points with shields, but to use details of the building (such as building corners, characteristic points of external walls, cornices, and distances between windows) instead.

3.1. Processing of the obtained data of the monument located at the top of the Wanda Mound in Krakow

Photos obtained as a result of field work were used to make three-dimensional models of the object using Agisoft PhotoScan and in VisualSFM and CloudCompare. Development of a 3D model in Agisoft PhotoScan consists of the following stages: importing photos to the program, finding key points in photos, aligning and orienting the photos, generating and cleaning a dense point cloud, reconstructing the object's surface from the obtained point cloud, texturing the model that raises visual effect of the model presentation Fig. 3, giving the model an appropriate scale.

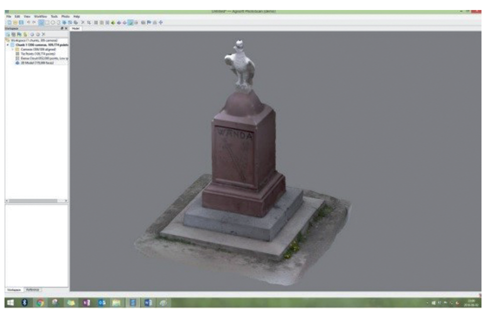

Fig. 3. The finished model after reconstruction and texturing in Agisoft PhotoScan

The first stage is loading photos, which is done by selecting the Add Photos option from the Workflow menu. The next step in developing the model in PhotoScan was to find key points in the photos and use them to make alignment and orientation of the photos. As a result, a rare point cloud was obtained. The Accuracy option was set to High. The alignment process took about 3.5 hours. As a result a rare cloud of almost 110,000 points was obtained. The program visualized both the cloud and the calculated positions and directions of each photo. The next step was to generate a dense point cloud. Generating the highest density point cloud from the photos, numerical spatial data and colour are determined for practically every image pixel of the examined object. After generating a dense cloud of points, the surface of the object was reconstructed. The program provides reconstruction in several levels of detail. From the available options, the most detailed reconstruction with a projected number of polygons of 180,000 was selected. PhotoScan allows to obtain realistic textures from photographs of an object. The imposition of phototexture was intended to increase visual attractiveness of the model, but it should not affect the accuracy of the measurements performed on the model. In order to give the model a real scale allowing for length measurements directly on the model, it was necessary to use one of the field control measures. Scaling was done using the Markers tool and the Scale Bar function. After indicating the segment "S" on the model, its real length was entered. The program then rescaled the entire model, while measurements of the remaining control measures were made with the use of markers. Ends of the remaining sections were marked with them. The next stage of work was to develop the model in VisualSFM and CloudCompare. Since VisualSFM can only generate point clouds from a series of object photos, it was necessary to use a second program to clean the cloud and create the actual model shape out of it. CloudCompare was chosen for this purpose. Until a dense point cloud is achieved, the work in VisualSFM is similar to the modelling process in Agisoft PhotoScan. Further modelling in CloudCompare required more contribution from the user. The work was as follows: loading photos into VisualSFM, searching for key points and orientation of photos as a result of which a rare point cloud was created. Uploading photos to VisualSFM is accomplished by selecting Open + Multi Images option. The search for key points in all photos was done using the Compute Missing Match option from the SfM menu (Pairwise Matching submenu). Then a rare point cloud was generated using the Reconstruct Sparse tool from the same menu. The next stage of work was to generate a dense point cloud. The Reconstruct Dense tool from the SfM menu was used for this purpose. The obtained .ply files were loaded into CloudCompare using the Open option from the File menu. Each file was loaded by the program as a separate layer, so the next step was to merge the layers into one using the Merge option. The obtained point cloud is characterized by a large number of redundant points belonging to the surroundings of the modelled object. In addition, there are also clearly visible points of different colour directly adjacent to the model surface. These points most likely come from a bright background of a cloudy sky. The neighborhood points were easily removed with the Segment tool. An important feature of this tool is the fact that the selected points are not permanently deleted, but only transferred to a separate layer. In case of a mistake, deleted points can be restored easily. Removing points adjacent to the model turned out to be more difficult, especially with the large number of details and light colour of the marble eagle figurine. Due to the slightly lighter colour that distinguishes them, the scalar fields function available in the program was chosen for use in initial cleaning – each point in the cloud was assigned a value that was the average of the RGB components of the colour of the point. The resulted values were visualized using a colour scale – from blue for small values (i.e. dark points) to red for the largest (i.e. bright points). A field value histogram was then generated to determine the optimal filtering thresholds. Based on the histogram and the trial and error method, it was decided to use the Filter By Value tool to reject all points for which the value exceeded 215. As a result of filtering, the cloud was initially cleaned of background points. The remaining unnecessary points that were not removed by filtering were manually removed with the Segment tool. In order to generate a model from the obtained point cloud, the Poisson Surface Reconstruction tool based on the Poisson algorithm was used. The basic parameter of the algorithm – density of the so-called Octree Depth – responsible for the quality of the obtained shape (and the number of polygons), was determined by trial and error at 12. Application of higher value resulted in significant extension of the reconstruction process and an increase in the model file size without any significant improvement in detail Fig. 4.

