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Original article

Assessment of the building's geometry and technical condition on the basis of the data acquired by means of 3D terrestrial laser scanning

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ABSTRACT

3D terrestrial laser scanning is a non-invasive method for capturing data of building objects. A point cloud obtained through measurement provides the basis for assessing the building's architecture and its finish details, analysing its technical condition and reproducing its construction system. Digitalised data can be used to describe the object's geometry and to analyse its damage and defects.

The paper describes, using examples, methods for examining the geometry of the historic building, whose structural condition has also been assessed.

KEYWORDS

3D laser scanning, reverse engineering, historic building, architectural and engineering documentation, wooden structure, structural condition

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Introduction

The 3D terrestrial laser scanning technology makes it possible to capture automatically raw spatial data of actual building structures in the form of a three-dimensional point cloud, providing the basis for further modelling in the virtual world. Individual points can be described in the 3D space as laser scanners measure their polar coordinates. Each of these points is represented by at least three coordinates *(X,Y,Z)* referred to the scanner's local system. Also the fourth coordinate is registered – the intensity of reflection of a laser beam *(I)* [1].

As a result of measurement performed with a laser scanner, a set of points, called a scan, is obtained at each measuring position. A single scan is not sufficient to collect the information about the whole examined object. Therefore, it is necessary to determine the number and location of measuring positions making it possible to visualise the object concerned. Data obtained at respective positions are subject to filtering and oriented. The filtering consists in cleaning the point cloud of all elements of the environment whose measurement was not intended, e.g. trees, cars or people. The orientation is a process of spatial integration of several scans into one point cloud, conducted by means of tie points, represented by the signals specifically set before the measurement is made. Owing to the use of these points the scans from all measuring positions can be combined into a coherent whole. As a result of all these activities a comprehensive data set is obtained, free from the unwanted noise recorded in the local system of coordinates of the instrument. Furthermore, it is possible to measure the coordinates of at least three control points by employing the classical measurement methods (e.g. GPS). This activity ensures the spatial transformation and conversion of coordinates of all points measured in the local system, in which the scans have been recorded, into the global system [2]. Data in the form of the oriented and clean point cloud are subject to modelling using appropriate software, and its final product is the complete information about the actual geometry of the examined object. In the context of obtaining data by means of a 3D laser scanner, the process is often referred to as digitisation and the device itself is called a digitiser. The digital image of the examined object is obtained through the application of the so-called reverse engineering. In order to obtain additional visual effects the image can be subject to further processing, and the final stage consists in the modelling of the object.

Reverse engineering provides the possibility of imaging the real object in the virtual space. The name of the process reflects accurately the way of performing subsequent activities, i.e. at first, there is a physical object which is digitised by means of scanning and placed in the virtual reality owing to the use of engineering methods. Reverse engineering comprises activities related to the collection of geometrical data of objects, reproduction of the geometry of the measured object and processing of the data to the form acceptable for CAD systems [3].

1. Characteristics of the object of the study

The measurement was conducted in Klewki, a location in the Warmia-Mazury Province (Poland). The historic St. Valentine and Roch's parish church has been selected as the object of the study. The first temple building was erected in this place approximately in 1352. Unfortunately, it was burnt at the beginning of the 15th century. The church was rebuilt, but it experienced another fire in 1718. During its reconstruction some parts, e.g. windows, were redeveloped. In 1829, the subsequent redevelopment took place, during which a timber tower was erected. The church is buttressed, which means that vertical counterforts have been used in it as structural members, transferring the load to the foundation and strengthening the walls. It is a Gothic church built of bricks and field stones. The timber tower adheres to its western side and the sacristy is located at the northern side (Fig. 1). The main body of the building is covered by the ridge roof, made as double collar-beam timber structure.

Fig. 1. North elevation of the church in the form of a point cloud with the superimposed photos
Source: Own work.

2. Assessment of the geometry and technical condition of the structural members

2.1. Survey of the structure

A laser scanner is an irreplaceable tool for surveying the structure. It is particularly useful when hard-to-access structures are surveyed. Examples of such structures include rafter framing, high ceilings or objects facing a threat of collapse. The laser scanning technology makes it possible to complete the tasks without the necessity of placing scaffolding, owing to which people performing the measurement do not have to work at heights, as the measurements can be taken from a significant distance. On the basis of the obtained point could the detailed survey of the object can be prepared, accurately reproducing the as-is condition of the structure, which is very important for increasingly often used design standards relying on the BIM technology (Building Information Modelling). It also gives the possibility of entering the acquired data to calculation programs and performing structural calculations for control purposes.

