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Scientific and Methodological Foundations of Artificial Intelligence Technologies In 3d Modeling of Historical Architectural Heritage

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Abstract: This article examines the scientific and methodological foundations of applying artificial intelligence (AI) technologies to digital documentation, 3D modelling and virtual reconstruction of historical architectural heritage. The study considers photogrammetry, terrestrial laser scanning, UAV survey, computer vision, neural networks, NeRF, generative models and HBIM as an interconnected technological chain for heritage conservation. The key argument of the paper is that a 3D model of a historical monument should not be treated merely as a visual representation, but as a digital scientific document integrating geometry, material evidence, historical interpretation, structural condition and restoration metadata. As a result, the paper proposes a stage-based methodological framework, validation criteria and ethical limitations for AI-assisted modelling of architectural heritage. The findings are relevant for the development of digital monitoring, virtual museums, educational platforms and scientific conservation projects in historic cities of Uzbekistan such as Samarkand, Bukhara, Khiva and Shakhrisabz.

Keywords: artificial intelligence, 3D modelling, historical architecture, cultural heritage, photogrammetry, laser scanning, NeRF, HBIM, virtual reconstruction, computer vision, digital conservation.

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Introduction

In the twenty-first century, the preservation of historical architectural heritage is no longer regarded solely as an issue of conservation and restoration. Instead, it has become a complex interdisciplinary challenge associated with digital security, scientific documentation, monitoring, tourism, education, and cultural diplomacy. Climate change, urbanization pressures, natural disasters, human activities, and armed conflicts are increasingly affecting the physical condition of historical monuments. Therefore, it is essential not only to preserve heritage assets in their current state but also to create accurate digital replicas, analyze their historical layers, and establish scientific databases that can support future restoration and conservation decisions[1].

Within the field of digital heritage, 3D modeling technologies provide opportunities to comprehensively document the volumetric and spatial structure of architectural objects, façade proportions, decorative features, structural components, and existing damage conditions. However, the scientific value of a 3D model is not determined solely by its visual resemblance to the original object. Its significance depends on measurement accuracy, source-based reliability, semantic information layers,

metadata integration, and its applicability to conservation and restoration processes[2].

Artificial intelligence (AI) technologies have introduced a new stage in this process. Computer vision techniques enable the extraction of architectural elements from images; machine learning algorithms facilitate the classification of point clouds; generative models support the probabilistic reconstruction of missing or damaged components; and approaches such as Neural Radiance Fields (NeRF) and 3D Gaussian Splatting significantly expand the possibilities for reconstructing spatial scenes from multi-view imagery. At the same time, it is important to recognize that AI-generated results should not be accepted as historical truth without critical evaluation. Every reconstruction must be verified through documentary sources, comparative analysis, and expert assessment[3].

The purpose of this article is to provide a scientific analysis of the potential, methodological stages, advantages, limitations, and future prospects of applying artificial intelligence technologies to the 3D modeling of historical architectural heritage, with particular attention to their implementation in the context of Uzbekistan[4].

Research Object, Subject, and Objectives

The object of the study is the process of digital documentation and 3D modeling of historical architectural monuments. The subject of the research is the scientific and practical application of artificial intelligence algorithms, photogrammetry, laser scanning, point cloud analysis, generative reconstruction, and Heritage Building Information Modeling (HBIM) systems within this process[5].

The objectives of the study are as follows:

- To analyze the theoretical foundations of 3D documentation and artificial intelligence technologies;
- To identify the methodological workflow integrating photogrammetry, laser scanning, and AI technologies;
- To evaluate the capabilities and limitations of generative models in reconstructing missing parts of historical monuments;
- To develop scientific criteria for validating AI-based 3D models;
- To propose recommendations for establishing a digital heritage platform for the historical cities of Uzbekistan[6].

