ISERDAR
International Science and Engineering Reviews: Development, Analysis and Research

Research Article

Digital Twin of Historical Structures Using Point Cloud: A Case Study of the Gümüşhane Metropolitan Rum Church

Mehmet Akif GÜNEN[1]*, Kaşif Furkan Öztürk[2], Şener Aliyazıcıoğlu[3]

[*1]Department of Geomatics Engineering, Faculty of Engineering and Natural Sciences, Gümüşhane University, 29100, Gümüşhane, Türkiye, akif@gumushane.edu.tr, ORCID: https://orcid.org/0000-0001-5164-375X

[2]Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Gümüşhane University, 29100, Gümüşhane, Türkiye, kasiffurkan.ozturk@gumushane.edu.tr, ORCID: https://orcid.org/0000-0002-6325-4222

[3]Department of Mining Engineering, Faculty of Engineering and Natural Sciences, Gümüşhane University, 29100, Gümüşhane, Türkiye, s.aliyazicioglu@gumushane.edu.tr, ORCID: https://orcid.org/0000-0002-5177-8221

ARTICLE INFO

Article history:

Received October 22, 2024
Received in revised form Novem. 27, 2024
Accepted December 06, 2024
Available online December 20, 2024

Keywords:

Point Cloud, Solid model, Historical building

Doi: 10.5281/zenodo.14514661

* Corresponding author

ABSTRACT

The research focuses on the Gümüşhane Metropolitan Rum Church, a culturally significant edifice that has deteriorated over time owing to natural and human-caused factors. High-resolution aerial photographs were obtained with the DJI Phantom 4 drone and processed using Agisoft Metashape to generate a detailed three-dimensional point cloud. This data was georeferenced with the Geomax Zenith 10 GNSS/GPS. Following the application of statistical outlier elimination to filter the point cloud data, the processed model was imported into SolidWorks for solid modeling. This approach enabled the creation of a realistic digital reconstruction of the structure, offering valuable insights for restoration design and structural analysis. The study highlights the pivotal role of point cloud technology in preserving cultural heritage by facilitating precise monitoring and restoration of historic structures.

1. Introduction

Historical structures are unique and significant in terms of culture and art, and they serve as important links to the past. In today's world, it is critical to preserve and pass on these structures to future generations [1, 2]. As part of this preservation effort, point cloud have received reputation for their ability to digitally preserve and analyze ancient structures, making them an indispensable tool in scientific research [3]. The use of 3D point cloud technology is now an essential component of both modern technology and cultural heritage preservation, allowing for the precise digital recording of architectural structures, sculptures, bridges, and other historical relics. This technology not only aids restoration efforts, but it also improves research by providing extremely precise data [4-6]. However, historical structures are prone to degradation with time, as well as harm from natural calamities and human activity. To solve these issues, point cloud build highly precise digital models, providing a solid platform for future conservation and restoration efforts. Point cloud make it easier to apply appropriate restoration procedures since they preserve the geometry, surface features, and texture of a building digitally. For example, in the event of damage, point cloud data can provide full guidance for the reproduction or repair of individual pieces, such as stones or columns, ensuring the most exact restoration possible. In contrast, traditional recording methods such as photography or hand sketching are generally labor-intensive and lack the precision required for such activities [7, 8]. In contrast, point cloud reach millimeter-level accuracy by photogrammetry or laser scanning, ensuring that even the most complicated geometric elements of a structure are correctly preserved without loss of information [9, 10]. This allows for not only the development of restoration plans, but also a full examination of the structure's original state.

Furthermore, periodic scanning enables for the monitoring of structural changes such as crack widening, stone degradation, or moisture-induced deformations. This proactive method to monitoring allows for early damage detection and appropriate remedies, perhaps avoiding more significant difficulties. Thus, point cloud are useful not only for restoration, but also as a resource for scientific research. While engineers may evaluate structural durability and pinpoint areas for improvement in building design, historians, archaeologists, and architects can use these data sets to investigate construction techniques, structural attributes, and historical usage patterns [11-13]. The incorporation of this technology into preservation efforts ensures that cultural heritage is accessible and well-preserved for future generations to study and value.

