Photogrammetry and Grounded Generative AI for Non-Visitable Cultural Heritage: A Serious Game Framework

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Abstract. A growing portion of European architectural heritage remains effectively inaccessible: closed for safety reasons, awaiting restoration, or excluded from established tourist circuits. This inaccessibility creates a self-reinforcing loop, where sites are difficult to communicate because they cannot be visited, and difficult to fund because they are not communicated. We address this challenge through an integrated photogrammetry and AI-based framework, applied to the church and former monastic complex of Santa Caterina d'Alessandria in Gaeta, Italy — a historically significant site deconsecrated in 1989 and currently not open to the public. The proposed approach combines: (i) a multi-modal acquisition pipeline integrating aerial drone photogrammetry for exterior reconstruction with 360° spherical photogrammetry for partially collapsed interiors, resulting in a unified textured 3D model of the site in its current state; (ii) a serious game built directly on this model, where historical phases are introduced as time-localized holographic overlays anchored to the surveyed geometry, leaving it unaltered; and (iii) the controlled integration of generative AI tools, including a grounded virtual assistant constrained to a curated, site-specific bibliographic corpus. A key documentary principle underlies the entire system: all system components are explicitly constrained by documented evidence, ensuring consistency with available historical evidence. We present a prototype implementation developed in Unity, demonstrating the potential of the proposed framework as an evidence-constrained design strategy for cultural heritage valorization, while highlighting its current prototype nature.

Keywords: Photogrammetry · Grounded Generative AI · Non-Visitable Heritage · Cultural Heritage · Serious Games

1 Introduction

A substantial portion of European cultural heritage is effectively inaccessible: sites are closed for safety reasons, deconsecrated, or included in restoration programs with long and uncertain timelines. This condition is particularly common for minor heritage, such as small monastic complexes and peripheral archaeological sites. The resulting communicative gap creates a self-reinforcing loop: sites are difficult to communicate because they cannot be visited, and difficult to fund because they are not communicated.

Advances in pattern recognition and computer vision have largely addressed the first part of this problem. Photogrammetric and laser-based 3D acquisition are now established techniques for documenting architectural heritage [7,18]. However, transforming these data into engaging and reliable experiences for non-specialist audiences remains an open challenge. The recent diffusion of generative AI further complicates this scenario: while it lowers the cost of content production, it also increases the risk of generating plausible but unsupported information, which is incompatible with the requirements of cultural heritage communication. In this work, we address both aspects through an integrated framework grounded in a single documentary principle: all system components are explicitly constrained by documented sources, ensuring consistency with available historical evidence. This constraint responds directly to the asymmetry introduced by generative AI, where plausible content can be produced more cheaply than it can be verified. The approach is instantiated on the case study of the church and former monastic complex of Santa Caterina d'Alessandria in Gaeta, Italy, a historically documented site, deconsecrated in 1989 and currently not accessible to the public, with a documentary record that is rich but fragmented across heterogeneous historical sources. Previous studies on the architectural heritage of Gaeta have highlighted the role of integrated digital survey and historical analysis in supporting the interpretation and valorization of complex sites [15].

The main contribution of this work is an evidence-constrained design strategy that consistently aligns 3D acquisition, interactive storytelling, and generative AI under a single documentary principle: the system never asserts more than the available sources can support. The proposed framework combines three tightly coupled components, each enforcing this principle in a different modality. First, a multi-modal acquisition pipeline reconstructs the site strictly in its current observable state, avoiding unsupported geometric hypotheses. Second, a serious game is built directly on the reconstructed model, where historical information is superimposed as time-localized overlays without modifying the documented geometry. Third, a generative AI component based on retrieval-augmented generation [8] restricts the accessible knowledge to a curated, site-specific bibliographic corpus, ensuring that generated content remains grounded in documented sources. By enforcing consistency between data acquisition, content generation, and user interaction, the proposed approach provides a transferable strategy for the valorization of non-visitable cultural heritage, particularly in scenarios characterized by limited and fragmented documentation.

2 Related Work

2.1 3D Acquisition and Reconstruction for Architectural Heritage

Photogrammetric and laser-based 3D acquisition is by now established practice for architectural heritage. Recent work on unmanned aerial vehicle (UAV)-based photogrammetry has further extended these approaches to multi-scale acquisition scenarios, enabling efficient survey from urban to architectural levels [16]. In parallel, neural radiance fields (NeRF) [11] have expanded the toolset, particularly for view synthesis and photorealistic rendering, while spherical photogrammetry has matured as a practical solution for indoor and constrained-access environments [2]. For our purposes the relevant trade-off is not visual fidelity but *geometric reliability*: once a 3D asset becomes the spatial substrate of an interactive application, its accuracy determines whether the resulting experience can claim documentary value.

