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Original Research Article

ANALYSIS OF THE APPLICABILITY OF PHOTOGRAMMETRY IN BUILDING FAÇADE

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Abstract

This article evaluates the accuracy of 3D models made from point clouds obtained from photogrammetry. Photographs were taken from ground level and using a drone, and data processing was performed in 3DF Zephyr. The models were compared with the actual dimensions of the buildings. Four different building objects with varying degrees of complexity were analysed. The aim of the research is to analyse the conditions for taking photographs and how they are transformed into a point cloud, and to see how and whether the complexity of the shape of the facade affects the accuracy of the 3D model made from the point cloud. The inaccuracy of the point cloud in the form of point spread for all analysed cases was 1.8±0.4 cm on average. The largest measurement error was found in the case of a multi-storey building. Despite the presented inaccuracies, it was considered advantageous to use the point cloud obtained through photogrammetry in the inventory. No difference was observed in the accuracy of the model depending on the complexity of the building. Recommendations were made regarding the conditions for taking photographs.

Keywords: photogrammetry, inventory, point cloud, 3D model

1. INTRODUCTION

Photogrammetry is defined by the American Society for Photogrammetry and Remote Sensing as a method of extracting information about the position of points

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I n space from photographic images. It is also referred to as SFM - Structure From Motion and is based on calculating the three-dimensional coordinates of object surface points from motion, where motion is a change in the position of a recording device such as a camera or laser scanner [34].

Photogrammetric technology is based on measuring conjugate points appearing in two images or measuring the conjunction of points in multiple images (minimum of three). In order to make a model of an object, it is necessary to pair these points and position them relative to each other in space to form a structure [21]. This requires determining the coordinate of the paired point from the changing 2D x and y coordinates of this and the other points in the image (in this case the pixels of the flat image). In simpler terms, it means determining the depth of the images taken based on a change in viewing angle, as is the case with stereoscopic vision, by which a person with healthy eyesight can judge the distance of an object from itself. Structure-from-motion (SFM) algorithms, can find a set of 3D points, camera rotation and position, given a set of images of a scene with corresponding 2D points. A set of such points distributed in 3D space is called a point cloud, which can be used to create a 3D model of a given object or space.

Photogrammetry is used for the preparation of topographic plans based on high-altitude terrain photographs, but also for the digital mapping of cubic objects, regardless of scale. The use of this method is becoming widespread in geography (GIS), architecture (CAD), industry, engineering, medicine, archaeology [17] and others. In the construction industry, the point cloud obtained from photogrammetry is also used to monitor the progress of construction [13], or to detect defects in the construction of external walls, but it gives the best results when the walls are flat without curves or concave and convex sections [29].

Building inventories use a scanner for 3D measurements. Using a 3D scan, the measurement error for existing buildings and their digital models is less than ±1 cm. The results of laser scanner measurements can significantly improve basic inventories and diagnostic studies for buildings and structures [27]. Studies [4] show that the number of points present in the point cloud from 3D laser scans is higher compared to 3D photogrammetry from drone imagery. In the measurement of large areas, there are no significant differences in the accuracy of the cloud from 3D scan and drone imagery [6]. The point cloud can be a source of data feeding the BIM database in object inventories [31, 18, 20, 22, 23], and a point cloud obtained from photogrammetry significantly reduces the time needed for data collection [15] and reduces costs compared to a 3D scan [6].

The higher the density of the point cloud, the higher the hardware requirements for data processing, but a dense point cloud is not always needed, as omitting some points does not necessarily degrade the quality of the virtual model representing the shape. There is a method for optimising a point cloud without loss of quality [2].

The photogrammetric inventory method is not new [14], but the hardware and analytical capabilities are still being developed.

Data collection involves taking multiple photographs of the object or film from which the frames are selected [7], with the camera positioned at different angles. Some of the photographs should show the entire object and others close-ups of the fragment being analysed [32]. The images are then analysed in the software by dedicated computational algorithms and a three-dimensional point cloud is obtained. One method for calculating the position of a point in a coordinate system is stereo matching using pairs of photographic images from a camera positioned at different positions and pointing at the same object [33, 9, 23]. Some analysis methods need detailed information about the camera positioning parameters, but there are also analysis methods from photographs with unknown parameters [8].

This method has the advantage of assigning a colour to a point. The file contains the coordinates: the position of the point in three-dimensional space and the RGB. This facilitates the subsequent use of the point cloud to model the shape of the object in BIM programmes. The combination of data collection methods: photogrammetry and laser scanning gives a more complete picture of the virtual twin [10, 18, 22, 23]. Laser measurements require a stably positioned scanner (on the ground or a stable platform), and obtaining data from a higher altitude is possible through the use of drones and lightweight cameras. It is a method of eliminating shadows in areas obscured by other elements. The more accurate the image, the more applications of the virtual model, e.g. in estimating the needs and plans for the renovation of a building [16].

Digital documentation makes it possible to identify object issues more quickly and to use the data in further processes [28], it can also be used to reconstruct partially destroyed historical objects and, together with VR, make it possible to feel spaces [26, 24] impossible to reconstruct in material form.

Access to the tools of digital three-dimensional reconstruction is nowadays possible thanks to mobile phones being equipped with good-quality cameras and thanks to available applications [30]. With a phone, it is not only possible to collect data, turn it into a 3D model in an app, but also send it to the recipient allowing collaboration on the same digital model in AR [25].