Digital models of historic structures can be produced by combining point cloud data with computer-aided design (CAD) software. Planning restoration in seismically active locations requires the use of these models to evaluate a structure's resistance to natural disasters like earthquakes and wind stresses. Additionally, structural simulations can identify regions that might benefit from reinforcement or restoration-appropriate materials [14, 15].

Furthermore, point cloud technology facilitates virtual tours of historical sites by accurately transferring these structures to the digital realm, benefiting cultural and educational initiatives beyond physical preservation [16]. Virtual museums, for instance, make historical buildings accessible to a wider global audience. Academic institutions specializing in architecture and archaeology can use this data to provide students with hands-on learning opportunities. Storing point cloud data digitally ensures that it is accessible to researchers worldwide, fostering interdisciplinary collaboration and enabling more comprehensive studies, particularly in global research projects. This approach significantly contributes to both scientific advancement and the preservation of historical structures [17, 18].

2. Materials and methods

The Gümüşhane Metropolitan Rum Church was selected as the study's primary focus due to its architectural and cultural significance within Gümüşhane's historical landscape. Over time, the church has experienced various structural degradations caused by natural and human-made factors. This study aimed to document the current condition of the structure and initiate the preservation process.

The point cloud generation and digital documentation processes enabled a highly accurate transfer of the church's structural and architectural features into a digital environment. To create a three-dimensional digital model, aerial photographs of the historic building were captured using a DJI Phantom 4 drone. The DJI Phantom 4, equipped with a high-resolution camera, is an effective tool for digital modeling, as it can capture precise and detailed images of structures. The technical specifications of the DJI Phantom 4 are listed in Table 1.

Table 1. Technical characteristics of DJI Phantom 4 [19].

Endurance (min)		28
Maximum driving speed (m/s)		20
Sensor Properties	Maximum camera Resolution (Mp)	12.4
	Sensor size (mm)	4.7x6.3
	Pixel resolution	4000x3000
	FoV in degree	94
	Focal length (mm)	20
	ISO	100–1600
Maximum flight altitude (m)		6000
GNSS system		GPS, Glonass

Drones are often favored for documenting complex and large-scale structures, such as historical buildings, because of their capability to capture images over extensive areas quickly and efficiently. In this study, the images obtained from drone flights were processed using Agisoft Metashape software to create accurate digital models. Agisoft Metashape is a powerful software used to perform photogrammetric analyses and convert two-dimensional images into three-dimensional point cloud. Hundreds of aerial photographs obtained from the drone were processed and aligned within the software to create a detailed and precise point cloud model of the historic structure. At this stage, the surface geometry and characteristics of the structure were converted into a highly accurate digital format, resulting in a georeferenced model. Consequently, the complex geometric details and surface features of the structure were accurately recorded.

To ensure high-precision georeferencing during point cloud generation, a Geomax Zenith 10 GNSS/GPS device was employed. This device played a crucial role in determining ground control points (GCPs). Ground control points facilitated the alignment of images obtained from the drone with their actual ground positions, enabling accurate positioning of the point cloud. The GNSS/GPS device was used to ensure the accuracy of these points along the x, y, and z axes. The accuracy assessment of the control points obtained in this study is presented in Table 2. The extremely low error levels enabled the modeling of the resulting point cloud with exceptional precision in both the horizontal and vertical axes. Figure 1 illustrates the interface of the Agisoft Metashape software and DJI Phantom 4 drone.

Table 2. Accuracy assessment of control points

	X	Y	Z
Accuracy (cm)	3.1	2.2	3.2

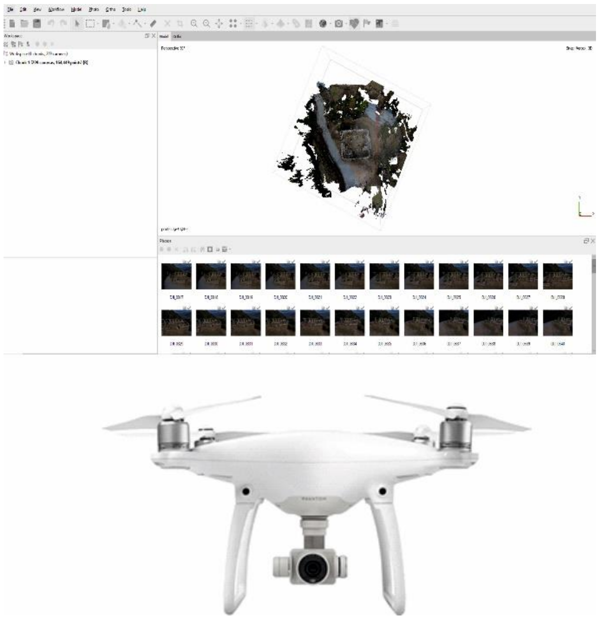

Figure 1. Interface of Agisoft Metashape software and DJI Phantom 4.