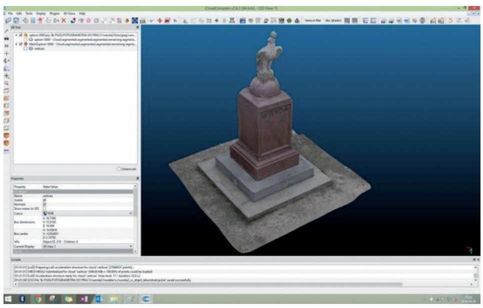

Fig. 4. Result of surface reconstruction in CloudCompare

As in PhotoScan, the model has been scaled to its actual size. In this case, it was also necessary to measure the value of the measure marked with the letter "S". on the model. The measurement was made with the Point Picking tool, which allows to select points on the model and calculate the distance between them. For the obtained result equal to 8.981 units, the scale was calculated on the basis of the value measured in the field (2.358 m), which was 0.262537. This scale was introduced to the Multiply/Scale tool available in the Tools menu, which resulted in a scaled model.

3.1.1. Presentation and evaluation of the accuracy of the obtained models

As a result of work with Agisoft PhotoScan, VisualSFM and CloudCompare, two 3D models of the same object – monument on the Wanda Mound in Krakow – were obtained. It was decided to evaluate two aspects of the models: their appearance, i.e. level and accuracy of mapping the details of the surface of the object, its texture or colour, realism of textures and the presence of significant distortions of the model body visible to the naked eye, their geometric accuracy, i.e. the possibility of carrying out reliable measurements of length directly on the models (this was done by comparing the results of measurements carried out on the models with the results of direct measurements on an object in the field). The model shown in Fig. 5 is the result of work with photographic material in VisualSFM and CloudCompare.

Fig. 5. Model from VisualSFM and CloudCompare. General view from the west

The first important feature is the greater number of details visible on the model. As with Agisoft PhotoScan, the combination of VisualSFM and CloudCompare also coped well with geometrically simple steps and pedestals. It can also be noticed that the shape of the spherical base on which the eagle stands, as well as the transition between this base and the main body of the monument, have been reproduced much better. In addition, the flat fragment of the plinth with a hemisphere and a small step below it have been correctly reconstructed. The decorative inscription and drawing on the western wall of the monument have also been reproduced. The model of the eagle's figure itself is also very detailed, and its shape does not differ from the real one. However, the resulting model is not perfect. The presence of non-existent characteristic surface irregularities, which are visible especially on the granite steps at the base of the pedestal and on its spherical top, draws attention. Their surface is covered with numerous small depressions. Distortions of the hemisphere have lighter discolourations, which suggests that they are the result of the negative influence of reflections from the shiny material of this part of the monument. The side walls also bear such deformations, but to a lesser degree. Slight discolouration also appeared on the other edges of the plinth, which results from the considerable difficulties encountered in cleaning the cloud from points that were directly adjacent to the modelled object. For VisualSFM and CloudCompare, it can be observed that the model is more detailed than the one with Agisoft PhotoScan. Based on the same photographic material, the program was able to accurately reproduce both the lower parts of the monument with a simple shape and a figurine with a more complicated form. The first analysed detail of the monument is the figure of an eagle Fig. 6.

It can be seen that for the model developed with VisualSFM and CloudCompare, the figure is more detailed. Moreover, these programs were able to obtain, unlike Agisoft PhotoScan, the correct shape of the upper part of the wings. Numerous details obtained by the second software package are noteworthy, there is a clear relief of the eagle's legs and claws, details of the feathers covering the wings (both on the front and back of the monument), as well as the element most difficult to reproduce due to its high position, i.e. the head of an eagle and a crown on it. In the case of the Agisoft PhotoScan model, these

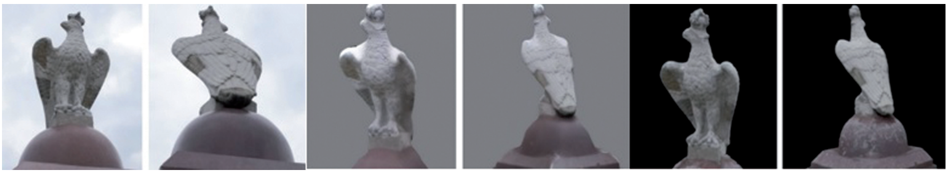

Fig. 6. Figure of an eagle. Agisoft PhotoScan model, VisualSFM and CloudCompare model

elements take a characteristic oval and generalized shape, while in the second model we see a much more detailed drawing of the beak, as well as some details within the crown. Another analysed detail was the decorative drawing on the west wall of the monument. Both programs coped with the detail representation to a satisfactory degree Fig. 7. VisualSFM and CloudCompare did a better job of mapping the sharp recess in the wall where the ornament was placed. It can be seen that the recess of letters "Wanda" was reproduced on the second model. The model from Agisoft PhotoScan shows distortions of the sharp edges of the monument.