There are detailed descriptions in the literature of the use of photogrammetry for inventory purposes, not only of buildings, but also of large areas or forests. In the described cases, various types of buildings and data processing software are presented, but rarely is attention paid to the conditions and method of taking photographs and the differences depending on the shape of the object.

The aim of the conducted research is to analyse the conditions of taking photographs and the methods of their transformation into a point cloud, as well as to check how and whether the complexity of the shape of the façade influences the accuracy of the 3D model made on the basis of the point cloud. The synthesis is based on tests carried out on various cubic objects using variable photographing parameters and computational algorithms. The article presents an analysis of the effects of photogrammetric measurements and recommendations for taking photographs and processing them to obtain a point cloud useful for making an inventory documentation of the building façade.

2. MATERIALS AND METHODS

2.1. Camera

While it is possible to take images for photogrammetry with a camera built into a smartphone, the best camera will be one that allows for extensive manual exposure settings.

An important aspect when choosing a camera is the size of its photosensitive sensor:

- for better results, it is recommended that the matrix size be no smaller than 1/2.3"; this is because the size of a single pixel should be larger than 2µm [28],
- the size of the pixels is more important than the number of pixels, therefore it is recommended that for SLR cameras with large sensors and a very large number of pixels (e.g. a full-frame camera with a resolution of 36 Mpix), photos should be taken at a lower resolution than the maximum available for the camera [28].

The lens should be selected according to the prevailing lighting conditions, the location of obstacles in the field, and the ability to move around. For full-frame cameras, lenses with a focal length of 25 mm to 50 mm are recommended [28], and for cameras with an APS-C sensor and smaller, lenses with a focal length of 18 mm to 35 mm are recommended, due to the crop of the image being taken [28]. Many programmes automatically interpret information about different lenses and sensors, calibrating the images taken between them. However, it is advisable to use tools with the same parameters if possible. This will speed up the reconstruction process and reduce the likelihood of errors [28].

Photographs are taken from the ground using cameras with manual or automatic settings and from a higher altitude using drones, which can have cameras mounted from above or below. When photographing canopy or bridge objects, it is useful to use a zenithal camera setting [19].

2.2. Lighting conditions of the photographed surface

Avoid direct light sources that can cast harsh shadows and hide other areas of the surface [35] – so it is worth avoiding sunny days, especially at sunrise or sunset. Overexposure is also undesirable, as it can be interpreted as a cavity lacking a clear texture or changing position with the movement of the observer.

Photography in very dark lighting conditions, which will require an increase in ISO or a decrease in aperture, is not recommended – noise and shallow depth of field is detrimental when creating texture from motion [35].

Light reflecting off shiny surfaces is a problem for 3D scanning, but photometric stereometry exploits the change in shadow and glare with varying angles of illumination [12].

2.3. Transforming images into a virtual 3D model

The larger the object and the more images taken, the more computing power and time is needed to perform the analysis. Conducting the calculations in the cloud offers the possibility to use a better class of computers and receive results faster [11].

For the analysis of different objects and the subsequent use of the 3D model, software from different manufacturers is used. A unified file-sharing standard gives greater freedom of choice of tools. One of these is the E57 format developed by The American Society for Testing and Materials for 3D image data, regulated by ASTM E2807-11(2019) [5, 1].

There are various programs for photogrammetric analysis. Some are available as paid subscriptions or offer free educational versions with limited capabilities. There are also programs that are completely free. The effectiveness of the programmes varies. The two programmes described below were used in the research described here.

2.3.1. Zephyr 3DF

The publisher offers a full version of the programme with no restrictions and a Lite version limited to 500 images – both are chargeable. A free version limited to the analysis of 50 photos is also available.

The programme analyses data from photographs and/or selects frames from a video. It is based on a multiview-stereo algorithm, which is completely automatic and even with a small number of photographs correctly fills in the gaps in the point cloud. The programme has many functions – it is possible to edit models, create orthophotos, make digital elevation models (DTMs), manage laser scan data and calculate area, volumes, angles, contour lines, etc. [35].

The programme has an easy-to-understand interface guiding through the steps of point cloud and model mesh reconstruction.

The point cloud resulting from calculations performed in 3DF Zephyr can be exported in the following file formats: PLY, PTS, PTX, XYZ, TXT, LAS, E57, DXF. For example, E57 and XYZ files can be directly imported into Archicad, and PTS, PTX, XYZ, TXT, E57 and LAS files can be imported into Recap (Autodesk) and then exported into Revit. The point cloud obtained from photogrammetry is the same as the point cloud obtained by 3D laser scanning and can be used to model the shape of the building façade.

The dense point cloud can be converted into a spatial mesh of triangles approximating the surface and exported in the following file formats: PLY, STL, OBJ/MTL, WRL, FBX, PDF 3D, Universal 3D, Collada. Most of these file formats can be opened in Blender (freeware), in which geometry can be easily edited and exported in the same or other formats. Files in Collada and STL formats can be opened directly in Archicad.

2.3.2. Visual SFM

A completely free programme for creating a point cloud in PLY output format. The number of images to be uploaded is unlimited.

VisualSFM is a GUI application for 3D reconstruction using structure from motion (SFM). It uses multi-core parallelism for surface detection and matching [3]. Uses several proprietary tools to improve final results. It is not too complex and has a simple interface.

Conversion in an external program such as MeshLab is required to obtain the point cloud in the popular TXT or E57 format.