LITERATURE REVIEW

In the scholarly literature on the 3D documentation of cultural heritage, photogrammetry and optical scanning technologies are widely recognized as the primary methods for recording historical monuments. Remondino provides a comprehensive analysis of the capabilities and limitations of optical sensors, photogrammetry, and 3D reconstruction techniques in the measurement and modeling of heritage objects. Likewise, Gomes et al. describe the process of cultural heritage 3D reconstruction through a sequence of data acquisition, registration, integration, and texturing stage[7].

In recent years, artificial intelligence and deep learning technologies have become significant directions in the digitalization of heritage assets. Models such as Convolutional Neural Networks (CNNs), Vision Transformers (ViTs), and PointNet architectures are increasingly employed for the automatic detection of architectural elements, classification of point clouds, and identification of damaged areas. Generative approaches—including Generative Adversarial Networks (GANs), diffusion models, and Neural Radiance Fields (NeRF)—have considerably expanded the possibilities of visual reconstruction. Nevertheless, from a methodological perspective, the outputs of these models should be regarded not as historical evidence but as probabilistic reconstructions requiring further verification through documentary sources and expert assessment[8].

The concept of Heritage Building Information Modeling (HBIM) integrates information concerning geometry, materials, structural systems, historical periods, technical conditions, and restoration interventions within a unified digital environment. Penjor et al. emphasize the importance of HBIM for the documentation, analysis, management, and conservation of cultural heritage, while also highlighting challenges related to interoperability, multidisciplinary collaboration, and the modeling of complex

historical details[9].

UNESCO considers digital technologies to be strategic instruments for the preservation, management, and dissemination of cultural heritage. Digital mapping, 3D modeling, virtual museums, and online visualization of cultural assets play an increasingly important role in ensuring the transmission of heritage values to future generations and in expanding public access to cultural resources.

MATERIALS AND METHODS

This article was designed as a theoretical and methodological study. International scientific publications, methodological approaches to digital heritage, 3D reconstruction technologies, and the practical capabilities of artificial intelligence algorithms were analyzed. The research employed historical-comparative analysis, a systems approach, graphic-model analysis, technological workflow modeling, and the development of scientific validation criteria[10].

The data used in the 3D modeling process were classified into four groups: (1) photogrammetric images; (2) laser-scanning or LiDAR point clouds; (3) archival drawings, historical photographs, and restoration documentation; and (4) architectural analogues validated by experts. Artificial intelligence algorithms can be applied to automatically clean, classify, semantically segment, and probabilistically reconstruct missing parts of these datasets[11].

Table 1. Methodological Stages of AI-Based 3D Modeling of Historical Architectural Objects

Stage	Input Data	Role of AI	Output
1. Survey	Photographs, drone imagery, LiDAR data, archival materials	Image quality assessment and automated selection	Raw digital data
2. Processing	Images and point clouds	Noise reduction and segmentation	Cleaned dataset
3. Geometry Generation	SfM/MVS outputs, mesh models	Element extraction and classification	Accurate 3D model
4. Reconstruction	Missing fragments	Probabilistic reconstruction using GAN, NeRF, and diffusion models	Hypothetical reconstruction layer
5. Validation	Measurements and expert assessment	Identification of error zones and inconsistencies	Scientifically validated model
6. Archiving	HBIM and metadata	Semantic linking and information integration	Digital heritage database

AI-Based 3D Modeling Algorithmic Framework

In the proposed framework, artificial intelligence is considered not merely as a supporting technology but as an analytical tool that facilitates the entire workflow, from data acquisition to scientific validation. Nevertheless, final decisions must be reviewed and approved by historians, conservation architects, archaeologists, and engineering experts. Therefore, the model distinguishes between two separate levels: the “AI-generated result” and the “scientifically validated reconstruction.”