Fig. 7. Inscription "Wanda". Agisoft PhotoScan model, VisualSFM and CloudCompare model

As it can be seen in Fig. 8, both programs well mapped the transition between the narrower and the wider part of the pedestal, although in the case of the VisualSFM and CloudCompare model edges and transitions are sharper and more closely correspond to the real geometry of the monument's body. In particular, the curvature of the concave transition and the slight step are better reproduced.

In the case of the monument on Wanda's Mound, its numerous damages are noticeable. One of them is, for example, a damaged corner of one of the granite steps. As can be seen

Fig. 8. Plinth. Model from Agisoft PhotoScan, model from VisualSFM and CloudCompare

in Fig. 9, Agisoft PhotoScan generalized this fragment of the model, so the damage was not reproduced. On the second model, the loss of the corner is clearly visible.

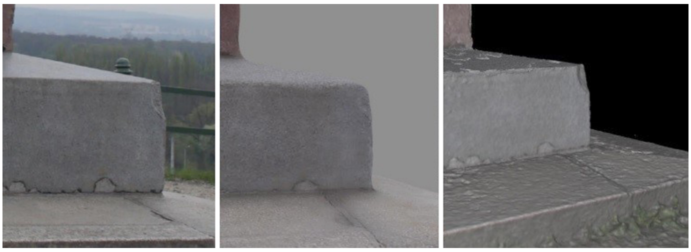

Fig. 9. Corner. Agisoft PhotoScan model, VisualSFM and CloudCompare model

In order to assess the quality of mapping the object geometry on the models and the possibility of making accurate length measurements on them, the deviations of the measures obtained on the models from the values of the same measures measured directly on the monument were calculated. The deviations of the measures are summarized in Table 1.

Table 1. List of deviations of measures obtained from models compared to real measures

Markings on the sketch	Deviation [cm]		Markings on the sketch	Deviation [cm]	
	PhotoScan	VSFM and CC		PhotoScan	VSFM and CC
S	0.0	0.0	18	–1.4	0.0
1	–2.0	–1.9	19	–1.7	–0.2
2	1.5	0.4	20	1.0	0.3
3	–0.8	–0.2	21	–0.2	–0.1
4	2.0	0.4	22	–0.4	–0.5
5	–2.4	0.0	23	1.8	0.5
6	–1.3	–1.0	24	–0.9	–0.5
7	–1.4	–0.1	25	1.2	–0.2
8	2.7	0.8	26	–1.8	–0.9
9	–1.9	0.1	27	–2.3	–0.6
10	–1.6	–0.5	28	–2.3	–0.3
11	1.5	0.8	29	2.0	0.8
12	–0.1	0.2	30	0.7	1.6
13	–0.5	–1.8	31	–1.2	–1.4
14	2.1	0.6	32	1.6	0.4
15	–0.9	0.2	33	–1.1	0.3
16	2.4	0.6	34	1.1	0.6
17	–2.5	–0.2	35	–1.9	–0.7

No deviation for the "S" measure indicates that the Agisoft PhotoScan model has been successfully scaled. The deviations of the measures collected on the model are in the range from −2.5 cm to +2.7 cm. While the mean of their absolute values was 1.4 cm. The standard deviation was 1.6 cm. The maximum relative deviation was 9.1% (measure 27), while the mean relative deviation of all the lengths measured on the model was 2.3%. Also, in the case of the VisualSFM and CloudCompare model, no deviation of the S measure used to scale the model was obtained. For this model, the deviations from the real measures are in the range from −1.9 cm to +1.6 cm, for measure 1 and 30, respectively. The measures 1.13 and 30 are characterized by greater than average deviations. While the mean of their absolute values was 0.5 cm. The standard deviation was 0.7 cm. The maximum relative deviation was 3.9% (measure 6), while the mean relative deviation of all the lengths measured on the model was 0.6%.

3.1.2. Comparison of models' accuracy

Based on a simple analysis of the obtained measurement results, it can be concluded that the VisualSFM and CloudCompare model is characterized by smaller deviations of the measured values from the real ones. While in the Agisoft PhotoScan model the dimensions with the greatest differences deviate from the values measured on the monument by about ±3 cm, on the model from the second software package, the worst measurements differ from the real ones by about ±2 cm. Also, the mean of the absolute deviations (0.5 cm compared to 1.4 cm) is smaller for VisualSFM and CloudCompare. It can also be noticed that the deviations in the Agisoft PhotoScan model are much more diversified, while in the case of the second model they mostly take similar values. This observation is confirmed by the smaller standard deviation for the dimensional differences of the second model (0.7 cm compared to 1.6 cm). The above observations apply to the absolute deviations of both models. It is equally important, however, how the obtained deviations relate to the measured values themselves. In the case of relative deviations, the difference in favour of the second model is even more pronounced (0.6% for VisualSFM and CloudCompare compared to 2.3% for Agisoft PhotoScan).