3. CASE STUDIES

In the preliminary studies, a number of photogrammetry trials were carried out on objects of different sizes and textures under different lighting conditions. The two programmes described above were used for the analyses in order to select one with the best efficiency. The conclusions from these analyses were used in the research presented in this article. Suitability assessments were conducted by visually comparing the shape of the features and selected distances measured in the real object and in the point cloud. The procedure of the conducted research was as follows:

- measurement stage:
  - taking photographs from ground level and from a drone,
  - measuring with a yardstick and rangefinder the distance between the selected control points,

- data processing stage:
  - two software programs were used in the preliminary studies: Zephyr 3DF and VisualSFM,
  - Zephyr 3DF software was selected for use in the survey of subsequent buildings,
  - export of point cloud to E57 format,
- modelling stage:
  - importing the point cloud and modelling in Archicad,
  - file format conversion in Recap, point cloud import and modelling in Revit,
- accuracy analysis stage:
  - comparison of the control dimensions of the actual building with those of the model,
  - analysis of the scatter width of the position of points on the plane.

Four objects were selected for analysis:

- A – a small building,
- B – a detail with a complex shape of a roofed belfry truss,
- C – a multi-storey building with a brick façade,
- D – a medium-sized building with a slope roof.

3.1. Small building

Photographs were taken of a small single-storey building with a simple shape. The façade was white in colour and the roofing was grey trapezoidal sheet metal. Approximately 40 photos were taken from the ground level and approximately 50 photos from the floors of the two neighbouring, taller buildings.

Fig. 1. Example photos of the building from the series – view of the roof

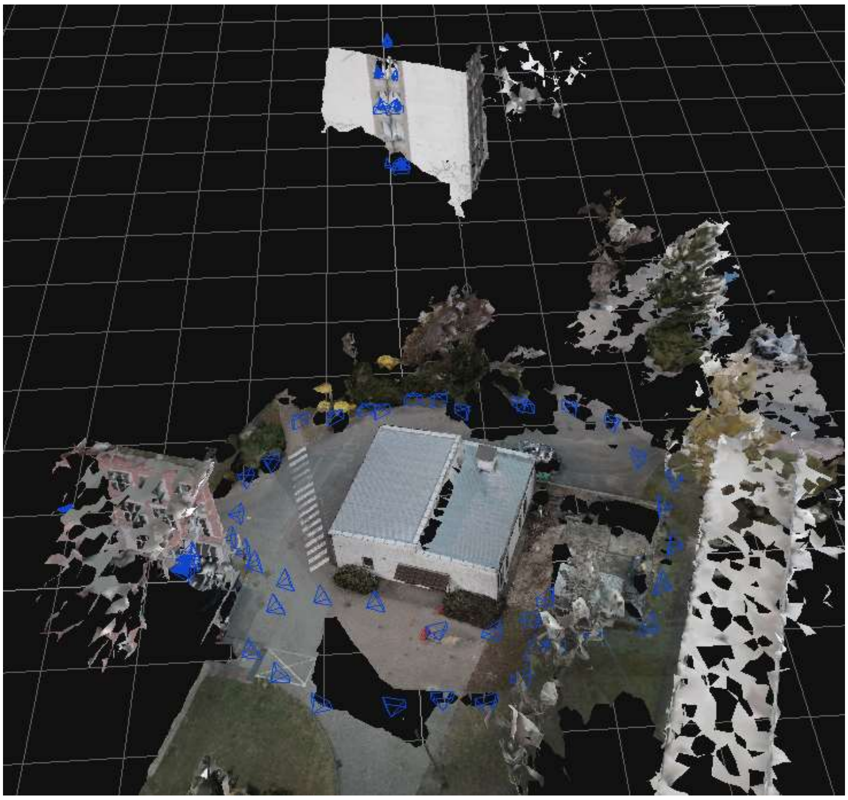

Fig. 2. The location and orientation of the photographs used are shown as dark blue symbols

A Sony a6300 camera with an APS-C sensor of 24.2 Mpix and 16mm and 50mm lenses was used for additional roof shots, due to the considerable distance.

The day was slightly overcast and there were no harsh shadows. The location and orientation of the images can be seen in Figures 1 and 2.

Two programs were used to develop the point cloud: Zephyr 3DF and the Visual SFM programme.

3.1.1. Zephyr 3DF results

The programme correctly reconstructed the structure of the building despite the limited access and the photographs of the roof in a distant view. By using a larger focal length lens, Zephyr 3DF correctly generated the surface points of the roof and attics with greater detail despite large areas with few elements and details.

A noticeable error in the model (Fig. 3) is a cavity in the roof area due to the obscuration and lack of additional images of this area due to the lack of access to the third of the neighbouring buildings.

Fig. 3. 3D model of a small building made in Zephyr 3DF software

3.1.2. Visual SFM results

Despite identical data, the programme misinterpreted the roof surface by generating it shifted in space (Fig. 4). In addition, many cavities appear on the surface of the walls and the roof, which the programme is unable to fill by itself through a uniform texture. The surrounding shrubs for the programme were impossible to reconstruct and voids were created in their places. Despite the glaring deficiencies in the point cloud, it would have been possible to determine the dimensions of the building geometry in Revit, for example.

