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Research paper

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Qualitative characteristics of a 3D windmill presentation based on laser scanning and photogrammetry data

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Summary

The cultural landscapes of each country are an important element of its heritage. An excellent example of this is the presence of objects that in the past fulfilled an important industrial and economic function in a region. This group of objects includes windmills, which have lost their economic importance due to ongoing industrialisation. However, their continued presence in the landscape is evidence of the economic development of a particular region. The growing cultural awareness of society and the increased protection of cultural heritage objects mean that windmills, which have been neglected for years, are increasingly subject to conservation measures. In order to carry out preservation work, it is necessary to take inventory and create visualizations of windmills, posing problems in connection with the selection of suitable measurement methods and techniques, as well as the integration of the obtained data. This study uses photogrammetry and laser scanning to measure windmill structure for 3D modeling and visualization. The object of this study was a typical 19th century wooden windmill, which was predominant in western Poland. The research employed the methods of terrestrial laser scanning, airborne laser scanning and low-level aerial photogrammetry. The results of the research were exemplary visualizations of a windmill created from the acquired measurement data, evaluated in terms of their suitability for the further creation of various cartographic representations. In addition, the potential for using the most advantageous source of measurement data about the examined object to develop a conservation tool was identified.

Keywords

3D models • topography • windmill • TLS • UAV • LIDAR

1. Introduction

As a result of progressive technological development, windmills have lost their economic importance, but they still hold the historical value . Considering the fact that many of these objects are deteriorating or have already completely disappeared from the landscape, it is important to develop a methodology to inventory and visualize windmills individually and together with the surrounding spatial structure (geovisualization). With the help of state-of-the-art measurement techniques, new forms of presentation of these objects can be developed for the purpose of conservation, inventory, but also promotion of the tourist aspect of a given region [Smaczyński et al. 2022].

By focusing on the form/geometry itself, we can capture the smallest details the objects and their environments. With such accuracy, we can take care of the object (plan its conservation), but in the case of objects that are have already been destroyed, it is possible to virtually recreate the object in an interesting way to fulfill educational or tourist purposes for future generations. Such studies, which focus on capturing the geometry of the destroyed object and presenting the virtually reconstructed object based on the obtained results, can be found in the article by Kolivand et al. [2018]. The article presents a virtual reconstruction of the Portuguese monument Malacca (Melaka, Malaysia) in the AR system. Thanks to the AR technology used, the reconstructed building can be displayed anywhere – it depends entirely on the user. Another example of research describing a single object is the article by Koutsoudis et al. [2013]. There, the authors focus more on evaluating measurement methods, but as a result, they also present visualizations of a historical object, the Kioutouklou Baba Bekctashic Tekke (Xanthi, Greece), of varying quality depending on the used measurement method.

When capturing an object together with its surrounding space, we focus more on the spatial aspect, than on the accuracy of the object model itself. The space created in this way together with the analyzed object can be called geovisualization. It can be represented by means of 2D maps developed according to the principles of cartographic design, but also by means of 3D models. Such a research was presented by Horbiński and Medyńska-Gulij [2017], who used publicly available data to create 2D and 3D geovisualizations and statistical maps of selected open-pit mines for natural aggregates. The researchers proved that presenting the same data in different cartographic representations and making them available online affects how effectively spatial data is conveyed to the user. Another approach to representing the terrain of a natural aggregate mine was proposed in the study by Halik and Smaczyński [2017]. In the study, a 3D model of a mine fragment was developed based on data obtained using an unmanned aerial vehicle (UAV), with the representation being developed in virtual reality (VR). In recent years, due to the destruction of culturally valuable objects, more and more work is being done on the inventory and presentation of cultural heritage objects. Research on reconstruction and presentation of cultural heritage objects in virtual reality has been presented, by Lütjens et al. [2020], Walmsley and Kersten [2020] and Büyüksalih et al. [2020], among others. In such work, it is very important to use different available data, such as analog historical documentation and digital spatial data.

Research results can be presented and made accessible in various forms. Research on the possibility of visualization and presentation of windmills has already been conducted and described by Smaczyński et al. [2022] and Smaczyński and Horbiński [2021]. The study discusses the modeling of the windmill structure using data from the UAV platform and the presentation of the facility online. In addition, the researchers combined digital survey data with historical cartographic studies. Alongside spatial objects, the phenomena occurring within them can also be the subject of geovisualization. One example is the representation of pedestrian movement dynamics using a series of color maps developed on the basis of observations with an unmanned aerial platform [Smaczyński et al. 2020]. Remote sensing data, in particular from UAV and LiDAR technology, is also used to observe the Earth's surface, for example in order to analyse the physical and chemical properties of soils [Kaźmierowski et al. 2015, Łukowiak et al. 2024].

In the following study, the attention is centered on the measurement method and parameters used to create a point cloud of a windmill. Documentation of architectural and archaeological objects and monuments requires obtaining information from various sources [Lerma et al. 2011]. The use of historical maps and current cartographic sources [Statuto 2017], as well as sources collected through field surveys in research, allows the identification of windmills present in the landscape, their remains or the virtual 3D reconstruction of those that no longer exist.