The completed surveying, being the real presentation of the as-is condition of the building, makes the assessment of the building's geometry a lot easier. The survey documentation is most often used to prepare renovation and repair works for the object [1]. It usually includes scaled plans of respective floors. Owing to the high accuracy of the scanner and the speed of taking measurements, the drawing of a plan of the object takes little time and any dimension can be checked. The completion of accurate survey measurements of the building offers the possibility of creating the three-dimensional model of the structure taking account of any damage and deformations. Such model, having been transferred to a calculation program, provides the possibility of making calculations for control purposes and verifying the behaviour of the structure under specific design conditions. Furthermore, being aware of such damage as the weakening of the cross-section or deflection, it is possible to foresee the consequences of the lack of repair or the further progression of damage. In addition, the scanning data can be used for a precise measurement of the surface area, owing to which it is easy to evaluate the scale of damage in the examined structures.

Fig. 2. Longitudinal section made using a point cloud with the discussed issue marked
Source: Own work.

In the course of research making use of a point cloud, the structural members of the church were identified. Measurements covered the whole of this typical sacral building. A rood beam, placed over the nave, turned out to be an interesting element. This architectural member usually performs a decorative function. However, after the longitudinal section of the object was prepared on the basis of the point cloud, it was observed that it performed also a structural function and it was positioned exactly in the same place as the rafters, thus forming a complete truss (Fig. 2). Between the fink trusses and also between the truss and the wall, the fixed number of attic trusses can be found. It shows certain dependencies exploited by the designer. It is difficult to notice these dependencies during the site inspection, as it is impossible to see all structural members of the roof at the same time. Thus, laser scanning made it possible to analyse the structure and describe the characteristics of the rafter framing and its component parts.

2.2. Measurements of structural members in the point cloud

The analysis of a point cloud provides the basis for the determination of the geometry of the whole building or any part thereof by reading such values as length, width or even deflection or deviation from the axis. It is possible to measure distances between specific points (Fig. 3) in the point cloud or angles between planes or points, thus providing the initial assessment of dimensions of the structure and its members. However, to arrive at more accurate geometrical parameters obtained from the point cloud it is necessary to adopt the appropriate system of coordinates and the position and direction of the axis.