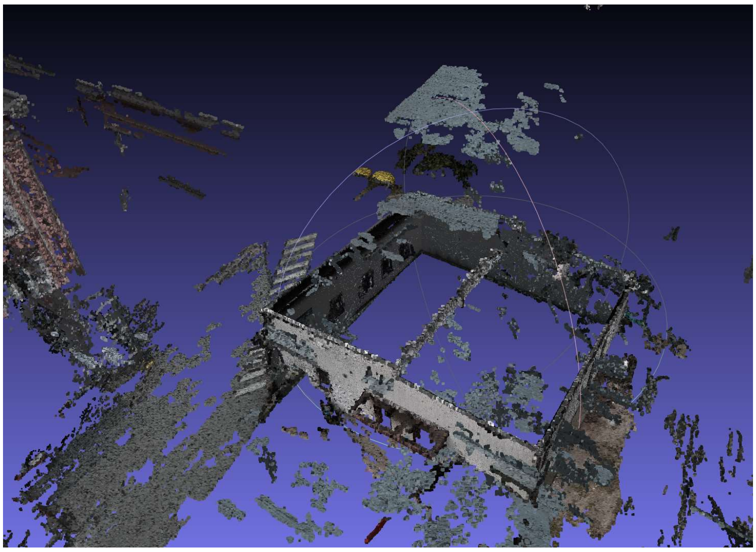

Fig. 4. Point cloud created with Visual SFM software

3.2. A detail with a complex shape

The spatial truss of the bell structure was chosen as a detail with a complex shape. A handicap was the lack of access from one side, so photographs were only taken from three sides. In addition, it was a sunny day, so there was a high contrast between lit and shaded elements. The photographs were taken with a Nikon D5000, 12 Mpix DSLR camera, AF-S 18-55 mm, 1:3.5-5.6G lens with manual focal length adjustment. The contrast parameters of the photographs were automatically selected when the shaded area under the canopy was indicated.
Analysis of the photographs, the point cloud and the three-dimensional model were performed in 3DF Zephyr Pro software. The results are shown in Figure 5.

Fig. 5. 3D model of a complex shape made in Zephyr 3DF software

Despite the difficult lighting and access conditions, the shape of the canopy truss is legible and can be used for inventory modelling. It is necessary to take some measurements of the available elements in order to scale the object.

3.3. Multi-storey building

A multi-storey building with a brick façade and smooth roof surface was chosen. There were a large number of corners on the walls, particularly at window openings and cornices. The photographs were taken in two stages.
In the first stage, the photographs were taken from a drone with a camera with the following parameters: DJI Mini 2, 1/2.3 CMOS 12 Mpix camera, f/2.8. The roof is not shaded and the day was sunny, but shadow was only present in small areas next to the chimneys.

The second stage used a Samsung Galaxy S7 mobile phone camera with the following specifications: 12 Mpix, f/1.7 26 mm. Photos and videos were taken from the ground, at different angles to the front wall surface. The façade was mostly in shadow (except on the top floor).
The location and orientation of the photographs taken are shown in Figure 6.

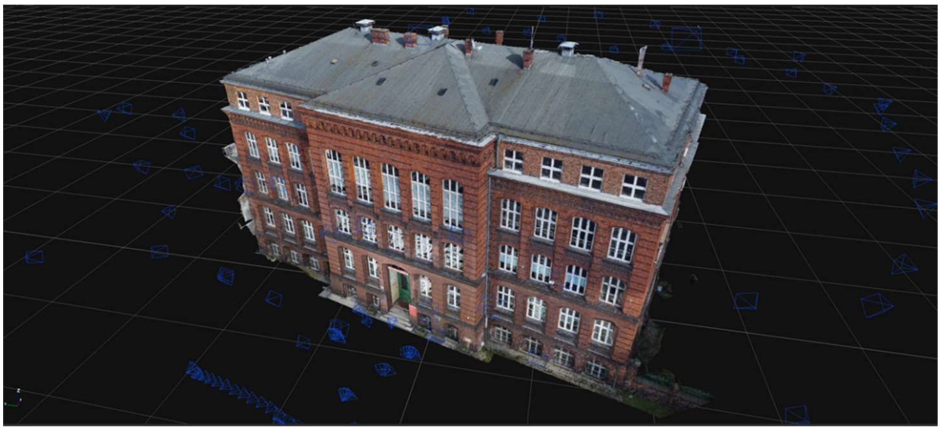

Fig. 6. Location of photographs taken

Analysis of the images, the point cloud and the three-dimensional surface were performed in 3DF Zephyr Pro software. The results from the first stage are shown in Fig. 7.a, and from the combined first and second stages in Fig. 7.b.

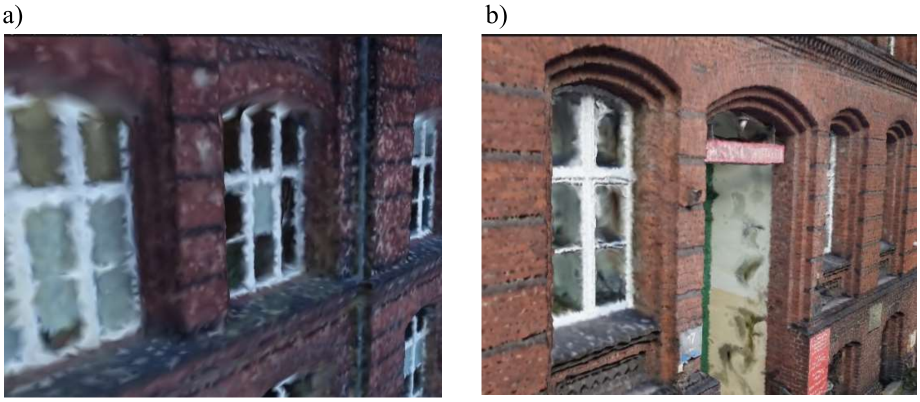

Fig. 7. 3D model of a multi-storey building made with Zephyr 3DF software: a) from the drone only, b) from the ground and from the drone

The model obtained from images from different heights is more accurate. Errors in areas with little data are eliminated.