The London Charter for the Computer-based Visualization of Cultural Heritage [9] formalizes this concern. Its fourth principle, *intellectual transparency*, requires that any visualization clearly distinguish what is documented from what is inferred. This principle has direct consequences for the design of narrative-driven heritage games, motivating approaches that avoid speculative reconstructions when the documentary base is insufficient to support them.

2.2 Serious Games for Cultural Heritage

The literature on serious games for cultural heritage is well established [1,12]. We adopt the notion of *cultural game* as a designed experience in which the ludic structure is constitutive of the cultural content, rather than merely decorative [3].

A number of existing projects provide relevant design references. *A Night in the Forum* [17] (CNR, Museo dei Fori Imperiali) addresses a condition similar to our case, where the original site is not physically accessible and the digital experience becomes the primary means of exploration; it also demonstrates the use of photogrammetric reconstruction as the basis for an interactive environment. Other projects, including *Father and Son* [19] (Museo Archeologico di Napoli), *Prisme7* (Centre Pompidou), *The Mooseman* [13] (Museo di Perm), and *Past for Future* [20] (Museo di Taranto), show that effective heritage games are those in which cultural content is not simply presented but *operationalized* through interaction. In this sense, the game mechanics themselves act as carriers of meaning, in line with Bogost's notion of procedural rhetoric.

2.3 Generative AI in Heritage Communication

The integration of generative AI technologies, including large language models, retrieval-augmented generation [8], generative video, and neural text-to-speech, into cultural heritage communication is rapidly emerging but remains methodologically under-constrained. The associated risks are well documented in the literature [4]: fluent generative systems, when not grounded in verifiable sources, tend to produce persuasive but unsupported content, leading to a fundamental asymmetry between the cost of generation and the cost of verification. In the context of cultural heritage, this issue is particularly critical, as the value of a communicative artifact depends on its alignment with the historical record. An assistant that generates plausible but unsupported historical details risks undermining public understanding instead of supporting it. This motivates a constrained use of generative AI in heritage applications. Instead of treating language models as free-form generators, recent approaches emphasize source grounding and transparency, for instance by restricting the retrievable corpus to curated domain-specific documentation and by explicitly exposing the limits of the available evidence. Similar concerns regarding transparency and epistemic reliability in AI-assisted heritage applications have been highlighted in [5].

3 Multi-modal Acquisition Pipeline

The acquisition pipeline defines the geometric and visual substrate of the proposed system and is therefore central to its overall methodological consistency. The pipeline is designed to document the site as it currently survives, including its limited accessibility and visible degradation, without introducing hypothetical historical states.

To this end, the 3D model that grounds the project was produced through three complementary acquisition strategies: aerial drone photogrammetry of the exterior, ground-based 360° spherical imaging of the interior, and supplementary close-range photogrammetry of selected architectural details. The integration of these modalities enables coverage of both accessible and partially inaccessible areas while preserving geometric coherence across scales. The adoption of a multi-modal strategy was motivated not only by the architectural complexity of the site, but also by the need to preserve continuity between documentary acquisition and interactive exploration. Since the reconstructed environment acts as the navigable space of the serious game, the pipeline was designed to prioritize spatial continuity and interpretability over geometric density alone. All datasets were processed in Agisoft Metashape Professional (v. 1.7.6), resulting in a unified textured 3D model that constitutes the common spatial foundation of the interactive and generative components of the system.

3.1 Exterior Acquisition via Aerial Photogrammetry

The exterior survey was conducted through low-altitude aerial photogrammetry using an UAV. The acquisition strategy was designed to ensure complete coverage of the architectural envelope while maintaining sufficient overlap between adjacent images for reliable photogrammetric reconstruction. Particular attention was devoted to the upper portions of the building, including roof structures, façades, and architectural elements not observable from ground level. The drone-based acquisition also enabled the documentation of areas affected by structural degradation and partial inaccessibility, which could not be reliably captured through conventional terrestrial imaging alone.