3.2. Processing of the obtained data of the National Stary Theatre

The first measurement included data obtained with the Leica ScanStation P40 scanner. As a result of the measurement, a coloured point cloud was obtained Fig. 10, which was created in the process of integrating the points with the photos taken by the scanner during the measurement. The entire façade of one of the walls of the building was subject to the measurement.

In order to perform the necessary measurements covering the entire range of the wall, it was necessary to place the scanner on two separate stations 10 m away from the scanned element. The accuracy of the measurement in the horizontal and vertical planes was set at 0.002 m on both stations. The scans at all measuring stations were made in the range of 360 degrees. The point cloud represents the object at the time of its measurement, maintaining key details on a scale of 1:1. Owing to this, it is possible to recreate the

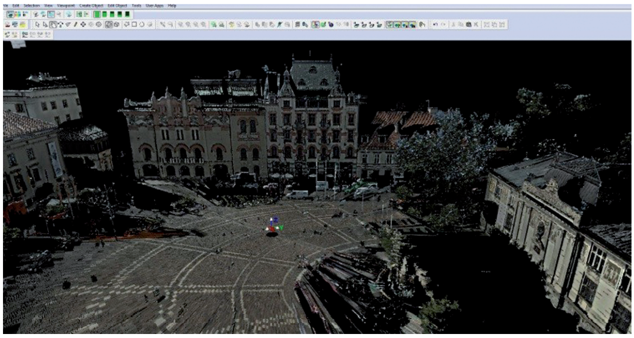

Fig. 10. Acquired point cloud

shape of the object, perform the analysis of the condition and purpose of the object, and perform measurements and calculations related to the object. Due to its features, a point cloud is an excellent starting material for the 3D modelling of an object. During the office works related to the initial processing of the point cloud, the dedicated software from the manufacturer Leica Cyclone was used. At a later stage, MicroStation V8i was used to process and create the documentation. In order to orient the point clouds in relation to each other and combine them into one collective point cloud, which represents the shape of the object under measurement, the characteristic elements of the building, measured from both positions and clearly identified were used. To maintain the appropriate accuracy, the number of vertexes was set at 24, and their distribution was planned and made in such a way that there was only one vertex on one vertical and horizontal plane. These activities had a key impact on obtaining the orientation error assumed in the project, which did not exceed 0.05m. Depending on the needs, it can be visualized in various ways. However, RGB display was chosen for further work, as it is the best in terms of identifying objects in the cloud. The second measurement was made using a DJI S 1000 multirotor. 86 photos of the building's façade were taken. Agisoft PhotoScan was used for image processing. The program builds high-quality 3D models from ordinary images, ensures precise alignment and does not require special shots when taking photos. The first step was to align. It includes Air Triangulation (AT) and Beam Block Adjustment (BBA). At this stage, Agisoft PhotoScan looks for feature points in images and aligns them with each other between images. The program also recognizes position of the camera for each image and improves the camera calibration parameters. The result of these activities is the visualization in the form of a rare point cloud and a set of camera positions. The rare point cloud is not directly used in further processing. However, it can be exported for further use by external programs. In turn, a compilation of camera positions is required for further 3D surface reconstruction. The actual distances between feature points on a given object were used to create a model in the real scale Fig. 11 and Fig. 12. The distance measurement was made by the geodetic method using an electronic total station and reflectorless measurement of characteristic points. A local control network was established in the area, selected points were measured, their local coordinates were determined and distances were calculated on their basis. Actual distances were measured with an accuracy of 1 cm. Then, Agisoft PhotoScan specified the distance between them using the option available in the program, which is adding the so-called scale bars. This procedure aims to present the mapped surface as accurately as