3.4. Medium-sized building

Photographs of a medium-sized building were taken on an overcast day (no clear shadows): approximately 100 photos with a camera from ground level and approximately 100 photos from the air using a drone.
The camera used was a Sony a6300 APS-C 24.2 Mpix, 16mm and the drone: DJI Mavic Air 1/2.3" CMOS 12Mpix, 24mm. The locations and orientation of the images can be seen in Figure 8.

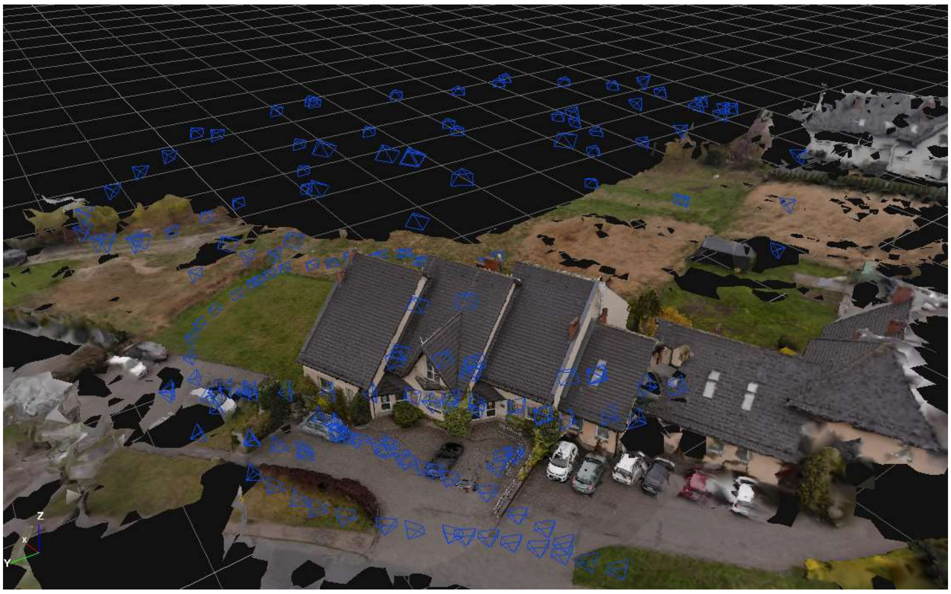

Fig. 8. Location and orientation of photographs of a medium-sized building

Analysis of the images, the point cloud and the three-dimensional surface were performed in 3DF Zephyr Pro software. The dense point cloud and the model made in Revit were compared with the drawing documentation (Fig. 9). The point cloud corresponds to the drawing documentation with slight deviations of a few centimetres, which can also be caused by the actual state of the building differing from the design.

Among other things, the point cloud allowed a clear interpretation of the edges of external walls, their corners or the double-hung window visible in Figure 10 as a double recess in the façade. Despite the visible points of the shrubbery adjacent to the wall, it is possible to define the edge of the wall thanks to the possibility to change the level and depth of visibility of the projection according to preference.

Fig. 9. Horizontal section of point cloud and sub-drawing from drawing documentation

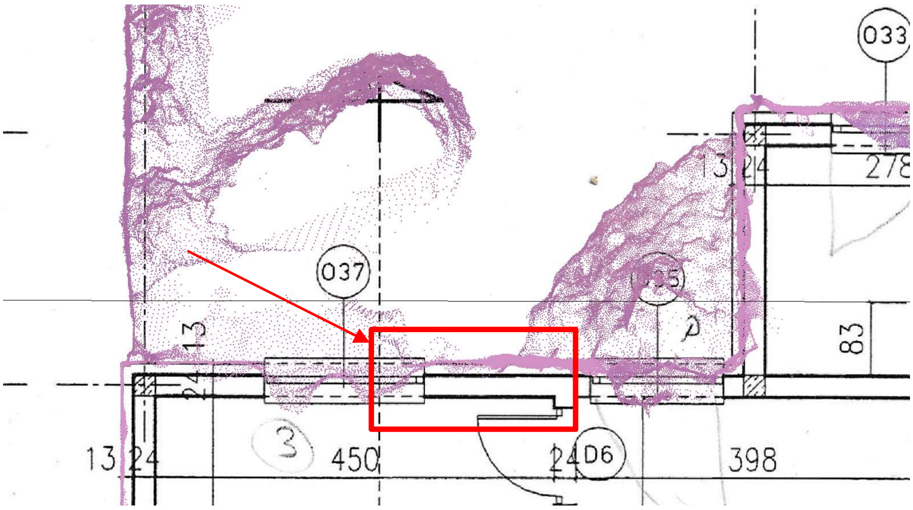

Fig. 10. Fragment of a point cloud with visible subdivision from drawing documentation

By using only a point cloud in the plans and views, it was possible to create a model of the building's elevation and the roof in Autodesk Revit (Fig. 11).

Fig. 11. Building model made in Autodesk Revit based on a dense point cloud

4. ANALYSIS OF RESULTS

The time required to generate the point cloud and 3D mesh in the programme depends on the number of photographs and the selected parameters for the accuracy of the results generation.

