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Methodology for Creating Digital Twins of Buildings Based on a Combination of LiDAR and HBIM Technologies (Case Study of Cultural Heritage Sites)

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SUMMARY

This study examines the creation of high-precision virtual copies of cultural heritage sites. Traditional architectural surveying methods do not provide the necessary speed and completeness of data, while existing digital solutions are often limited to static models that do not allow for comprehensive real-time monitoring of structures. This paper presents a comprehensive methodology for creating digital twins based on the synergy of laser scanning technologies and heritage building information modeling. The methodological approach includes four sequential stages: field collection of geospatial data (ground-based and aerial scanning), office-based processing of point clouds, semantic modeling of elements, and the creation of an intelligent digital twin of the monument. To implement this methodology, modern hardware and a specialized software environment were used to convert discrete data into parametric objects. The main results of the study are the development of an algorithm for creating semantically rich models that integrate information about materials, structural features, and the current condition of the monuments. The study identified the need to adhere to strict standards of metric accuracy, under which the permissible error in data alignment does not exceed 6 millimeters. The authors confirm that digital twins are dynamic systems that enable the creation of an objective digital record of a heritage site. This allows for the effective identification of design discrepancies, restoration planning, and monitoring of deformations, which is critically important for preserving the authenticity of historical sites.

Keywords: Digital twins; Cultural heritage; Laser scanning; Point clouds; Semantic modeling; Intelligent information models; Software tools.

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Introduction

In the era of digital transformation in the architecture and construction industries, the concept of digital twins is becoming a key tool for managing the lifecycle of various structures.

This approach takes on particular importance in the field of cultural heritage preservation. Historic buildings are constantly subject to the effects of time and natural factors, and in today's reality in Ukraine, they are also subject to direct destruction due to military actions.

Traditional methods of measurement and documentation are no longer capable of providing the necessary speed, accuracy, and completeness of data. In this context, laser scanning (LiDAR) technology, combined with building information modeling (BIM), offers an unprecedented solution that enables the creation of highly accurate three-dimensional (3D) metric models of physical objects in the real world, including buildings and structures, as well as those that constitute cultural heritage.

The rationale and development of a comprehensive methodology for creating digital twins of buildings from laser-scanning data, along with a demonstration of its effectiveness through practical case studies of cultural heritage sites, define the relevance and objective of this study.

Method and Theory

The theoretical foundation of this study is a combination of the principles of optoelectronic remote sensing, computational geometry, and the HBIM (Heritage Building Information Modeling) concept. The spatial coordinates of points are obtained from measurements of slant distances and scan angles using either the pulse or phase measurement principle.

To merge data sets from different monitoring stations, the following deterministic mathematical algorithms were applied: the 7-parameter Helmert transformation (for rigid alignment to the geodetic network) and the Iterative Closest Point (ICP) algorithm for mutual surface registration.

In accordance with the principles of non-destructive inspection set forth by the International Council on Monuments and Sites (ICOMOS' documentary resources – ICOMOS, 2026), digital documentation must provide an accurate representation of the monument's actual condition. The raw point cloud is the most complete digital representation of the object's geometry at the time of surveying.

The proposed methodology for creating a digital twin of a cultural heritage object is end-to-end and consists of four sequential stages: fieldwork; processing of point clouds obtained from laser scanning; semantic HBIM modeling; and the direct generation of an accurate digital twin of the physical object.

Examples

Numerous studies by both domestic and foreign researchers have focused on the application of laser scanning and BIM technologies, particularly HBIM. A general overview of selected publications, as examples of research conducted, reveals a shift in focus in modern geodesy, geoinformatics, and cartography from the static recording of objects to the creation of dynamic, semantically rich digital twins that integrate data from laser scanning, photogrammetry, and geoinformation technologies.

Researchers are actively studying the role of digital twins in heritage preservation (Akyol & Avci, 2025); describing the creation of geometric digital twins of specific temples in Montenegro and Iraq (Jelenić & Raznatovic, 2024; Lazim & Hillal, 2025); analyzing the challenges and strategies for developing 3D simulation models for digital twins of cultural heritage (Shabani et al., 2022); investigating the integration of survey data for cultural heritage analysis using virtual reality technologies (Elefante et al., 2025); describing 3D scanning tools and methods used to create phantom models of architectural objects (Tovbych & Popovych, 2023); providing examples of the application of technologies used to ensure the integrity of structures (Biehichev & Ishutina, 2023; Krotenko, 2023).

However, despite a substantial theoretical foundation, the practical aspects of developing an end-to-end methodology – from field scanning to the creation of a functional digital twin capable of integrating "live" data from sensors – for objects with complex, irregular geometry (which is characteristic of architectural monuments) remain insufficiently explored.

At the same time, most existing solutions are limited to creating 3D visualizations or static CAD models. There is a clear technological gap between obtaining the initial point cloud and transforming it into a semantically rich digital twin that could be used for monitoring deformations, planning restorations, and managing the site in real time. Furthermore, the adaptation of the methodology to specific architectural heritage case studies requires further elaboration, taking into account limited access to structures and their dilapidated condition.