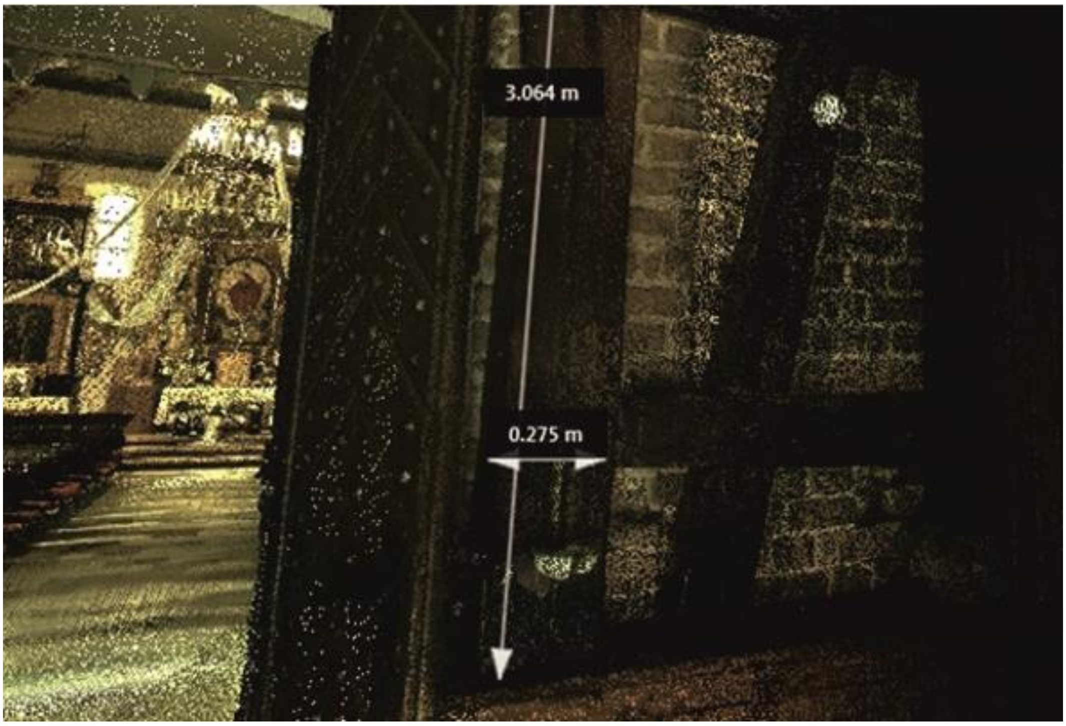

Fig. 3. Simple measurements taken on the scan
Source: Own work.

Measurements with a scanner are taken using a levelled tripod, owing to which the scanner can determine the vertical direction and plot it in the form of a system of axes onto the point cloud. The laser scanner used in research, ScanStation C10 made by Leica, supports a two-axis compensator, which automatically corrects minor deviations in the position of the scanner. However, if the deviation of the scanner exceeds the operating range of the compensator, the instrument reports an error and discontinues scanning. In such case it is necessary to level the instrument again manually.

In the computer program there is a possibility of shifting the centre of the coordinate system to any place while maintaining the coordinate axis system. After the transformation of the system, the axes of the new coordinate system *(X'Y'Z')* remain parallel to the axes of the original coordinate system *(XYZ)*. If needed, it is also possible to rotate the coordinate system around one of the axes.

For the assessment of truss members it is necessary to adopt the appropriate coordinate system. One of the axes has to be positioned along the theoretical main axis of the member and the remaining axes in the directions of expected deformation (Fig. 4). Therefore, in the course of analyses the rotation around the *Z* axis was made, owing to which the *X* and *Y* axes could be positioned in the way ensuring the performance of measurements indispensable to assess changes in the geometry of the beam in relation to its longitudinal axis [4].

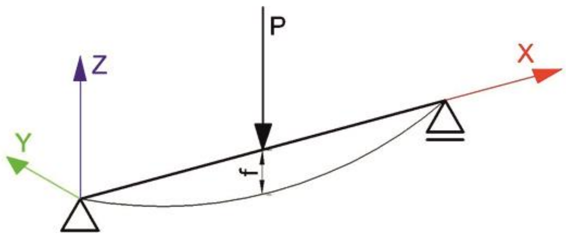

Fig. 4. System of axes for measuring deformations of truss members
Source: Own work.

Measuring points at which the coordinates of the truss were read were placed along the beam (Fig. 5). Theoretically, to measure the deflection of a simply supported bent beam three measuring points are sufficient, one at the centre of the span and two at the supports. However, they are not sufficient in practice, as deformations may be caused by different errors made at the stage of execution or installation, which are unpredictable.

These errors are caused mainly by [5]:

- incorrect fastening of the lines during the lifting operations performed by the crane, which may result in the buckling of slender members or in the operation of these members under load conditions other than the designed ones,
- lack of or improper execution of temporary supports,
- improper transport and storage of prefabricated elements.