This photogrammetric analysis is based only on photographs – for this reason, the scale of the model imported, e.g. into Revit, is highly likely to be skewed in contrast to clouds created with laser scanners, which simultaneously measure distances. It is therefore necessary to scale the point cloud to a value corresponding to reality. To do this, it is necessary to know some reference dimensions of the building (measured in situ). It is then necessary to measure the distances on the cloud at the locations corresponding to the measurements taken. Knowing the length of a given part of the building in the real world and in the point cloud, it is possible to calculate the current scale and how many times the cloud needs to be increased/decreased to coincide with the real state, so that the scale of the cloud and the object is 1:1. It is also worth noting the orientation of the point cloud in all three planes of rotation.

Photographs taken from one level give an incomplete picture of the three-dimensional shape due to the lack of data not covered by the photographed area. Taking photographs from the ground lacks information about the shape of the window sills, and photographing from a drone the edges of the window at the lintel are not visible. Only a combination of views from two heights gives satisfactory results.

An object with a complex shape can also be imaged with a point cloud and a three-dimensional mesh approximation. This requires more photographs to be taken, as some may not be suitable (the algorithm itself chooses which photographs it uses for analysis): out of 43 photographs, only 17 were used, yet in the visual analysis the result is satisfactory and the model can be used as an indicative reference object.

A point cloud imported into a programme in which a building can be modelled three-dimensionally is a reference object. The displayed small-depth sections of vertical and horizontal plans shows the shape, dimension and location of the elements on the façade. Figure 12 shows an example of cross-sections: a horizontal one at the height of the window openings and a vertical one also passing through the windows. It is possible to determine the dimensions using the projection and section of the point cloud, where the opening is interpreted as a cavity in the wall contour. However, if the window was not captured by close-up photographs with sufficient detail during the cloud reconstruction, it is likely that the openings will be difficult to interpret and approximate. The point cloud also allows the window to be interpreted as double-hung not only from the elevation view, but also on the projection in the form of two recesses in the wall edge.

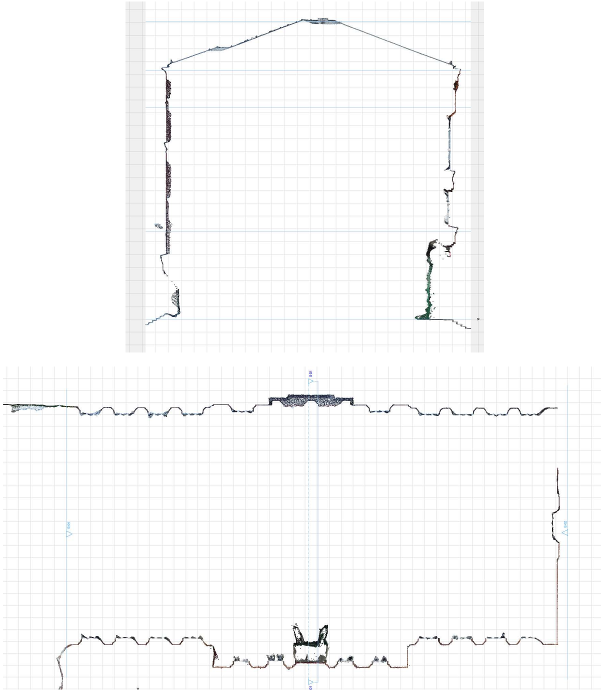

Fig. 12. Vertical and horizontal section of a dense point cloud in Archicad

The point cloud can also be used in the 3D view to refine the shape of elements on the façade (Figs. 13 and 14).

Fig. 13. Example of lintel detail modelling in Archicad using a point cloud

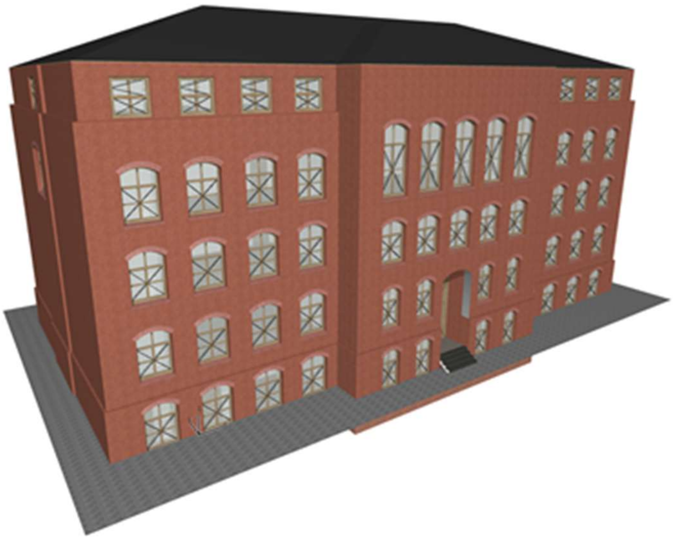

Fig. 14. Model of the building made using, among other things, a point cloud obtained from photogrammetry, created in Archicad (without modelling details on the façade yet)

More work is required to accurately model the decorative elements of the façade, but this is easier with a reference object underlay (Figures 15 and 16).

Fig. 15. Façade detail modelled in Archicad (model author: Jan Okoniewski, ZSB in Poznan)

Fig. 16. Railing detail modelled in Revit

The optimum solution is to check the dimensions of the openings both on the facade and on sectional views. In order to determine the exact dimensions of the individual joinery components from the elevation view, such as frame widths or glazing dimensions, it is necessary to reconstruct the point cloud in high resolution, which allows a clear interpretation of the edges and a simple connection of the points in the approximation in Revit.