Therefore, this study addresses the following tasks: formalizing the stages of collecting and preprocessing laser scanning data (point cloud registration, noise filtering); developing an algorithm for the semantic modeling of elements of historic buildings based on the obtained geospatial data; and analyzing the practical results of implementing the methodology on specific cultural heritage sites, while evaluating the accuracy and optimization of the resulting models.

Results

During the *field stage* of creating a digital twin of a cultural heritage site, data was collected in the form of point clouds by designing a scanning grid and conducting combined terrestrial laser scanning (TLS) of exteriors and interiors, as well as airborne laser scanning (ALS) to capture roofs and inaccessible areas.

Additionally, for example, in the case of a large-scale building, mobile laser scanning (MLS) using Simultaneous Localization and Mapping (SLAM) technology may be performed at this stage, designed for rapid surveying of complex interior passages, enclosed spaces, attics, or basements, where repositioning a stationary scanner would result in, at the very least, a loss of time for the overall completion of the work.

The fieldwork phase was carried out using a Leica RTC360 (for TLS) and a DJI Matrice 350 RTK (for ALS). For an optional step, a Leica BLK2GO or GeoSLAM ZEB Horizon can be recommended.

The *point cloud processing stage* generally involves filtering geometric noise, mutually stitching scans (or point clouds) based on markers and geometric features using the "point cloud to point cloud" principle, as well as georeferencing to a reference geodetic network using the global navigation satellite system (GNSS).

A comprehensive image of the cultural heritage site, obtained from the results of the field survey, is shown in Fig. 1. Additionally, in accordance with the specifics of the client's case study, two-dimensional building drawings (Fig. 2) should be produced as separate deliverables during the office processing phase.

The software selected for this stage consists of Autodesk products: AutoCAD and ReCap. Since AutoCAD does not work directly with "raw" scanner formats (LAS, E57, PLY), it is necessary to prepare an indexed file in ReCap, where the final stitching takes place (if this was not done in the scanner manufacturer's software), noise filtering, and export to Autodesk's native RCP or RCS format.

Creating drawings is the most labor-intensive step in this phase, during which AutoCAD's automated tools are combined with the specialist's manual work to achieve architectural precision.

Figure 1. *A 3D image of a cultural heritage site, rendered in AutoCAD*

Figure 2. *A precise 2D drawing of a cultural heritage site, created by processing point clouds in AutoCAD in conjunction with Autodesk ReCap*

The semantic HBIM modeling consists of transforming a discrete point cloud into parametric 3D objects by applying a mathematical approximation method (embedding geometric primitives into the point cloud) and manually modeling irregular historical structures. To this end, the proposed methodological framework uses Revit software, in which an intelligent 3D parametric model of the study object is created, where each of its elements (facades, roof contours, pediments, cornices, window and door openings, decorative elements, and other structural details) contains information about its geometry, material, and historical condition.

The interaction between ReCap and Revit forms the basis of the modern process of transferring field measurement data into digital information modeling and the HBIM concept for cultural heritage sites. These programs operate in a direct (or, one might say, classical) workflow, where ReCap serves as the tool for initial processing of spatial metrics (acting as a data provider or “donor”), while Revit serves as the environment for creating the digital model (acting as the “recipient”), as well as in the reverse direction, which is particularly useful for comparing design and actual results. Specifically, 3D objects or design solutions can be exported from Revit in FBX or OBJ format and imported into ReCap. This allows you to superimpose the future 3D model of a cultural heritage site’s reconstruction onto the actual point cloud and visually check for inconsistencies (for example, whether a new beam will intersect a historic wall that has a slope).

In the proposed methodology, the HBIM model is considered the informational foundation of a digital twin, which can be expanded through integration with monitoring systems and sensors.

The *final* and *most critical stage* before putting the digital twin into operation is the accuracy assessment and optimization of the resulting models (both point clouds and parametric HBIM models). This process ensures that the model is metrically accurate and that its file size will not overload the computer system’s hardware.

A successful evaluation of a digital twin project includes the following acceptable value parameters: the average error in the mutual alignment of scans in ReCap did not exceed 6 mm; the maximum deviation of the HBIM geometry from the point cloud at critical nodes must be within 15 mm for deformed historic walls; the model contains no geometric inconsistencies, specifically intersecting walls or beams that overlap one another; and file sizes are optimized for comfortable visualization and subsequent integration with IoT platforms. These objectives were essentially achieved in this work.

Conclusions

In today's environment, the preservation of cultural heritage requires a shift from traditional surveying methods to the creation of dynamic, semantically rich digital twins based on a combination of LiDAR and HBIM technologies. The proposed end-to-end methodology consists of four stages: comprehensive laser scanning (ground-based, aerial, and mobile) using state-of-the-art equipment (Leica RTC360, DJI Matrice 350 RTK), post-processing and filtering of point clouds in ReCap, intelligent parametric modeling in Revit, and the creation of the final digital twin. This approach ensures high metric accuracy (with an alignment error of up to 6 mm), allows for the objective documentation of the authentic condition of objects, identifies discrepancies, and integrates "live" sensor data for real-time deformation monitoring and restoration planning.

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