Modeling of past reality and present state is possible by creating accurate 3D models in special computer software, based on which further spatial analysis and consequently their visualization and dissemination can be performed [Wilson 2005, Blanco-Pons et al. 2019]. Currently, most of the data for 3D modeling are obtained using LiDAR technology [Miřijovský and Langhammer 2015] and photogrammetry [Rossi et al. 2018]. Both airborne (ALS) and terrestrial laser scanners (TLS) enable fast and efficient generation of high-quality and accurate geospatial data, which is why they are often used in 3D modelling [Lopez et al. 2018, Klapa 2022]. Researchers point out that the airborne laser scanning method (ALS) is particularly suitable for 3D modeling of large areas and photogrammetry for smaller areas. One of the measurement methods that enables the creation of 3D models is laser scanning technology. This technology enables the acquisition of detailed point clouds. In particular, terrestrial laser scanning (TLS) enables accurate coverage of the environment, but its range is much smaller compared to airborne scanning. These devices are used in industry for design, prototyping or quality control, as well as in engineering and architecture, to capture plants, buildings or landscapes. Laser scanners are an invaluable tool for obtaining precise spatial data in the field of cultural heritage recording. They are particularly useful in architecture, providing surveys of architectural, technical and industrial objects. Precise data from laser scanning can form the basis for documentation of a particular object, which is very important for proper maintenance, management and repair of culturally valuable structures [Haddad 2008]. Heritage Building Modeling (HBIM) makes it possible to understand, document and virtually reconstruct historic buildings, as well as to inventory and visualise them [Lopez et al. 2018, Klapa and Gawronek 2023].

Another data source that enables the creation of 3D models is photogrammetric studies based on images taken from low altitude using an unmanned aerial platform. Low-level aerial photogrammetry, which, thanks to digital image processing, allows the creation of 3D models in high quality, makes it possible to collect photographs. These photographs not only are a source for the creation of a 3D model, but also provide photographic documentation of the windmills [Koutsoudis et al. 2014, Themistocleous 2016].

These methods of data collection allow the development of advanced visualizations, such as 3D models, which are very difficult to create using traditional cartographic methods of field mapping and simple measurements [Smaczyński and Horbiński 2021]. They are based on scans of the point cloud (TLS) and photogrammetric images of the UAV platform, and can be defined in a specific coordinate system using the adopted reference points [Eugster and Nebiker 2008, Nex and Remondino 2014, Smaczyński and Medyńska-Gulij 2017, Ravi et al. 2018]. The methods of laser and photogrammetric 3D data acquisition are non-invasive, prevent damage to archeological objects and allow digital documentation and visualization of geometry [Lerma et al. 2010].

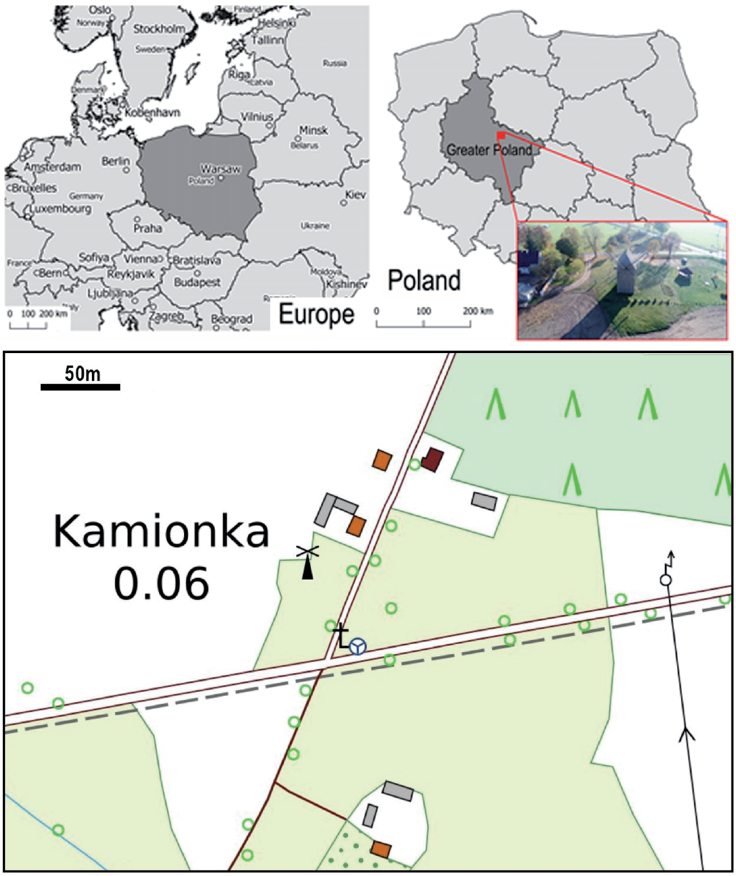
In these considerations, the use of photogrammetric technologies and laser scanning to obtain a 3D raw model of the windmill and its features, as well as the evaluation for conversion into different types of 3D models, is of crucial importance. The basic problem is to specify the features and parameters of such a raw model, which can serve as the basis for reconstruction in a desktop and virtual environment.

Choosing the right methodology, adopting suitable measurement methods and techniques, and using appropriate data is important for any research. Only by properly combining these factors is it possible to achieve reliable research results. In addition, each type of data we obtain through measurements and research allows us to perform different types of spatial analyzes and develop different types of geovisualizations. This study uses the photogrammetric method and laser scanning to measure the windmill structure and represent its geometry in the form of 3D models, as well as map the topography of the surrounding area. In order to solve the problem of characterizing and evaluating the created point clouds for the development of different types of 3D models, the evaluation parameters on the basis of which the conclusions will be drawn must be specified. In addition, the authors of the study will indicate the possibility of using the most advantageous source of measurement data about the studied object can be used to create a tool that is helpful in conservation work. The most frequently used data in cartography for designing geovisualization are studies at topographic scales. However, such studies do not allow to obtain detailed data about the geometry and details of objects through the applied generalization. The described study aims to verify the quality of photogrammetric and laser scanning data for geovisualization of topographic objects.

2. Research area and research objects

Windmills played a particularly important role in shaping and developing the cultural landscape of Greater Poland, one of the main regions of Poland [Brykała and Podgórski 2020]. They shaped the landscape of Greater Poland in the pre-industrial period and in the early industrial period of these areas in the 19th century [Lorek and Medyńska-Gulij 2019]. The remains of windmills still testify to the agroindustrial character of Greater Poland, and thus are a tangible evidence of the cultural heritage of this region. Considering the fact that many objects of this type in the landscape of Greater Poland have deteriorated or have already completely disappeared, the authors of the study decided to conduct research in this area.