An analysis of the accuracy of the point cloud was carried out. The scatter of points that should be on the plane was analysed (Fig. 17). When modelling a single wall, its start and end coordinates are chosen – these coordinates will be the points of the cloud. However, the points that constitute the wall in a shallow depth projection do not form a one-dimensional line, but are scattered over a certain width. For the accuracy analysis, the thickness of the point cloud was determined for each wall. This made it possible to estimate with what accuracy its location is determined. The width of the point cloud was measured at three randomly selected locations, then the arithmetic mean and standard deviation of the mean were calculated. Due to the small number of measurements, the Student-Fisher coefficient was taken into account. The data are presented in table 1.

Table 1. Width [cm] of point cloud with measurement error

A		B		C		D	
No.	Section width of the point cloud	No.	Section width of the point cloud	No.	Section width of the point cloud	No.	Section width of the point cloud
A.1.1	0,4	B.1.1	1,3	C.1.1	2,3	D.1.1	1,1
A.1.2	1,1	B.1.2	1,4	C.1.2	1,1	D.1.2	0,8
A.1.3	2,1	B.1.3	0,8	C.1.3	3,5	D.1.3	0,9
A.2.1	0,4	B.2.1	1,6	C.2.1	1,1	D.2.1	0,5
A.2.2	2,9	B.2.2	0,7	C.2.2	4,7	D.2.2	0,6
A.2.3	1,7	B.2.3	1,5	C.2.3	3,3	D.2.3	0,5
A.3.1	3,5	B.3.1	1,8	C.3.1	1,3	D.3.1	1,1
A.3.2	0,9	B.3.2	0,9	C.3.2	2,8	D.3.2	0,7
A.3.3	0,5	B.3.3	2,0	C.3.3	5,1	D.3.3	4,0
A.4.1	3,1	B.4.1	2,1	C.4.1	2,1	D.4.1	0,5
A.4.2	3,4	B.4.2	2,2	C.4.2	4,6	D.4.2	0,9
A.4.3	3,0	B.4.3	1,3	C.4.3	5,0	D.4.3	0,6
A.5.1	0,6	B.5.1	0,7	C.5.1	1,9	D.5.1	0,6
A.5.2	1,6	B.5.2	2,5	C.5.2	6,4	D.5.2	1,1
A.5.3	2,0	B.5.3	1,7	C.5.3	0,8	D.5.3	0,6
Average	1,8	Average	1,5	Average	3,1	Average	1,0
Standard deviation of the average	1,1	Standard deviation of the average	0,6	Standard deviation of the average	1,7	Standard deviation of the average	0,9

The range and average thickness of the dense point cloud on the wall was, for:

- A (small building): 0.4-3.5 cm, average 1.8±1.4 cm,
- B (detail): 0.7-2.5 cm, average 1.5±0.6 cm,
- C (multi-storey building): 1.1-6.4 cm, average 3.1±1.7 cm,
- D (medium building): 0.5-4.0 cm, average 1.0±0.9 cm.

In comparison, a 3D scan made with a laser scanner had a spread of 0.3–0.8 cm, with an average of 0.6 cm.

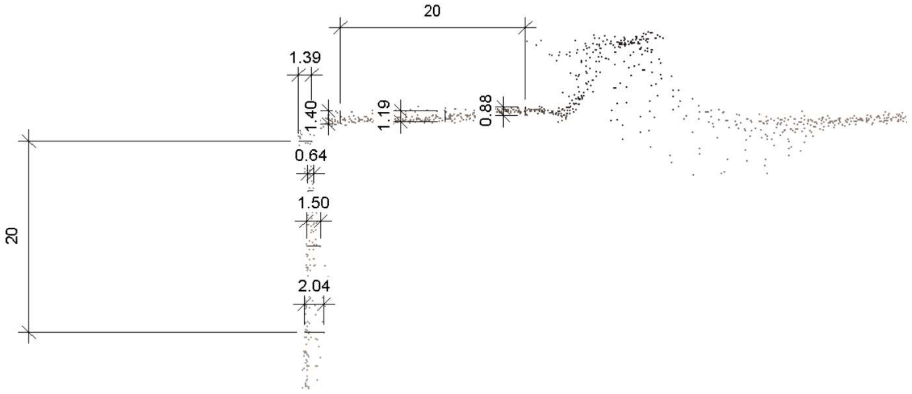

Fig. 17. Enlargement of building corner with marked measurements of point cloud thickness [cm]

The second aspect of the accuracy analysis was to compare the lengths of the sections selected for comparison in each case study separately. Five sections were selected for the larger buildings and three sections for the smaller buildings. Each measurement was taken 5 times. The length of each section in the actual building was measured with a yardstick or laser rangefinder. 1 mm was taken as the accuracy of the measurement. The same distances were measured in the point cloud and in the model made from it. A measurement accuracy of 1 mm was assumed. The dimensions of the medium-sized building were additionally compared with the drawing documentation. The differences in dimensions ranged from 0 to 3 cm, with an average of 1.6 cm. Comparison with the background in the form of a scan from the design documentation made it apparent that there were inaccuracies in the workmanship of the building. The wall was found to be offset by 26 cm and there were no right angles between adjacent walls. Many slight errors are very often due to the approximate position of the element in relation to the points of the cloud. Table 2 shows the average lengths of the individual model control sections, the point clouds and the actual building dimensions, as well as the differences in average lengths, together with the calculated measurement error. The difference in the length of the control sections between the average actual dimension and the model was, for case:

- A (small building): 2.3±0.5 cm,
- B (detail): 1.8±1.7 cm,
- C (multi-storey building): 1.7±4.2 cm,
- D (medium building): 1.5±1.3 cm.