3. Result and Discussion

Following the generation of the point cloud using Agisoft Metashape, CloudCompare software was employed to enhance data quality and facilitate more effective analyses. The point cloud processing involved the initial elimination of noise and unwanted data. This step was crucial for removing erroneous points, which are inevitable in drone-derived data, and preserving only the necessary surfaces of the structure. Figure 2 illustrates the details of the cleaned point cloud, clearly revealing the geometric features of the structure. In CloudCompare, undesirable components such as vegetation, ambient noise, and transient objects were eliminated from the point cloud through the use of statistical outlier removal filtering methods and manual selection tools. The Statistical Outlier Removal filter computes the average distance between nearby points around each point and removes any points that differ considerably from this average. This removes points that are not part of the original structure and were produced by measurement errors. This procedure improves the accuracy of the model, resulting in a cleaner and more trustworthy point cloud. This stage created a smoother modeling foundation and increased the point cloud's analyzability. In order to create a solid model, the cleaned point cloud was then imported into SolidWorks software. Processing point cloud to create three-dimensional solid models is a key function of SolidWorks, a popular CAD program in engineering and design processes. Surfaces were created in order to model the main geometric characteristics of the structure throughout the shift from point cloud to solid model.

With its comprehensive 3D scanning and reverse engineering features, Geomagic for SolidWorks is a complex tool that enhances the SolidWorks environment. By enabling users to rapidly blend mesh models and point cloud data into SolidWorks, this program simplifies the process of turning point cloud data into solid models. Usually, point cloud acquisition is the first step in the procedure.

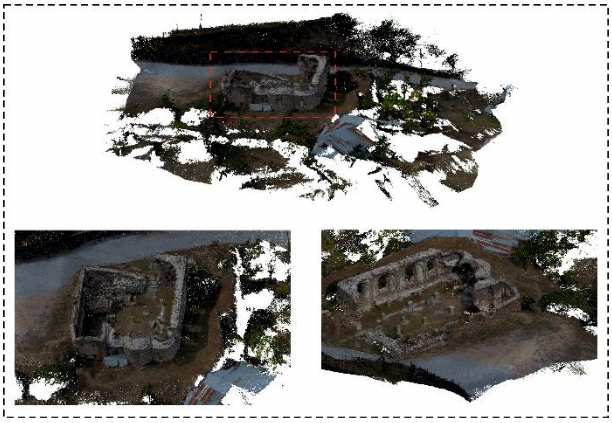

Figure 2. The study area is marked in red and viewed from various angles.

Point cloud filtering, alignment, and simplification are among the processing options offered by Geomagic for SolidWorks when data is received. Users can utilize filtering techniques to reduce noise and outliers in order to guarantee that the point cloud is of high quality and appropriate for further modeling. Following preprocessing, the application provides choices for generating surfaces from point cloud data. Users can create Non-Uniform Rational B-Splines (NURBS) surfaces that closely resemble the scanned object's geometry in order to handle and represent it correctly within the SolidWorks environment. NURBS is a mathematical modeling technique that provides a flexible and exact way to represent complicated geometries and surfaces. The software also offers capabilities for solid model development from extracted surfaces, making it easier to create and modify parts that are based on real items. Furthermore, Geomagic for SolidWorks facilitates the creation of parametric models, allowing users to update and modify designs more quickly. Technology for dimensioning and tolerancing is incorporated to guarantee that the final models satisfy technical requirements. Figure 3 shows the mesh model that is used as the basis for creating the sections from the imported point cloud.