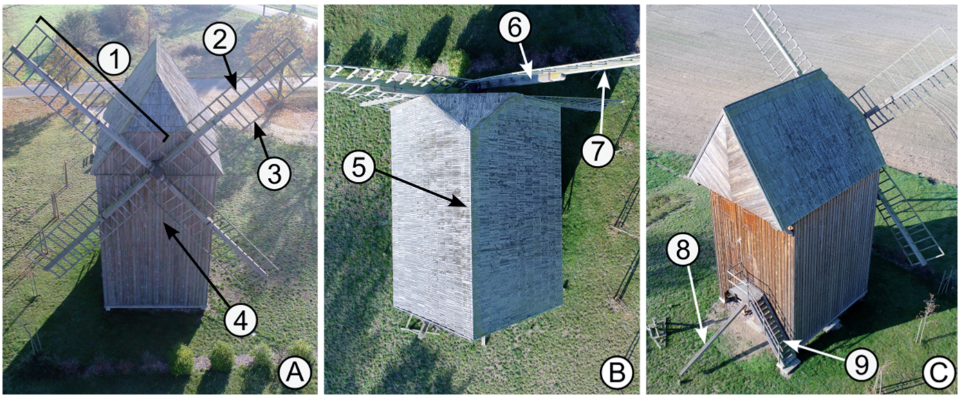
Windmills are an important part of agro-industrial development of the areas of the Wielkopolskie Voivodeship (Greater Poland) in the 19th and early 20th centuries. Over time, fewer and fewer of these objects can be seen in our surroundings. The windmill under study was located in the western part of Poland, in the Wielkopolskie Voivodeship, in the village of Kamionka (Fig. 1). It was a representative example of the region in terms of its construction and topographic structure. In 2014, the windmill was faithfully restored and opened to the public.



Source: Authors' own study

Fig. 1. Location of the research area

Windmills are extremely interesting examples of architectural and technical monuments. They are characterized by an unusual architectural form and a high level of carpentry. The studied windmill is a type of a post mill. The ground plan of the windmill is rectangular. The structure of the walls made of wood consists of four corner pillars connected with horizontal transoms and diagonal struts [Maksymowicz 2015]. A vertical formwork sealed with battens is attached to them from the outside. The whole is covered with a gable roof, cut in the shape of a pediment from the side of the wings. The roof is covered with shingles. A wooden staircase, located outside the building, leads to the inside of the windmill. At the back of the windmill is a wooden tail pole, which allows the structure to be rotated so that the wings are directed towards the direction from which the wind blows. The most important part of any windmill is its operating mechanism. Four wings of the windmill are mounted in the head of the shaft. The wing axis consists of two beams. A second beam is attached to it as its extension. Horizontal bars are nailed to the wing rungs, to which horizontal laths – frames are attached, forming the side frame of the wing. The space between the glazing bars and the frames is filled with split boards to form the reveal of the sash. Figure 2 shows the main elements of the windmill structure [Shepherd 1990].



A. view of the front facade B. Roof view C. Rear and side elevation view

1. Sail 2. Sail bars 3. Hemlath 4. Wooden facade 5. Wooden shingle roof 6. Stock 7. Whip 8. Tail pole 9. Steps

Source: Authors' own study

Fig. 2. Exterior elements of the windmill structure: A. front facade view; B. roof view; C. rear and side view

3. Materials and methods

In order to achieve the goal set in the study and to obtain information on the application potential of data from terrestrial laser scanning (TLS), photogrammetric low altitude flight (UAV) and airborne scanning (LIDAR) for the modeling of cultural heritage objects and environmental topography, six main research phases were distinguished:

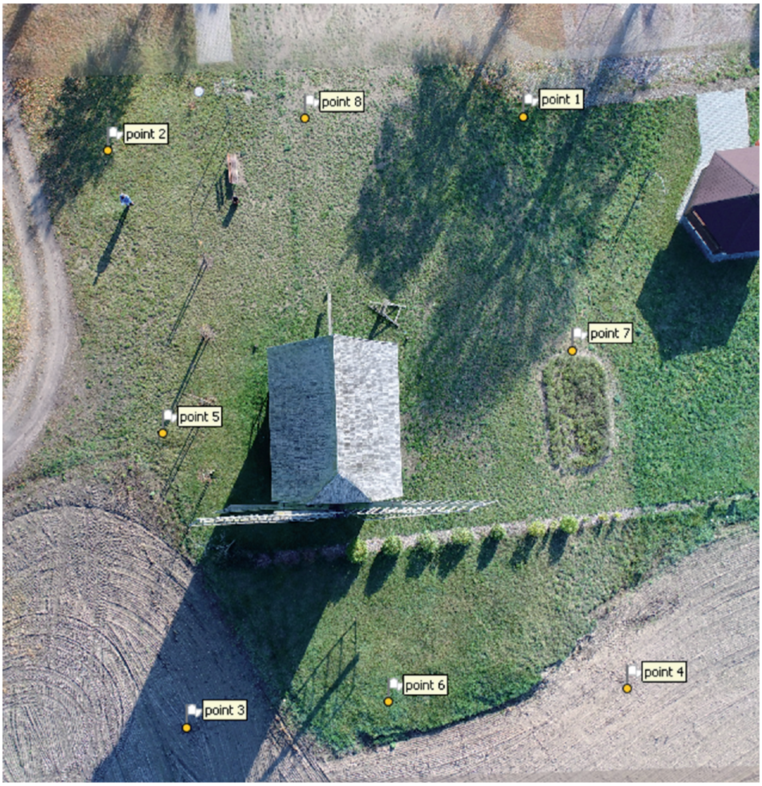
- adoption of evaluation criteria (Section 3.1),
- photogrammetric data processing – UAV (Section 3.2),
- processing data from terrestrial laser scanning – TLS (Section 3.3),
- airborne scanning data processing – LIDAR (Section 3.4),
- visualization (Section 3.5),
- evaluation of the geovisualization according to the adopted criteria (Section 3.6).