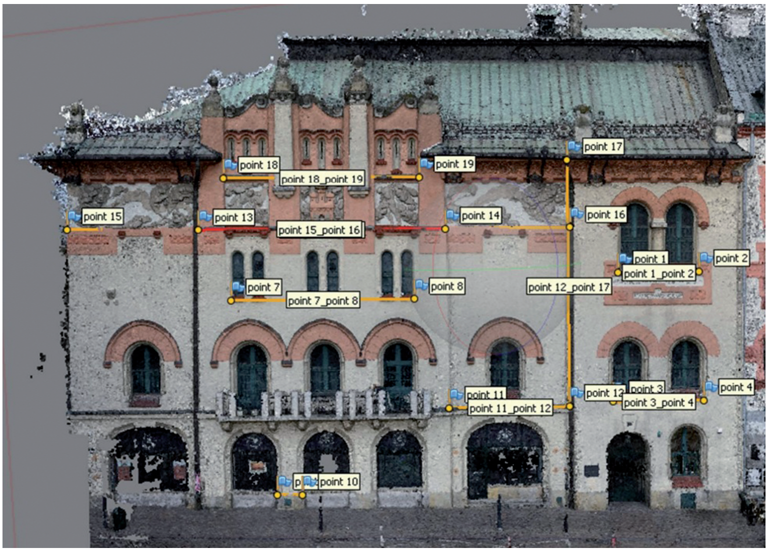

Fig. 11. Marked feature points

Fig. 12. Building elevation

possible in order to eliminate potentially possible distortions such as twisting or shrinkage. Using the Create Scale Bar tools, measures between adjacent points were added into pairs defining the sections measured in the field, distances were entered in the Distance column. With the distance between adjacent photo points added, the rare point cloud has been refreshed.

In this way, the distances were obtained, thanks to which the model was scaled to real dimensions Table 2.

Table 2. Actual distances between points

Label	Distance [m]
point 1_point 2	4.067
point 3_point 4	4.555
point 7_point 8	9.034
point 9_point 10	1.266
point 11_point 12	5.997
point 13_point 14	12.113
point 15_point 16	24.823
point 12_point 17	12.287
point 18_point 19	9.581

The program made optimization in order to check the positioning errors of the marked points and to align the photos. Its purpose is to show the value of linear error of the points position. The position error is 0.02 m Table 3.

Table 3. Linear error of point position

Label	Distance [m]
point 1_point 2	0.016
point 3_point 4	–0.025
point 7_point 8	–0.012
point 9_point 10	0.012
point 11_point 12	0.031
point 13_point 14	–0.036
point 15_point 16	–0.007
point 12_point 17	0.001
point 18_point 19	0.020
Total	0.021

The final step was to mesh the 3D model from a dense point cloud, check the topology and generate orthomosaic. Comparison of the generated 3D models shows advantages and disadvantages of the basic inventory methods: scanning and UAV. It should be remembered that the model created using a scanner is only a semi-finished product prepared for comprehensive processing depending on the inventory needs. The first comparison concerns protruding elements and decorations Fig. 13. The protruding elements (in this case it is a cone with a ball) are reflected by the laser scanning very well. There are some distortions in the UAV technique at the test site. This is due to the poor matching of photos and small number of photos in this place. Such elements need a few or even a dozen or so detailed photos taken from a short distance and with a lot of coverage. The façade decorations were perfectly captured in the UAV method. In the case of laser scanning, the reproduction of decorations is unsatisfactory.

Fig. 13. Comparison of protruding elements and decorations

Another comparison presents the edge of the model Fig. 14. The end of the roof in the UAV model is poorly photographed compared to the model obtained from the scanning. Some distortions due to the low coverage and the specificity of the element (protruding, longitudinal element) can be observed.