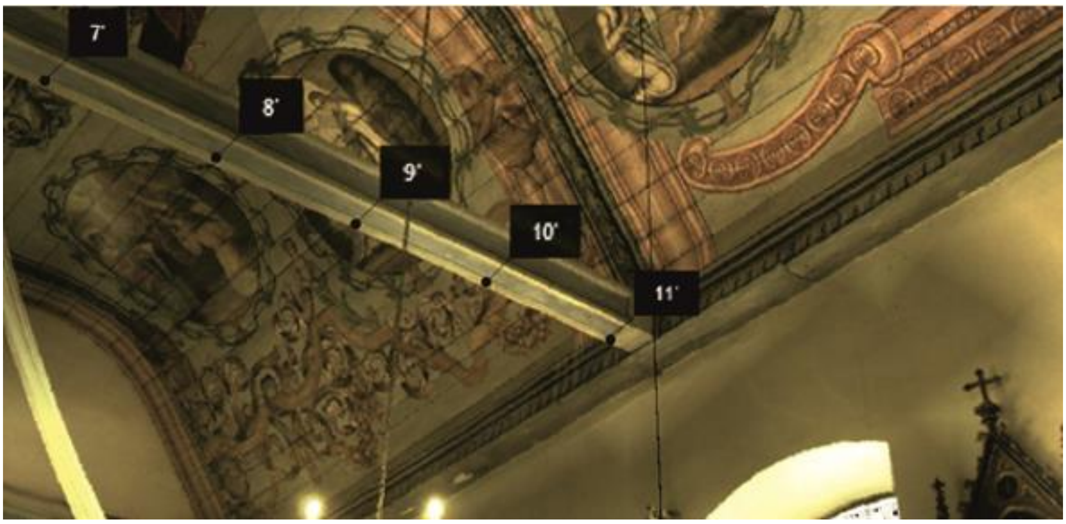

Fig. 5. Examples of measuring points on the rood beam
Source: Own work.

2.3. Assessment of the deformation of the beam

A timber beam located over the nave of the church was examined. In the course of conducted research the analysis of the shape of the beam was made, using two mutually independent reference systems to enhance the reliability of the obtained results. The first new coordinate system *(XYZ)* was established at the point located on the floor (Fig. 6). After adopting the ordinate of the floor at the point of intersection of two diagonals running between the corners of the building *z = 0.00 m*, the coordinates of the points located at the bottom of the beam were read. Analysing the difference in height the deformation of the member can be observed as well as the difference in the height of the support. The second coordinate system *(X'Y'Z')* was created on the beam support (Fig. 6). The set reference plane, passing through the *X'* and *Y'* axes, provides the basis for comparative analysis.

Fig. 6. Established coordinate systems: *(XYZ) on the floor and (X'Y'Z') on the beam*
Source: Own work.

After comparing the results of measuring the beam deformation from the two different reference systems it can be stated that the change in the position of the centre of the coordinate system has no impact on the measurement results (Table 1).

Table 1. Results of deformation measurements

Examined member	Ordinate in relation to the centre of the coordinate system *(XYZ)*	Ordinate in relation to the centre of the coordinate system *(X'Y'Z')*
A support	6.470 m	0.047
B support	6.423 m	0.000
Span	6.433 m	0.010

Source: Own work.

The results of the detailed analysis of the beam deformation are presented in the form of a chart (Fig. 7). It shows that up to the seventh meter the deformation is within the limit of 1 cm, however, after passing this distance the beam is deflected upwards by 4.7 cm in relation to the second support. Such deformations could occur as a result of slipping of the southern wall of the building.

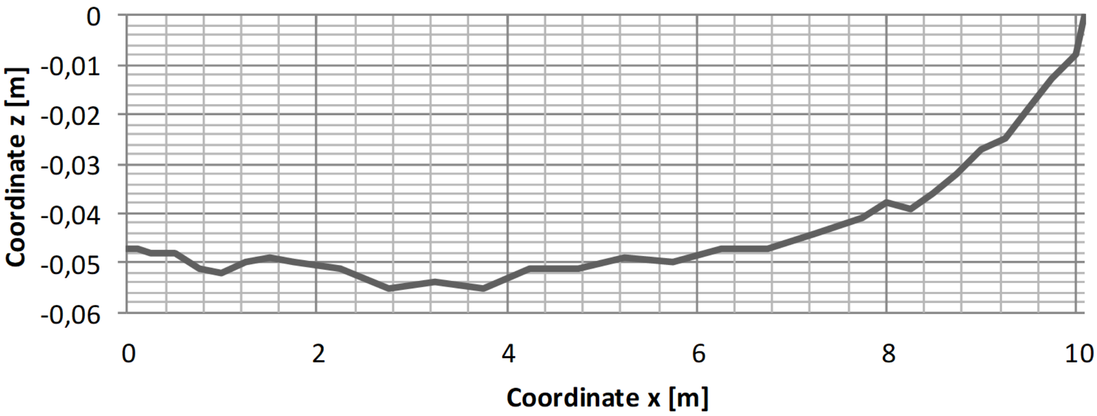

Fig. 7. Results of measurements of the deformation of the beam
Source: Own work.