3.1. Adoption of evaluation criteria

Referring to the set research issues, the authors decided to evaluate the individual registered structural and architectural elements of the studied windmill. This is necessary to determine the potential for the creation of other cartographic forms. It became necessary to define and adopt the evaluation parameters to which the created 3D models will be subjected. This study involved a qualitative evaluation of the registered external structural and architectural elements of the windmill. Nine architectural elements of the structure were defined for this purpose; these are the windmill's characteristic external parts. All structural elements that were evaluated are shown in Figure 2. The details of the registered architectural elements, i.e. their shape, were assessed. Additionally, the possibility of registering the textures of the tested structure examined and evaluated, i.e. the possibility of identifying the building material used for the construction of the structure. This is very important from an architectural point of view and due to the uniqueness of the construction of the windmills, which were made of wood.

3.2. Photogrammetric data processing – UAV

The authors of the paper chose to gather photogrammetric data from low-level aerial photogrammetry. The premises of the study were critical to the selection of the unmanned aerial vehicle platform and the methodology for obtaining photogrammetric data. In order to create the most accurate 3D model of the windmill, the images were acquired with the structure-from-motion (SfM) algorithm [Westoby et al. 2012]. The chosen data acquisition technique, as well as the size and geometry of the structure under study, suggested that the most appropriate type of platform would be a multirotor unit. The use of the structure-from-motion algorithm allows for accurate acquisition of the object from each side, allowing the windmill structure to be modelled as faithfully as possible. It was decided that the raid would be carried out from a height of 15 meters, 30 meters and 50 meters. The popular DJI Phantom Advanced+ platform, equipped with a 1" CMOS matrix camera and a 20-Mpx lens, was selected for capturing the image data. In order to perform the triangulation of the captured aerial photogrammetric images, a network of photogrammetric control points (GCP) was established [Nex and Remondino 2014, Padró et al. 2019]. One of the methods for measuring the coordinates of ground control points is the GNSS RTK technique [Clapuyt 2016, Klapa et al. 2022]. The measurement and determination of the coordinates of the photogrammetric control points were performed using the Trimble R10 Model 2 GNSS receiver. For the satellite measurements, the surface corrections provided by the reference stations of the VRSNet system were adopted and taken into account. A total of eight photogrammetric control network points were established around the tested structure. The location of the ground control points is shown in Figure 3. The numbers 1–4 indicate the photo points, and the numbers 5–8 indicate the control points.



Source: Authors' own study

Fig. 3. Ground control points and check points used in the aerotriangulation process

The photogrammetric data was processed using Agisoft Metashape Professional software. The used methodology allowed to perform aerotiangulation based on the points of the photogrammetric control network and to calculate the RMSE value. The formula [Herrero-Tejedor et al. 2020] was used to calculate the RMSE value:

$$RMSE = \pm\sqrt{\sum_{i=1}^{n} \frac{(X_{i,est} - X_{i,in})^2 + (Y_{i,est} - Y_{i,in})^2 + (Z_{i,est} - Z_{i,in})^2}{n}}$$

where:

$X/Y/Z_{i,in}$ – the actual value of a particular coordinate,

$X/Y/Z_{i,est}$ – the estimated value of this coordinate.

It became possible to determine the deviations of the assumed reference points by taking in the calculations the coordinate values from the direct measurement and the values calculated on the basis of the created model (Tables 1, 2).

Table 1. Calculations of error on the basis of the chosen ground control points

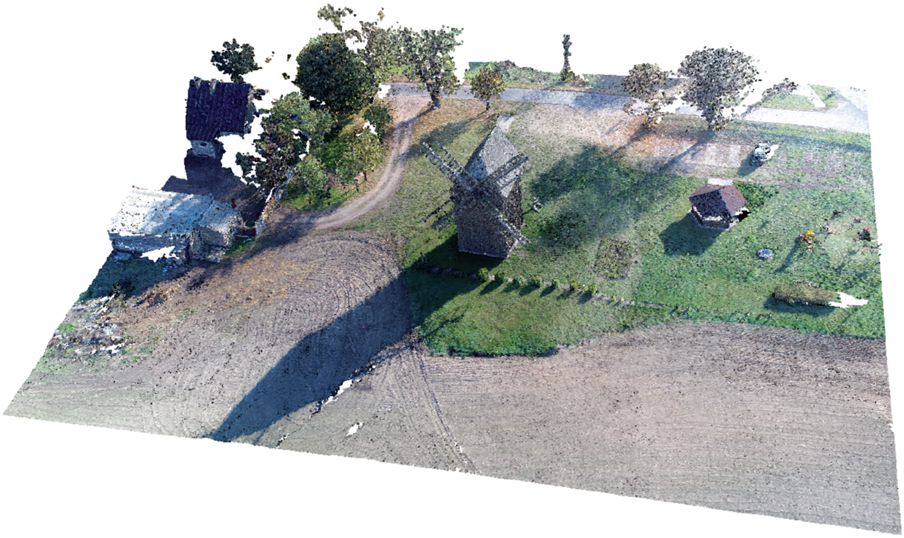
GCP	*X* error [m]	*Y* error [m]	*Z* error [m]	Total [m]
Point 1	–0.005	–0.013	–0.003	0.014
Point 2	0.002	0.002	0.002	0.004
Point 3	–0.015	0.003	–0.025	0.015
Point 4	0.018	0.007	0.025	0.020
Total	0.012	0.008	0.002	0.014