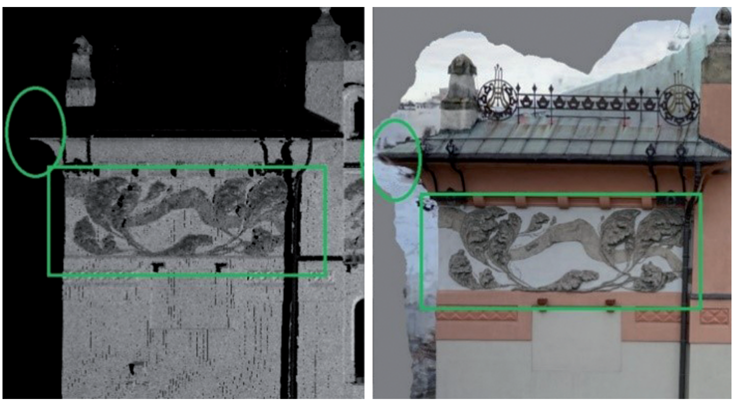

Fig. 14. Comparison of the model edges

4. Conclusions

Currently, the standard for the inventory of historic buildings that require renovation, etc. is to show the object in a digital version. Models created by developing laser scanning and photos obtained by UAV method accurately reproduce the examined object, but differ diametrically in the method of obtaining data. In case of large and simple objects, laser scanning is much faster method than UAV, considering both office and field works. However, there are many important factors that must be met by the object in order to be reproduced as well as possible, i.e. lack of any elements obscuring the object, lack of small decorations in large spaces, possibility of a stable setting of the instrument in a convenient place. UAV is a time-consuming method. In the first step, we need to establish a raid plan on the tested object. The next step is to choose the right photos, which, after sometimes many hours of development in the program, will allow to create a 3D model. However, unlike scanning, we can change the distance from the tested object depending on the needs, so that complex elements are reproduced more accurate. There is an option of replacing a defective photo (containing elements obscuring the object) with another photo without these defects. In addition, the colour 3D model from the photos looks realistic, which cannot be said about the colour model obtained with a terrestrial scanner. If we have both tools for acquiring UAV images and laser scanning, such studies are sufficient in terms of accuracy in every field that requires such an inventory. Currently these methods are most popular. Models obtained with both methods can be compatible with each other, and thanks to the correlation of programs it is possible to eliminate errors with each other. The aim of the study was to assess and compare the quality of three-dimensional models generated by the available software. Development of 3D models was performed on the basis of photos obtained from a non-metric camera, unmanned aerial vehicle and data obtained from terrestrial scanning. For its implementation, Agisoft PhotoScan Professional was used as an example of paid commercial software and a combination of VisualSFM (point cloud generation) and CloudCompare (cloud cleaning and surface reconstruction) – free programs for non-commercial and academic applications. In order to compare performance of both software packages reliably, it was decided to use them to create models of the same test object, based on exactly the same set of photos taken in the field. The usefulness of the presented sample programs, such as Agisoft PhotoScan, VisualSFM and CloudCompare, is additionally enhanced by the not too complicated interface, as well as logically grouped functions and tools. The obtained models were characterized by a satisfactory reconstruction of the body of the object and its texture. In addition, they were characterized by a sufficiently high accuracy of mapping the geometry of the developed object, so that reliable measurements could be made on them. The generated models not only have a significant aesthetic value, but also a scientific one and can be used for simple measurement purposes if an accuracy of a few centimetres is sufficient. Photos of architectural objects taken from an unmanned aerial vehicle and 3D models developed on their basis allow for detailed documentation of technical condition of external elements of tested objects. Digital model of an object supports easy and quick generation of fragments needed for accurate research. They can be the beginning of further comparative analyses.

The analysis of models or photos obtained from several drone raids allows for a detailed assessment of the scope and scale of changes in the geometry or technical condition of the entire object or its part. To sum up, terrestrial laser scanning is a technology that can be successfully used to protect valuable architectural objects. The speed of obtaining data using this technology and their accuracy allows to keep the most complex details, as well as to create many studies from the same measurement. Owing to this flexibility of data, it is possible to create both classic architectural and construction studies as well as modern 3D models. The photogrammetric method is a very complicated process that entails carrying out many technically and computationally demanding processes. However, if the goal of modelling is to achieve the best geometric accuracy, metricity and detail, this method is indispensable. Contemporary architectural inventory of buildings, as well as inventory of historic buildings are based on this method. Each of the presented methods has both advantages and disadvantages. Both are connected by the tool used to obtain information about the object, but the choice of the modelling method must depend primarily on the purpose of the visualization.

Acknowledgements

Financed by a subsidy from the Ministry of Education and Science for the University of Agriculture in Kraków for 2022.

References

[1] J.A. Bell, "3ds max 6", Effective solutions. *Helion*, 2004, Warszawa.

[2] F. Biljecki i in., "Applications of 3D City Models: State of the Art Review", *International Society for Photogrammetry and Remote Sensing Journal of Geo-Information*, 2015, no. 4, pp. 2843–2889, DOI: 10.3390/ijgi4042842.

[3] A. Boroń, A. Rzonca, A. Wróbel, "The digital photogrammetry and laser scanning methods used for heritage documentation", *Roczniki Geomatyki,* Kraków, 2007, vol. 5, no. 8, pp. 133–139.

[4] H. Boulaassal, C. Chevier, T. Landes, "From laser data to parametric models: towards an automatic method for building façade modelling", *Lecture Notes in Computer Sciences*, 2010, vol. 6436, pp. 42–55. [Google Scholar]

[5] A. Bujakiewicz, D. Zawieska, M. Kowalczyk, "Three dimensional modelling of architectural structure", *Archives of Photogrammetry, Cartography and Remote Sensing*, Materials of the National Geoinformation Symposium "Geoinformation as an integrated tool for spatial research", Wrocław – Polanica Zdrój, 2003, vol. 13B, pp. 325–337, http://ptfit.sgp.geodezja.org.pl/archiwum.html#:~:text=eISSN%202391%2D9477%2C-doi%3A%2010.14681,-Archiwum%20Fotogrametrii%2C%20Kartografii.

[6] W. Changchang i in., "Multicore Bundle Adjustment", *Computer Vision and Pattern Recognition*, 2011, pp. 3057–3064, DOI: 10.1109/CVPR.2011.5995552.

[7] C. Chevrier, N. Charbonneau, P. Grussenmeyer, Parametric Documenting of Built Heritage: 3D Virtual Reconstruction of Architectural Details, *International Journal of Architectural Computing*, 2010, vol. 08, issue 02, pp. 132–146, DOI: 10.1260/1478-0771.8.2.135.