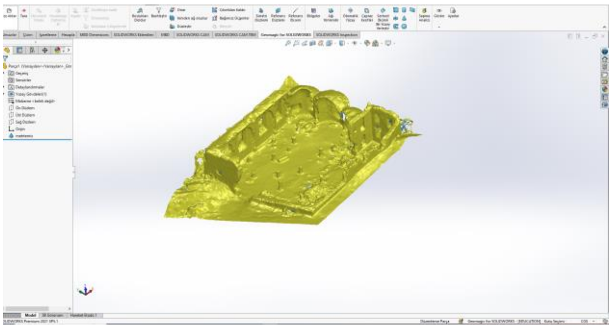

Figure 3. The mesh model of point cloud on Geomagic tool for SolidWorks.

Basic SolidWorks tools were used to optimize the surface spacing after the solid model was built, producing a solid model with noticeably better physical characteristics. The overall look of the solid model made in SolidWorks is seen in Figure 4, which also shows how the structure's intricacies were faithfully recreated in a digital setting.

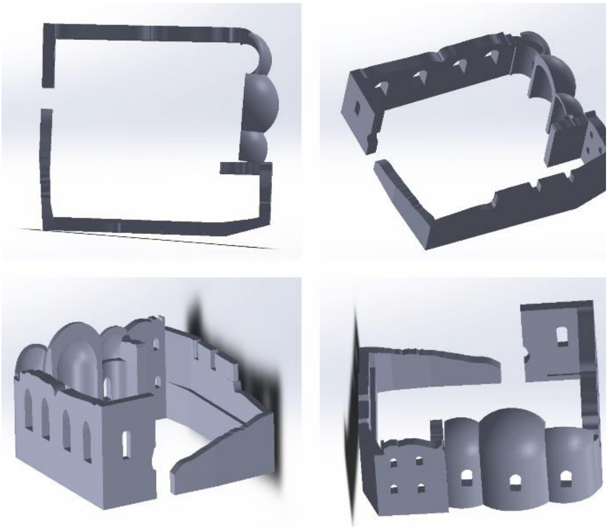

Figure 4. The solid model generated in SolidWorks, shown from different viewpoints.

This method created a reliable model that is currently a helpful digital tool for engineering studies, planning restorations, and structural assessments of the historic structure. The high degree of precision achieved during the conversion from the cleaned point cloud to the solid model ensured a comprehensive and accurate representation of the structure in the digital environment. As a result, every aspect needed for restoration work may be examined in the most original way possible. Comprehensive studies of the structure's existing condition and possible structural problems can be conducted by doing visual analyses and different simulations of the solid model.

A total of 30 measurements were made from different parts of the model and compared to field measurements using a steel tape measure. After comparing, the model exhibited an average error value of ±2.5 cm and a standard deviation of 0.8 cm. These results show that the model has a very high accuracy in general and that the historical structure is successfully represented in the digital environment. These errors confirm that the model is sensitive enough for scientific research and restoration planning.

4. Conclusion

Point cloud, which offer accurate and thorough digital recording, are essential for maintaining ancient structures. Using techniques like CAD and photogrammetry, this project presents a realistic recreation of the Gümüşhane Metropolitan Rum Church. The findings show that point cloud-based documentation is useful for scientific and technical evaluations in addition to restoration. By facilitating the early detection of structural deterioration, this method enables prompt treatments to stop additional damage. Furthermore, the development of 3D models opens up possibilities for educational and virtual tour applications, increasing access to cultural assets across the globe. Such buildings will continue to be a vital component of our cultural heritage, accessible for future generations to examine and enjoy thanks to digital preservation. This research provides considerable benefits in restoration efforts by allowing for the direct insertion of digital models into the restoration process. In particular, the high-precision solid model obtained provides a full and detailed depiction of the structure's current state. This model can be used as the primary data source to calculate the structure's surface geometry, dimensional deviations, and damage regions. Furthermore, it allows for the use of engineering calculations such as load distribution, material strength, and damage scenarios in structural assessments on a dependable digital platform.

Ethics committee approval and conflict of interest statement

There is no conflict of interest with any person / institution in the article prepared.

Authors' Contributions

MAG is responsible for writing, conceptualization, and application of methods; KFÖ is responsible for writing, research, editing, and literature search; ŞA is responsible for writing, research, interpretation, and editing.

Acknowledgement

This research received no specific grant.

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