Table 2. Calculations of error on the basis of the chosen control points

Control points	*X* error [m]	*Y* error [m]	*Z* error [m]	Total [m]
Point 5	–0.009	–0.003	0.004	0.010
Point 6	–0.005	0.003	0.006	0.008
Point 7	0.005	0.003	0.003	0.007
Point 8	–0.039	–0.027	0.008	0.048
Total	0.020	0.014	0.006	0.025

In addition, the mean square error values of 1.4 cm (Table 1), calculated during aerotriangulation based on the GCP, and 2.5 cm (Table 2), from the control points, indicate that the images obtained were correctly aligned. The frontal and side overlaps were 85–90%. The ground sample distance (GSD) value was 1 cm/px. Therefore, the authors of the paper proceeded with the next steps of image data processing. Further work on intimate processing of photogrammetric data resulted in the creation of a point cloud in Agisoft Metashape Professional software. The process was performed using the original sizes of the acquired images, and the resulting point cloud included 15,565,803 points (Fig. 4).

The resulting point cloud became the basis for the development of further visualizations of the tested windmill.



Source: Authors' own study

Fig. 4. Point cloud created from the photogrammetric raid

3.3. Processing data from terrestrial laser scanning – TLS

The study involve laser scanning using a terrestrial laser scanner (TLS – Terrestrial Laser Scanning) during the measurements. The Trimble TX 8 terrestrial laser scanner was used for the measurements. The device can take measurements up to 340 meters above the ground. The priority of this study was to capture the windmill as accurately as possible, so it was decided to perform the measurements in standard mode near the studied structure. Special software for the Trimble RealWorks instrument was selected to process the data from the laser scanning. In order to capture the tested object correctly, and as accurately as possible, the measurement was conducted from a total of six stations located around the windmill, adjusting their position to the shape of the terrain and obstacles in the terrain. The location of each site is shown in Figure 5. In addition, the range of scanning from each measurement site is shown in different colors in the figure.

Registered scans from all stations were stored in .tzf format (Trimble's binary format for rasterized scan data). A total, of 315,575,139 points were recorded from six positions. The scans were then extracted in the program and the sampling procedure was performed, assuming a resolution of 0.001 m. After its execution, a point cloud of 55,972,947 points was obtained. The next step was to integrate the scans. The software allows the user to automate the combination of the scans using the planes registered in the scan area. Unfortunately, the registered area was very different in terms of land cover, especially because of vegetation. Such situations have very negative effects on the calculation algorithms of the machines implemented in the software, and the automated combination of scans becomes very difficult to obtain satisfactory results. Therefore, in this study, the clouds were combined manually. The initial reconstruction of the alignment of the scans, and then the completion of the process, were performed manually by processing individual scans. As a result of the internal and computational work, the acquired scans were combined with an accuracy of ±0.004 m. The generated point cloud is shown in Figure 6.

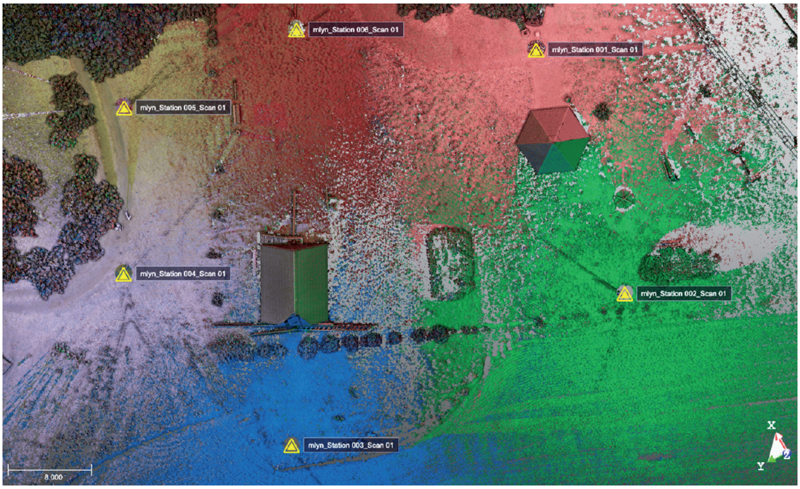


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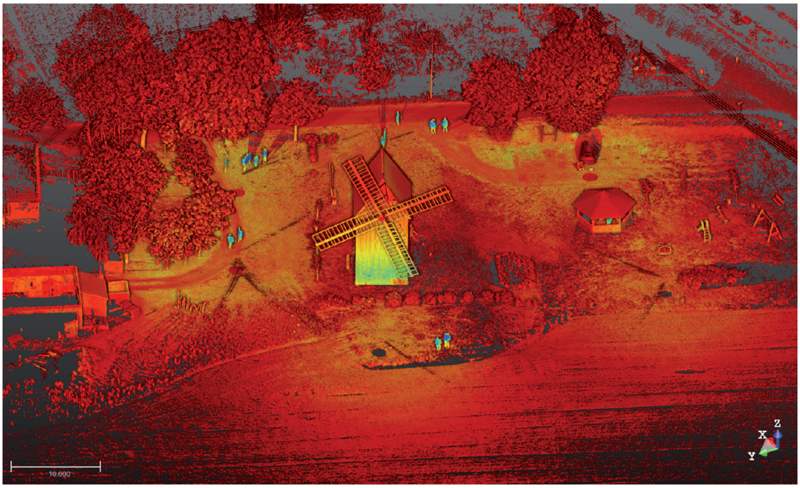
Fig. 5. Location of the measuring stations and scanning range