[8] A. Habib, M. Ghanma, R. Al-Ruzouq, E.M. Kim, "3-D Modelling of Historical Sites Using Low-Cost Digital Cameras", *XXth International Society for Photogrammetry and Remote Sensing Congress*, Istanbul, Commission 5, SS4-CIPA-Low-Cost Systems in Recording and Managing the Cultural Heritage, Stambuł, Turkey, 2004, pp. 570–575.

[9] K. Hämming, G. Peters, "The structure-from-motion reconstruction pipeline – a survey with focus on short image sequences", *Kybernetika*, 2010, vol. 46, no 5, pp. 926–937.

[10] M. A. Herman i in., "Fundamentals of Physics for College and University Candidates", *Państwowe Wydawnictwo Naukowe*, Warszawa, 2009.

[11] T. Jebara i in., "3D structure from 2D motion", *Institute of Electrical and Electronics Engineers Signal Processing Magazine*, 1999, vol. 16, issue 3, pp. 66–84, DOI: 10.1109/79.768574.

[12] T. Ju, "Fixing Geometric Errors on Polygonal Models: A Survey". *Journal of Computer Science and Technology*, 2009, vol. 24, no. 1, pp. 19–29, DOI: 10.1007/s11390-009-9206-7.

[13] S. Kostka, "Photogrammetry – an old technique in a new edition", *Wydawnictwo Jaskinie,* 2014, no. 3 (76), pp. 14–16.

[14] B. Kwoczyńska, A. Rzepka, "Application of non-metric camera in modelling of small architecture objects", *Infrastruktura i ekologia terenów wiejskich, Państwowe Wydawnictwo Naukowe*, Oddział w Krakowie, Komisja Technicznej Infrastruktury Wsi, 2013, no. 2/II, pp. 31–41, DOI: 10.14597/infraeco.2014.1.1.001.

[15] Z. Kurczyński, "Photogrammetry", *Państwowe Wydawnictwo Naukowe*, Warszawa, 2015.

[16] D. G. Lowe, "Object recognition from local scale-invariant features", *Proceedings of the International Conference on Computer Vision in Corfu*, Kerkyra, Greece, 1999, pp. 1150–1157, DOI: 10.1109/ICCV.1999.790410.

[17] D. G. Lowe, "Distinctive image features from scale-invariant keypoints", *International Journal of Computer Vision*, 2004, vol.60, no. 2, pp. 91–110, DOI: 10.1023/B:VISI.0000029664.99615.94.

[18] E. Nowak, J. Nowak, "Modelling 3D views based on amateur photography", *Acta Scientiarum Polonorum. Geodesia et Descriptio Terrarum*, 2009, vol. 8, no. 2, pp. 39–52.

[19] R. Pilecki, "Applications of terrestrial laser scanning", *Czasopismo Techniczne Wydawnictwo Politechniki Krakowskiej*, 2012, no. 26.

[20] Praca zbiorowa, "Photogrammetry and the laser scanning in the 3D modeling", *Publisher: Wyższa Szkoła Inżynieryjno-Ekonomiczna*, Rzeszów, 2015, pp. 5–6.

[21] Praca zbiorowa, "Modeling and visualization of 3D data based on photogrammetric measurements and laser scanning", *Publisher: Wyższa Szkoła Inżynieryjno-Ekonomiczna*, Rzeszów, 2015, pp. 5–7.

[22] Pu Shi, G. Vosselman, "Automatic extraction of building features from terrestrial laser scanning", *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2006, vol. 36, part 5, pp. 147–160.

[23] A. Salwierz, T. Szymczyk, "Methods of creating realistic spaces – 3D scanning and 3D modelling, 2020, vol.14, pp. 101–108, DOI: 10.35784/jcsi.1584.

[24] P. Sawicki, "Unmanned aerial vehicles in photogrammetry and remote sensing – state of the art and trends", *Photogrammetry and Remote Sensing Archive*, Olsztyn, 2012, vol. 23, pp. 365, 366, 373, http://ptfit.sgp.geodezja.org.pl/archiwum.html#:~:text=eISSN%202391%2D9477%2C-,DOI%3A%2010.14681,-Archiwum%20Fotogrametrii%2C%20Kartografii.

[25] W. Baturo, "Subject Dictionaries. Mathematics", *Państwowe Wydawnictwo Naukowe*, Warszawa, 2011.

[26] A. Takaaki, S. Yasuhito, "3D Facial Model Creation Using Generic Model and Front and Side Views of Face", *Ieice Transactions on Information and Systems*, 1992, vol. E75-D, no. 2, pp. 191–197.