Standard PN-EN 1995-1-1:2010 [6] specifies the limit bending value for timber members (w_{fin}) which for beam members of the rafter framing is *l/200*. The length of the beam was read from the scan: *l = 10.1 m.* The calculations showed that the limit bending value had been exceeded and it totalled (1):

$$w_{fin} = \frac{10100}{200} = 50{,}5mm < \ w \ = \ 55mm \tag{1}$$

The standard [6] provides for increasing the limit value by 50% for calculations for members of old and renovated objects. When the above assumption is adopted, the condition is not met, while the limit bending value is not exceeded (2):

$$w_{fin} = 1{,}5 * \left(\frac{10100}{200}\right) = 75{,}75mm > w = 55\ mm \tag{2}$$

2.4. Determination of the member's cross-section – measurement of the column's crack

Data obtained from the measurements taken with a scanner make it possible to read from the point cloud the dimensions of the cross-section of the structure with the use of the basic measuring functions available in the programs for point cloud processing. When the accuracy of the conducted measurements is appropriately increased by the densification of points and spacing of the measuring positions in relation to the examined object, it is possible to measure the surface area of the weakened cross-section.

Table 2. Decrease coefficients α and β

Total of cracks	α coefficient	β coefficient
<1/10 of the cross-section width	0.95	0.91
<1/20 of the cross-section width	0.98	0.96

Source: [7].

Timber cracks may have a significant influence on the load-bearing capacity of the cross-section. If for a timber member the total of cracks along the fibres on one side of such member is determined, on the basis of Table 2, depending on whether the said total is smaller than *1/20* or than *1/10* of the width of the member's cross-section, the following coefficients can be adopted [7]:

α – decreasing the surface area of the A element,

β – decreasing the bending strength ratio, W_y, of the cross-section.

To illustrate the above, the analysis focused on the column of the timber tower, located in the vestibule of the church, as during its macroscopic examination a crack, probably caused by drying, was detected. Shrinkage cracks, resulting from varying timber properties (strength, degree of swelling, etc.), occur in the tangential and radial direction (the phenomenon of anisotropy). Below the fibre saturation point (timber moisture of about 30%) non-uniform shrinkage produces stresses which lead to the occurrence of cracks.

In order to read properly the depth of the crack in the column, the coordinate system was oriented on its scan, at the deepest point of the cross-section, so that one of the axes could be positioned in parallel to the face of the column and the other one along the examined crack (Fig. 8). The measurement of the crack depth was taken by setting up a plane in the face of the cross-section and orientating it with reference to the established coordinate system. On the basis of the results thus obtained it was stated that the dimensions of the column's cross-section were 275×235 mm, and the maximum depth and width of the crack running along the whole column were 43 mm and 18 mm, respectively.

Fig. 8. On the left: crack of the column on the digital photo, on the right: point cloud – cross-section of the column with the established coordinate system
Source: Own work.

The spot of the laser used for taking measurements, owing to its small dimensions, makes it possible to measure small cracks and defects. However, it is always necessary to take account of a limitation caused by the impossibility of examining the timber for its internal damage, which the laser beam could not reach.

The weakening of the cross-section caused by cracking was calculated according to the procedure described by Nowak [7] and compared with Table 2, from which the α coefficient, decreasing the surface area of the member, equal to 0.98, and the β coefficient, decreasing the cross-section's bending strength ratio, equal to 0.96, were taken. From the coefficient values it can be inferred that the crack does not have a significant impact on the load-bearing capacity of the structural member. It should be emphasised, however, that its significance in another member, e.g. a bent one, would be different, so the presented method is useful for a relatively quick inspection and identification of damage in the structure composed of numerous elements.

2.5. Examination of damage caused by insects

During the in-situ examination of the structural members of the church tower damage caused by insects from the family Anobiidae was detected, in the area where the beam is connected to the transom (Fig. 9). Therefore, an additional high-resolution scan was made for the timber column located on the second storey of the timber tower, in the staircase used as the entrance to the attic and to the church bell.

Fig. 9. Damage caused by insects
Source: Own work.

To read the depth of the cross-section's damage, a reference plane was established in the point cloud, overlapping the face of the column from its damaged side. Such location of the reference plane made it possible to examine the depth of defects and to evaluate the scale of damage to the structural member. The measurement of the size of the defect was carried out by the determination of the distance from any point (on the defect) in the direction perpendicular to the reference place (Fig. 10).