Source: Authors' own study

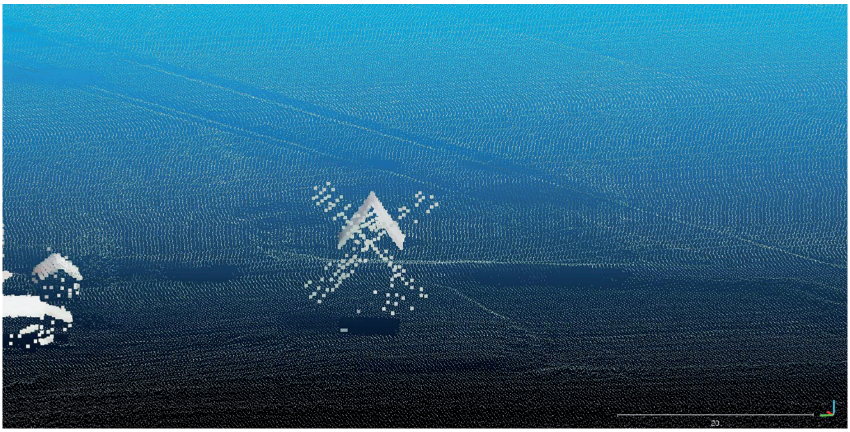
Fig. 6. Point cloud created from terrestrial laser scanning

The calculated point cloud formed the basis for further activities to visualize the analyzed object.

3.4. Airborne scanning data processing – LIDAR

The study used data from ALS (Airborne Laser Scanning). In Poland, Airborne Laser Scanning data are publicly available, free of charge and provided through the National Geoportal (www.geoportal.gov.pl). They represent an area in the form of a cloud of measurement points with specific XYZ coordinates. The files are stored in LAS format and, in addition to the coordinates of the points, include information about the class of a particular point and the intensity of the signal reflection, among other information. Since the files of LAS are very large, a compressed version of LAZ is provided, which is much more convenient and does not lose any data of the original file. The timing and quality of the data depends on the location. In Poland we cover the whole country with ALS data with different point density, ranging from 4 points/m^2, mainly in non-urban areas, to 20 points/m^2 in urban areas.

Airborne laser scanning data collected for the study area is as of April 29, 2014. The point cloud was defined in the horizontal coordinate system PL-1992 (EPSG: 2180) and in the vertical coordinate system Kronsztad 86 (PL-KRON86-NH). The density of the analyzed point cloud was 4 points/m^2, and the average height error was 0.15 m. Point clouds are archived and made available for a given map section. Since the object under study was located at the edge of the section, four point clouds were acquired. The downloaded airborne laser scanning data was imported into CloudCompare. Figure 7 shows the generated point cloud. To isolate the tested windmill and facilitate its identification in the point cloud, the size of the points representing it was increased.



Source: Authors' own study

Fig. 7. Point cloud created from airborne laser scanning

3.5. Visualization

The point clouds obtained by the photogrammetric method (Fig. 4), terrestrial laser scanning (Fig. 6), and airborne laser scanning (Fig. 7) were processed using specialized software. Figure 8 shows the point clouds representing the structure of the tested windmill for each of the used methods, i.e. for the photogrammetric method (Fig. 8A), for the terrestrial laser scanning (Fig. 8B) and for the airborne laser scanning (Fig. 8C).

Based on the obtained point clouds, 3D models of the windmill were created (Fig. 9). In the case of photogrammetric data and terrestrial laser scanning, it was possible to texture the 3D model because photographs were taken during the measurements using these methods (Figs. 9A, 9B). In the case of the airborne laser scanning data, texturing with real photos was not possible (Fig. 9C).

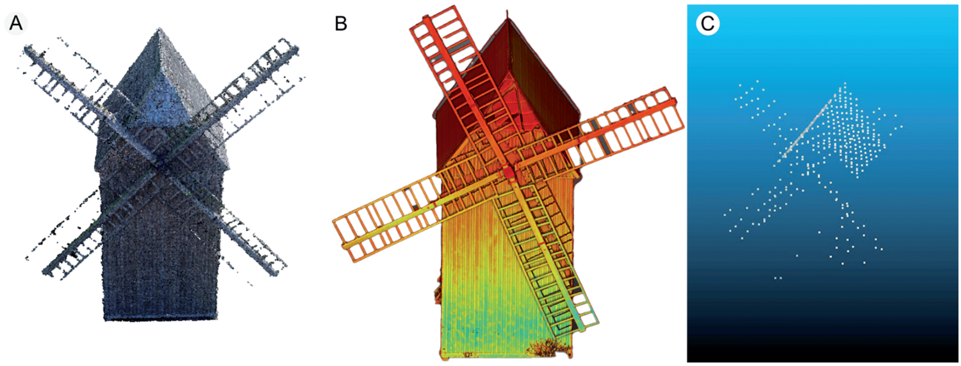


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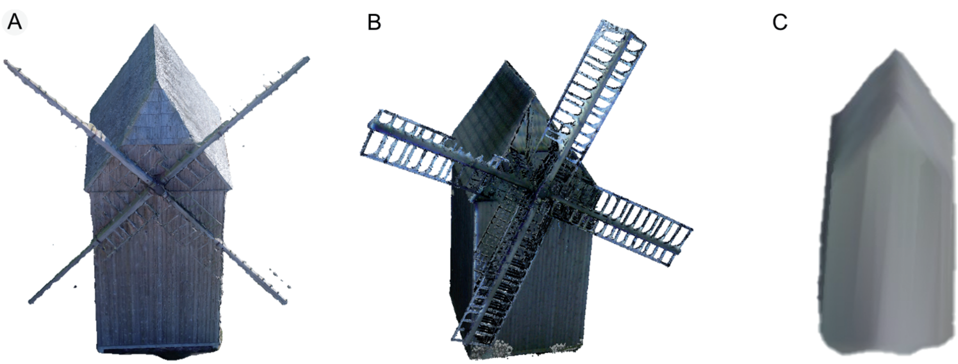
Fig. 8. Registered point clouds of the analyzed windmill: A photogrammetric method; B. terrestrial laser scanning method; C. airborne laser scanning method



Source: Authors' own study

Fig. 9. Windmill 3D models: A. photogrammetric method; B. terrestrial laser scanning method; C. airborne laser scanning method

3.6. Evaluation of the geovisualization according to the adopted criteria

The point cloud obtained by the photogrammetric method allowed the shapes of the windmill walls and the roof structure to be registered in detail (Fig. 8A). The construction of the stairs and the wooden tail pole that enable the structure to rotate were also captured. In addition, the main part of the propeller structure (stock and whip) was registered, however, the photogrammetric method could not satisfactorily capture the smaller wooden elements of the propellers (sail bars and hemlath).