[27] R. Tokarczyk, A. Boroń, "An investigation of digital photographic cameras for the close-range photogrammetry", *Archiwum Fotogrametrii, Kartografii i Teledetekcji*, Kraków, 2000, vol. 10, pp. 63–1:63–10, http://ptfit.sgp.geodezja.org.pl/archiwum.html#:~text=eISSN%202391%2D9477%2C-,DOI%3A%2010.14681,-Archiwum%20Fotogrametrii%2C%20Kartografii.

[28] Uchański i in., "The problem of standardization of terrestrial laser scanning techniques for architecture inventory purposes", *Archiwum Fotogrametrii, Kartografii i Teledetekcji*, Międzyzdroje, 2008, vol.18, pp. 636–637, http://ptfit.sgp.geodezja.org.pl/archiwum.html#:~:text=eISSN%202391%2D9477%2C-DOI%3A%2010.14681,-Archiwum%20Fotogrametrii%2C%20Kartografii.

[29] Scan-3D "Drony – fotogrametria". [Online]. Available: www.scan-3d.pl/oferta/drony-fotogrametria.

[30] https://dronereport.pl/uslugi-dronem/modele-3d-chmury-punktow.

Modelowanie 3D z wykorzystaniem metod fotogrametrycznych

Słowa kluczowe: modelowanie 3D, wizualizacja, naziemny skaning laserowy, bezzałogowe statki powietrzne, kamery niemetryczne

Streszczenie:

Niezwykle intensywny rozwój technologii od początku obecnego stulecia, zaowocował wieloma innowacjami, również w dziedzinie geodezji i kartografii, a w szczególności w zakresie fotogrametrii i teledetekcji. Oprócz ewolucji znanych już form pomiarów jak przejście ze zobrazowań analogowych na cyfrowe, pojawiły się też nowe metody pozyskiwania danych przestrzennych jak skaning laserowy, bezzałogowe statki powietrzne czy cyfrowe kamery niemetryczne, będące przedmiotem niniejszego opracowania. Integracja tych danych stała się nowym narzędziem, które rozszerzyło dotychczasowe możliwości pomiarowe, jak również znalazło zastosowanie poza branżą geodezyjną, na przykład w modelowaniu 3D, archeologii czy konserwacji zabytków. Dzięki skaningowi otrzymujemy współrzędne niemal każdego punktu skanowanej powierzchni w dowolnym miejscu, nawet już po zakończeniu pomiaru i opuszczeniu obiektu. Otrzymujemy zatem pełną i szczegółową informację o wymiarach obiektu, o znajdującej się wewnątrz infrastrukturze niekiedy trudno dostępnej bądź skomplikowanej. Poziom zaawansowania technicznego aparatów cyfrowych pozwala już od kilkunastu lat na stosowanie ich z powodzeniem w fotogrametrii bliskiego zasięgu [27], a od niedawna także i w fotogrametrii lotniczej niskiego pułapu (bezzałogowe statki powietrzne). Bezzałogowe statki powietrzne okazują się świetnym narzędziem wspomagającym proces zbierania danych o wysokorozdzielczych metrycznych zdjęciach elewacji budynków.

Do zrealizowania zamierzonego celu wybrano 2 różne obiekty testowe.

Za pierwszy obiekt testowy przyjęto pomnik, zaprojektowany przez Jana Matejkę, który znajduje się na około 14 metrowym szczycie kopca Wandy. Składa się on z prostego w formie prostopadłościennego postumentu wykonanego z brązowego marmuru. Na jego szczycie umieszczona została figura z białego marmuru przedstawiająca zwróconego w kierunku zachodnim orła w koronie. Na ścianie zachodniej postumentu wykonany został napis “Wanda” oraz rysunek przedstawiający miecz skrzyżowany z kądzielą. Za wyborem pomnika przemawiały następujące elementy: ciekawa bryła obiektu, który zawiera w sobie zarówno proste formy geometryczne o dużych i płaskich powierzchniach (postument), jak i bardziej szczegółowe powierzchnie (figura orła); szczegółowa tekstura obiektu (skomplikowane żyłkowania marmuru, detale skrzydeł) zapewniająca dużą liczbę punktów szczegółowych, w oparciu o które oprogramowanie może odtworzyć głębię sceny; obecność zarówno elementów matowych, łatwych do przetworzenia przez oprogramowanie, jak i lekko połyskliwych, które mogą generować mylące oprogramowanie odblaski. Drugim badanym obiektem był Teatr Stary im. Heleny Modrzejewskiej. Jest to najokazalsza kamienica znajdująca się w samym sercu starego miasta tuż przy Rynku Głównym. Budynek został przebudowany na styl wiedeńskiej secesji, aby w pełni komponował się z resztą zabudowy. Pomiary obejmowały dane pozyskane z kamery niemetrycznej, skanera Leica ScanStation i wielowirnikowca DJI S 1000.

Received: 11.02.2022, Revised: 24.04.2022