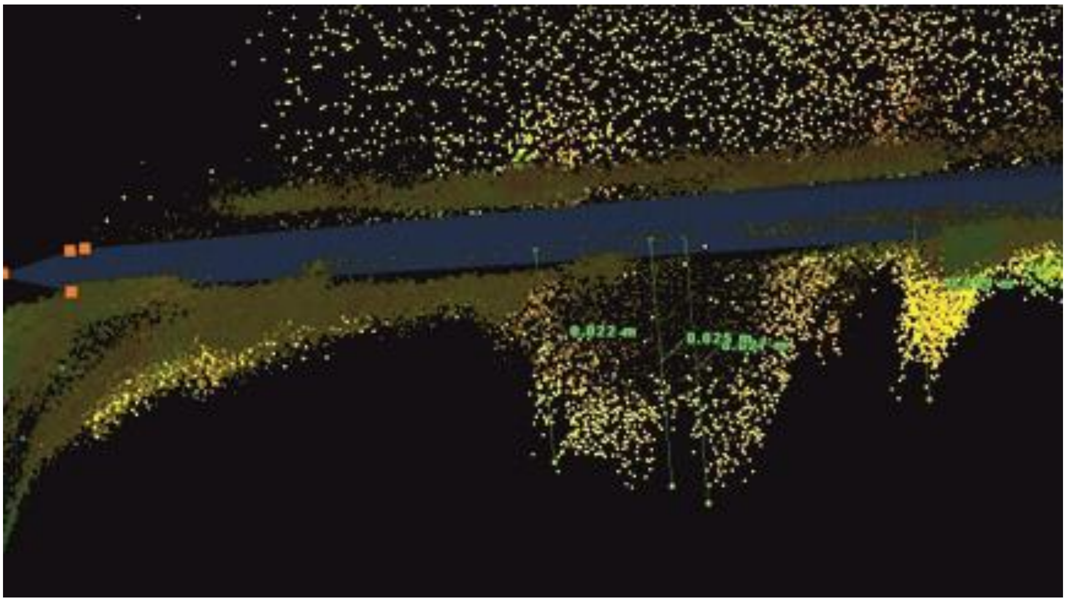

Fig. 10. Taking measurements in the cross-section of the column in relation to the reference plane marked in blue
Source: Own work.

Summary and conclusions

The 3D terrestrial laser scanning technology is characterised by its exceptional speed of measurement accompanied by high accuracy, which renders it very competitive in relation to traditional methods. Furthermore, this instrument operates with the minimum interference with the examined object, which is extremely important during the surveying of historic and hard-to-access objects.

The paper demonstrates that the data captured during the scanning can be used to determine the deformation of the truss members and to record and monitor the irregularities in the geometry of the whole object. The performance of highly accurate in-situ measurements makes it also possible to inspect damage and losses caused by the activity of insects in the structural members made of timber. Also the possibility of establishing the surface area of the weakened cross-section or the size of cracks may facilitate the identification of the structure's behaviour during its further operation and planning of indispensable repairs to prevent the occurrence of its instability.

On the basis of the obtained results it can be stated that a 3D laser scanner can be a useful tool for surveying and assessing the geometry of the building and also for examining the technical condition of the structure. Owing to the quick preparation of three-dimensional models of buildings in this technology, combined with the possibility of inserting annotations and dimensions onto the point cloud, such models may form an integral part of the technical documentation of the object.

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Conflict of interests

All authors declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

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Biographical note

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Ocena geometrii i stanu technicznego budynku na podstawie danych z naziemnego skaningu laserowego 3D

STRESZCZENIE	Naziemny skaning laserowy 3D jest nieinwazyjną metodą pozyskiwania danych o obiektach budowlanych. Dzięki uzyskanej z pomiaru w chmurze punktów można ocenić architekturę budynku i jego detale wykończeniowe, przeprowadzić analizę jego stanu technicznego, a także odtworzyć jego układ konstrukcyjny. Zdigitalizowane dane pozwalają na opisanie geometrii obiektu oraz analizę jego uszkodzeń i wad. W pracy opisano na przykładach sposoby badania geometrii budynku zabytkowego i oceniono stan jego konstrukcji.

| **SŁOWA KLUCZOWE** | skaning laserowy 3D, inżynieria odwrotna, budynek zabytkowy, dokumentacja architektoniczno-budowlana, konstrukcja drewniana, stan konstrukcji |

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