Terrestrial laser scanning, similar to the photogrammetric method, was used to record the shape of the windmill body and the roof structure in detail (Fig. 8B). In contrast to the photogrammetric method, terrestrial laser scanning made it possible to accurately render all propeller elements. This is true for the main part (stock and whip) as well as for smaller elements (sail bars and hemlath). The structure of the stairs and the tail pole were also successfully captured.

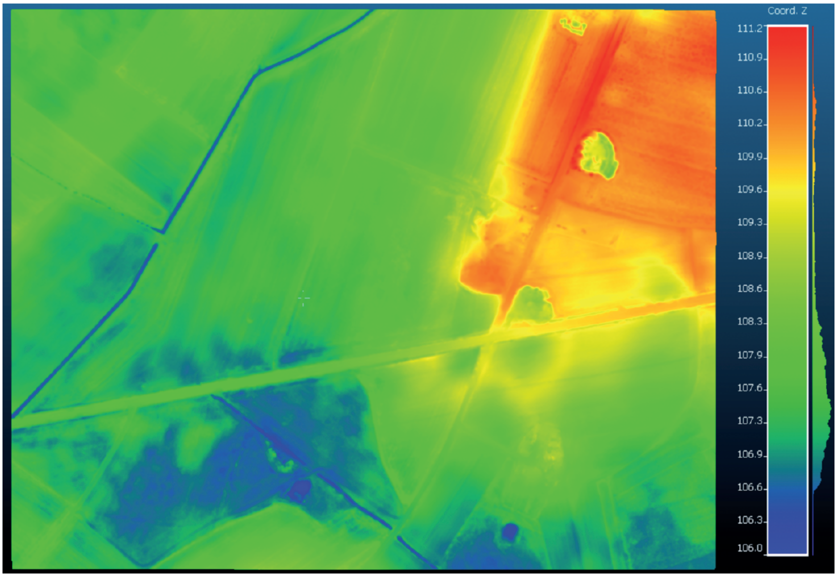
The data obtained from airborne laser scanning did not allow for detailed registration of the shapes of the windmill studied (Fig. 8C). Due to the methodology of ALS data acquisition, it was only possible to capture the roof surface, but the registration of the walls was not performed in detail. Some of the points represented windmill propellers in a general way. It was not possible to identify the individual parts of the propeller. Likewise, it was not possible to register the structure of the stairs and the tail pole.

Given the fact that 3D models are created based on a point cloud, the most detailed rendering of the geometry of the studied windmill was possible only with the help of terrestrial laser scanning (Fig. 9B). The dense point cloud allowed precise modeling of the walls, the roof structure, all elements of the windmill propellers, as well as the stairs and tail pole.

As shown in Fig. 9A, accurate modeling of windmill propellers with the photogrammetric method was impossible. However, it was possible to model the windmill's body, i.e. tail pole, walls, roof, and stairs structure.

The point cloud from airborne laser scanning allowed the creation of a general 3D model (Fig. 9C). It was not possible to reconstruct the windmill propellers. The points representing them caused a significant degradation of the 3D model of the windmill body. This was due to the insufficient density of the point cloud, which prevented the software's algorithms from connecting the points correctly.

While the data from the airborne laser scanning could not be used for detailed registration of the windmill structure and its 3D modelling, it could be used to create a digital terrain model (Fig. 10). The advantage of the data from ALS is that it is publicly available and provided through the national geoportal (www.geoportal.gov.pl). They allow a detailed representation of the terrain. This is particularly important for the spatial analysis of windmills as it enables the analysis of the topography of the area, including the determination of existing obstacles in the terrain, and the assessment of the most effective locations for operating windmills.



Source: Authors' own study

Fig. 10. Digital terrain model obtained using airborne laser scanning

The point cloud obtained from the measurement carried out with the terrestrial laser scanner (Fig. 8A, enabled all elements of the windmill structure to be captured in detail. Such data can be a valuable resource for conservation work related to the protection of cultural assets. It can also form the basis for the development of special reconstruction projects of the object. The authors of the study also propose a tool that implements the obtained measurement data by presenting the current technical condition of the building and the hypothetical model of the reconstruction project, providing the possibility to directly compare and contrast them. The following research tool was programmed to present a comparison of the hypothetical windmill model with the generated point cloud (Fig. 11). The Three.js library [Stanton et al. 2017, Benesha et al. 2020] was used for programming, in particular for the comparison of several scenes (https://threejs.org/examples/# webgl_multiple_scenes_comparison). The hypothetical model was created in Blender and added to the tool in GLTF format [Smaczyński and Horbiński 2021], while the point cloud was converted to the PCD extension. Both models were set to the same reference point so that the smallest differences or gaps could be seen in the point cloud. The tool itself was placed on the website (http://th31483-gamescartography.home.amu.edu.pl/model/model_comparison.html).