Algorithmic Workflow of AI-Based 3D Modeling of Historical Architectural Objects

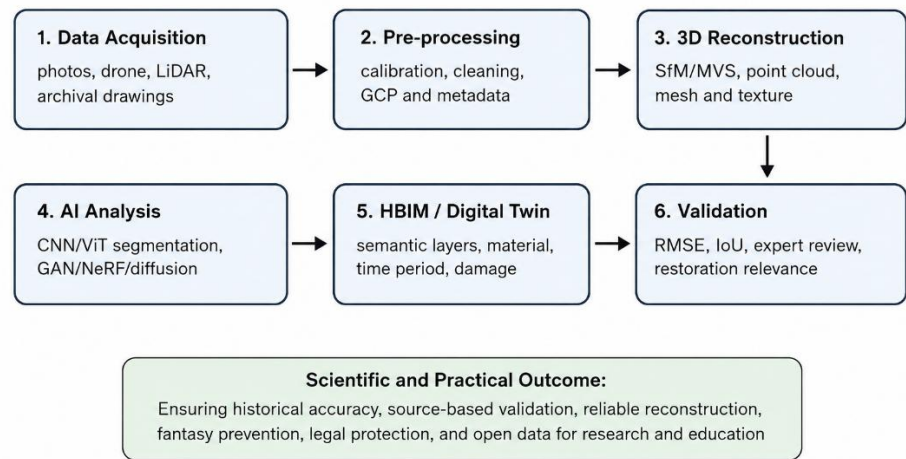


Figure 1. Algorithmic workflow of AI-based 3D modeling.

The principal advantage of this workflow is that it treats a historical monument not as a one-time visual model but as an evolving digital scientific document. For example, façade cracks, missing tile coverings, zones of structural deformation, and levels of material deterioration can be incorporated as separate semantic layers. These layers can subsequently serve as a valuable basis for monitoring activities and restoration decision-making processes[12].

Scientific Analysis of Technological Approaches

Although photogrammetry is an effective and cost-efficient method for the digital documentation of historical monuments, its accuracy largely depends on image quality, camera calibration, lighting conditions, and the availability of ground control points. Laser scanning provides a high level of metric accuracy; however, it requires expensive equipment, specialized expertise, and the processing of large datasets. Artificial intelligence plays an integrative role between these two approaches by enabling automated image selection, point-cloud segmentation, geometric feature recognition, and damage detection[13].

Neural Radiance Fields (NeRF) and related approaches, particularly 3D Gaussian Splatting, offer significant opportunities for the visualization and presentation of heritage monuments. Nevertheless, such models do not always provide the metric accuracy required for restoration purposes. Therefore, their application is most effective when combined with laser-scanning and photogrammetric data within a comprehensive scientific documentation framework.

Table 2. Applications of AI Technologies in 3D Modeling of Cultural Heritage

Technology	Primary Function	Strength	Risk / Limitation
CNN / ViT	Detection of images and architectural elements	Fast segmentation	Dependent on training datasets
GAN / Diffusion	Probabilistic reconstruction of missing parts	Visual content generation	Risk of historical speculation
NeRF / 3DGS	Spatial reconstruction from multi-view images	Realistic visualization	Requires metric accuracy control
PointNet / ML	Point cloud classification	Creation of semantic layers	Sensitive to noise and point-density variations
HBIM + AI	Documentation and heritage management	Long-term monitoring and	Standardization and interoperability

		data integration	challenges
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Practical Significance for the Historical Cities of Uzbekistan

In the context of Uzbekistan, AI-based 3D modeling is particularly relevant for historic cities such as Samarkand, Bukhara, Khiva, Shakhrisabz, Termez, and Kokand. In these cities, architectural heritage is represented not only by individual buildings but also by ensembles, neighborhoods, streets, panoramas, and historical landscapes. Therefore, digital modeling should document not only the façade of a monument but also its role and context within the broader urban environment.