In most cases, the model was slightly larger than the real object. The largest difference in dimensions was for case A (small building), but was only slightly larger than the differences in the other cases. The largest measurement error was obtained in case C (multi-storey building).

Table 2. Average lengths of control sections and length difference

No.	Dimension of the model	Average dimension of the point cloud	Standard deviation of the arithmetic average	Average actual size	Standard deviation of the arithmetic average	Length difference in dimensions between actual and model	Difference in dimension length between actual and average point cloud
A.1	731,5	731,0	1,3	729,3	0,8	-2,2	-1,7
A.2	431,2	430,0	0,9	429,3	0,8	-1,9	-0,7
A.3	777,1	776,8	0,9	774,3	1,1	-2,8	-2,5
Arithmetic average of the difference						**-2,3**	**-1,6**
Standard deviation of the arithmetic average including Student-Fisher coefficient						**0,5**	**1,0**
B.1	477,8	478,4	3,4	474,2	0,6	-3,6	-4,3
B.2	165,3	163,5	2,5	164,5	0,7	-0,8	1,0
B.3	13,0	13,1	0,4	12,0	0,1	-1,0	-1,1
Arithmetic average of the difference						**-1,8**	**-1,5**
Standard deviation of the arithmetic average including Student-Fisher coefficient						**1,7**	**2,8**
C.1	1629,3	1628,9	4,4	1630,4	0,8	1,1	1,5
C.2	471,2	414,1	119,2	479,0	1,0	7,8	4,9
C.3	1109,0	1112,3	454,1	1104,3	0,9	-4,7	-7,5
C.4	463,5	464,0	2,0	467,9	0,8	4,4	3,9
C.5	220,0	222,9	1,7	219,8	0,3	-0,2	-3,2
Arithmetic average of the difference						**1,7**	**-0,1**
Standard deviation of the arithmetic average						**4,2**	**4,6**
D.1	695,3	695,1	1,1	693,3	0,6	-2,0	-1,7
D.2	272,0	272,2	0,7	272,2	0,7	0,2	0,1
D.3	729,4	730,2	1,4	726,7	1,2	-2,7	-3,5
D.4	288,0	288,6	0,8	285,1	0,4	-2,9	-3,4
D.5	736,1	736,3	0,6	735,9	0,8	-0,2	-0,4
Arithmetic average of the difference						**-1,5**	**-1,8**
Standard deviation of the arithmetic average						**1,3**	**1,5**

5. CONCLUSIONS

Photogrammetry is a very useful tool for improving and speeding up the designer's work. It is important to take the photos correctly and to become familiar with the capabilities of the programme being used. The quality and final results obtained in photogrammetric analysis programmes vary. A major advantage is that there is no need for specialised equipment such as a LIDAR laser scanner, only a camera. The technology is being developed and is also available from smartphone apps giving more and more possibilities.

Based on the research, the following recommendations were made:

- photographs should be taken under favourable lighting conditions, i.e. sharp shadows should be avoided,
- it is most advisable to take photographs during a cloudy day (grey skies) when sunlight is diffused and objects are evenly lit,
- uniformly textured surfaces can be difficult for software to interpret and should therefore be avoided or supplemented with more textured photos,
- if possible, it is advisable to take photographs of buildings from ground level and from the drone, as this gives the best complete results,
- use cameras that allow manual settings of exposure and white balance,
- it is advisable to use wide angle lenses, but if necessary due to the distance of the subject, longer focal length lenses can be used,
- photographs should be taken in large numbers; each part of the scene should appear in at least three separate views,
- keep the object in the centre of the frame,
- do not set a high ISO value,
- it is recommended to keep aperture settings as high as possible for a large depth of field,
- images should be free of blur.

The inaccuracy of the point cloud in the form of point spread for all cases analysed was on average 1.8±0.4 cm, so it is higher than for the 3D laser scan, for which it was 0.6 cm. The largest measurement error was obtained for the multi-storey building. This may be due to the distance of the higher storeys from the ground-level photograph and the lower storeys from the drone's flight level.

The detail of the bell tower was not modelled in its entirety, despite capturing the entire building in the frames. This may be due to the difficulty in interpreting the photographs by the software due to the similarities in colour and background in the lower part of the columns. It would be necessary to repeat the photographs under different lighting conditions when the shadows are less sharp.

No difference in model accuracy was observed depending on the complexity of the shape.

When using the point cloud as a reference object, the scatter of the position of the points relative to the plane must be borne in mind. Confidence in the dimensions must also be limited due to the need to scale the point cloud. The final dimensions will depend on which point is selected for scaling.

Despite the inaccuracies presented, it was considered beneficial to use the point cloud obtained through photogrammetry in the inventory. The reference object underlay facilitates modelling and orientation in the shape of the object. If greater model accuracy is needed, a 3D scan should be used.

Making an inventory of the façade of a building, especially one with multiple storeys or a complex shape, requires time spent on detailed measurements. Sometimes it is necessary to use scaffolding to obtain measurements at height. Using the described method to collect building shape data is non-invasive and quick, and the results in the form of a point cloud or three-dimensional model can be directly transferred into a programme where a virtual twin can be modelled and documentation drawings can be obtained automatically with quantitative statements generated.

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