Source: Authors' own study

Fig. 11. A tool for comparing measurement data and design model

4. Discussion

The use of photogrammetric images for 3D modeling is already a popular method. The advantages of its application in archeology have been described several times. More than two decades ago, the usefulness of aerial images in works related to archeological documentation and cultural heritage was described in [Bryan et al. 1999, Bewley 2003, Desmond and Bryan 2003, Arias et al. 2006, Perez-Martin et al. 2011]. Laser scanning technology, in contrast to the photogrammetric method, allows accurate registration of the geometry of the studied object in high resolution. As a result, laser scanning has become an alternative technology to the classical techniques of geodetic measurements, which additionally enables the development of a geovisualization of a particular object. Similar to photogrammetric technology, laser scanning has proven useful in works related to archeology and documentation of cultural heritage objects, with works describing its application emerging over two decades [Robson Brown et al. 2001, Diaz-Andreu et al. 2005, Doneus et al. 2008, Entwistle et al. 2009, Lerma et al. 2011, Gomes et al. 2014, Pritchard et al. 2017]. Most of the works related to the recording of cultural heritage objects focus on the detailed modeling of the individual objects. However, to date, no studies have been conducted that perform work involving the use of photogrammetry and laser scanning on larger areas with additional consideration of spatial analysis. For this purpose, it is necessary to determine the suitability of the laser scanning method and photogrammetry for such analyzes. This research could help our understanding of the spatial relationships between cultural heritage objects, such as windmills. The results of the conducted research will allow in future works to perform spatial analyzes of the correlation between terrain topography and the location of windmill structures. This will enable us to determine the effectiveness of their location when the use of geographic information systems (GIS) is not possible. The research is a continuation and development of retrospective research on windmills [Smaczyński and Horbiński 2021, Smaczyński et al. 2022]. One more aspect that also should be emphasized is the possibility of implementing the created models and their visualization using virtual reality technology (VR). This is very important in view of the technological limitations of VR technology, which are related to the size of the files that can be smoothly visualized. Therefore, it should be pointed out that the conducted case study provides a basis for further research in the field of visualization methods.

In the light of this study, it may be interesting to use modern visualizations of cultural heritage objects in retrospective research with historical maps (i.e. Urmesstischblätter and Messtischblätter), archival record cards, or han-drawn sketches of windmills. If the presence of a windmill at a particular location is confirmed and the windmill no longer exists, this information can be correlated with data from modern measurements. If the potential area of the windmill is significantly larger than that of the surrounding area, this could form the basis for further archeological investigations and the use of GPR (Ground Penetrating Radar). These devices can be used for various tasks – from inventorying underground infrastructures, locating historical objects, i.e. undergrounds, crypts, foundation remains, to determining where pipeline failures or leaks occur [Klewe et al. 2021]. Mobile georadars, also integrated with other mapping instruments, such as laser scanners or photogrammetric cameras, transported on suitable platforms, allow obtaining comprehensive 3D data over the measured space – both above and below ground [Pieraccini et al. 2020]. The positioning of the GPR trajectory can be supported by GNSS receivers using multisystem satellite constellations, improving the work, increasing the positioning accuracy [Gabrys and Ortyl 2020], and allowing the precise determination of the presence of non-preserved windmills. The use of GPR technology in work related to windmills will be carried out in parallel by the authors of the work, and published after its completion. During testing, it was shown that it is possible to locate an underground windmill stone that has not been dismantled or moved since the windmill ceased its operation. Furthermore, elements of the windmill structure, that have been covered by a layer of soil over the years, can be detected.

5. Conclusions

The study of the registration and inventory of windmills is significant from the point of view of the protection of these cultural heritage objects. The authors focused on determining the potential of application of laser scanning method and photogrammetric method in research related to the 3D reconstruction of windmills, as well as and in the study of the topography of areas in Greater Poland where windmill are found in large numbers. The conducted analysis led the authors to determine the effectiveness of the referring to the research issues. They then proceeded to evaluate the individual registered structural and architectural elements of the studied windmill. This is necessary in order to determine the potential for the creation of other cartographic forms representation of the cultural heritage object windmill, which was developed on the basis of low-level aerial images, terrestrial and airborne laser scanning. This was made possible thanks to the determination of the evaluation parameters, namely the criterion related to the possibility of registering the shapes of certain architectural elements of the windmill structure. In addition, a criterion was defined for registering the texture of the studied windmill. The obtained research results form the basis for conducting research in a wider area.

Summing up the research, a specific scheme for the research procedure should be adopted. If the goal is to make an inventory of the existing windmill, and accurately determine its shape and texture in detail, it is most advantageous to use the method of laser scanning (Fig. 8b, 9b). However, if one wants to create a DEM model of the immediate surroundings of the windmill, the use of laser scanning becomes too time-consuming and labor-intensive, and the obtained data are qualitatively similar to photogrammetric studies. In a situation where the relationship between the windmill and its immediate surroundings needs to be determined, it is better to use photogrammetric data from a UAV at low altitude. This technology allows us to create a DEM model of the windmill's immediate surroundings. However, the data gathered with UAV technology does not allow such an accurate and detailed coverage of the wind turbine itself (Figs. 8a, 9a). The use of airborne laser scanning is particularly useful for conducting spatial analysis using GIS over large areas (Fig. 10). The airborne laser scanning data of the windmill itself, however, does not enable detailed reconstruction (Fig. 8c, 9c). The library and file extensions used enable models to be implemented and the methodology to be repeated easily (Fig. 11). The proposed tool can make an important contribution to the reconstruction of a cultural heritage objects and simplify the planning work. We are aware that a visual comparison of a point cloud and a model on a general level does not add anything substantial to the question of the quality of models, their geometric accuracy or the possibility of modelling and visualising very detailed architectural details. Our approach lacks elements such as a difference model for point clouds that allows the assessment of the consistency of the captured data and shows the mapping of details onto the point cloud and the model generated from this cloud. The authors want to expand on these deficits in further research. The currently created tool is a basis, and testing it on further collected data will also lead to increased functionality. The current tool is largely illustrative, showing the scope of the collected data and the possible ways of interacting with it. In addition, it has been demonstrated that the data from a photogrammetric flights using a low-flying aircraft (UAV) and terrestrial laser scanning (TLS) can be successfully used to design the geovisualisation of topographic objects while maintaining a high level of detail of these objects.

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