An AI-based digital heritage platform could perform the following functions: (1) creation of 3D archives documenting the current condition of monuments; (2) monitoring of structural damage and deformation processes; (3) support for scientifically informed

Direction	Applied Technology	Scientific Outcome	Practical Benefit	Risk Control
Documentation	LiDAR + Photogrammetry	Accurate geometric representation	Digital heritage passport	GCP and RMSE verification
Restoration	HBIM + AI Segmentation	Identification of damage layers	Prioritization of restoration interventions	Expert validation
Reconstruction	GAN / NeRF / Diffusion Models	Probabilistic reconstruction of missing fragments	Visual reconstruction and interpretation	Source reliability assessment
Monitoring	AI Analysis + Time-Series Data	Detection of change dynamics	Early warning and preventive conservation	Periodic re-scanning
Education and Tourism	VR/AR + 3D Models	Interactive presentation of heritage	Public engagement and accessibility	Scientific interpretation and annotation

oration projects; (4) development of virtual tourism and educational content; and (5) assessment of the impact of new construction within protection zones on historical panoramas and urban skylines.

Table 3. Application Areas of an AI-Based Digital Heritage Platform for the Historical Cities of Uzbekistan

Results and Discussion

The results of the analysis indicate that AI-based 3D modeling of historical architectural heritage produces three major scientific outcomes. First, the metric geometry and visual condition of a heritage object can be documented with a high degree of accuracy. Second, architectural elements can be organized into semantic layers, allowing their structural, artistic, and historical values to be recorded and analyzed separately. Third, the reconstruction of missing components can be implemented as a source-based probabilistic model rather than as an unquestioned representation of historical reality[14].

The most significant aspect of the methodological approach proposed in this study is the interpretation of AI-generated outputs not as absolute truth but as scientific hypotheses subject to expert evaluation and verification. This principle is particularly important within the framework of international conservation ethics. Reconstructed

elements, surviving original elements, and components inferred through analogical comparison should be clearly distinguished through graphical representation, color coding, textures, or metadata annotations.

At the same time, AI technologies possess several limitations. First, deep-learning models require large, diverse, and high-quality datasets for effective training and reliable performance. Second, historical monuments often contain repetitive and visually similar architectural forms, which may result in classification errors and misinterpretations by algorithms. Third, generative models may produce visually convincing reconstructions of missing elements; however, these reconstructions are not necessarily historically accurate. For this reason, every AI-assisted reconstruction should be evaluated according to a defined level of reliability: high confidence for reconstructions supported by existing measurements and archival documentation; medium confidence for reconstructions based on verified architectural analogues; and low confidence for reconstructions generated primarily through AI-based prediction[15].

Scientific Contribution

- The process of AI-based 3D modeling is interpreted as a comprehensive methodological framework for the preservation and management of cultural heritage.
- The 3D model is conceptualized not merely as a visual replica but as a digital scientific document integrating geometry, historical information, material characteristics, deterioration data, and restoration records.
- A reliability assessment framework is proposed for components reconstructed through generative AI techniques.
- A digital heritage platform model is developed for the historical cities of Uzbekistan, integrating HBIM, AI-based monitoring systems, and virtual reconstruction technologies.

Conclusion

1. Artificial intelligence technologies significantly enhance the processes of documentation, analysis, monitoring, and virtual reconstruction of historical architectural heritage, introducing a new level of efficiency and scientific accuracy to 3D modeling workflows.
2. The integration of photogrammetry and laser scanning with AI technologies improves metric accuracy, enables advanced semantic analysis, and facilitates more effective management of heritage data.
3. Generative models are valuable tools for the hypothetical reconstruction of missing architectural fragments; however, their outputs should not be regarded as historical evidence. Instead, they should be treated as scientific hypotheses that require validation by experts.
4. HBIM and Digital Twin approaches are essential not only for the preservation of historical monuments but also for long-term monitoring, restoration planning, and the management of heritage protection zones.
5. The development of an AI-based digital heritage platform for the historical cities of Uzbekistan represents an important strategic direction for safeguarding national cultural heritage, strengthening scientific research, and promoting education and cultural tourism.

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