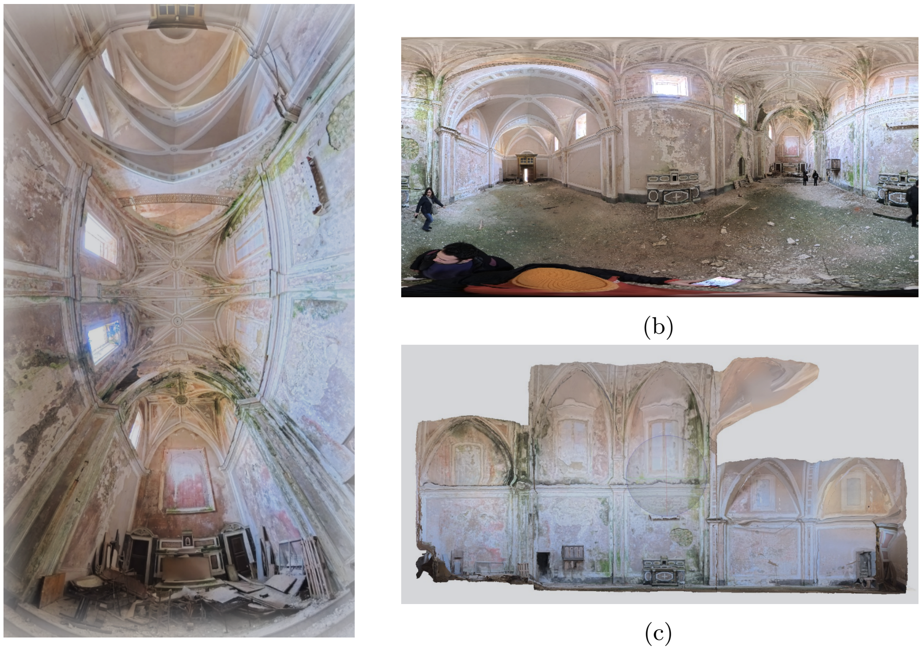
(a) Aerial view.

(b) Frontal view.

(c) Lateral view.

Fig. 1: Exterior photogrammetric reconstruction generated from the acquired aerial imagery.

The acquired imagery was processed through a standard Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflow in Agisoft Metashape Professional. From the acquired imagery, consisting of 1,141 images, the SfM alignment produced 614,747 tie points, from which a textured 3D reconstruction of the entire complex and its surrounding urban context was generated. Figure 1 illustrates different views of the reconstructed exterior environment obtained from the photogrammetric pipeline. Dense reconstruction at medium quality produced a point cloud of about 45.3×10^6 points (45,281,065), from which the final textured mesh was derived.



(a) (b) (c)

Fig. 2: Interior acquisition and photogrammetric reconstruction workflow.

3.2 Interior Acquisition via Spherical Photogrammetry

The interior spaces of the complex presented significantly different acquisition constraints compared to the exterior survey. Partial collapse, narrow passages, limited illumination, and restricted accessibility prevented the use of conventional terrestrial photogrammetric workflows in several areas of the site.

To address these limitations, the interior acquisition was performed through 360° spherical imaging using a dual-fisheye camera (Insta360, native resolution up to 8K per frame), enabling rapid and continuous capture of the navigable spaces while minimizing operator movement within structurally fragile environments. Figure 2a shows a 360° interior acquisition of the church nave, while Fig.2b reports the corresponding equirectangular projection generated from the spherical imagery. The acquired data were subsequently processed within a photogrammetric workflow in Agisoft Metashape Professional, producing a textured 3D reconstruction of the accessible interior spaces, illustrated in Fig.2c. This approach also facilitated the documentation of spatial continuity across rooms and corridors, which was essential for the subsequent integration of the interior and exterior models. While the resulting geometry is less detailed than that obtained through close-range photogrammetry, the adopted strategy provided a robust compromise between geometric coverage, operational safety, and documentary fidelity in a partially inaccessible environment.

Fig. 3: Photogrammetric reconstruction imported into the Unity environment as the navigable spatial framework of the serious game prototype.

3.3 Model Integration and Processing

The exterior and interior reconstructions were aligned and merged into a unified textured 3D model of the site. The integration combined aerial, spherical, and close-range photogrammetric acquisitions within a common spatial reference, enabling continuous navigation across the complex. The alignment was performed through a combination of automatic feature matching and manual control point placement, particularly in transition areas where the field of view of the aerial and spherical acquisitions partially overlapped. Particular attention was devoted to preserving geometric coherence between modalities characterized by different acquisition scales and reconstruction densities. Supplementary close-range acquisitions were used to refine selected architectural details insufficiently resolved in the large-scale surveys. Beyond geometric integration, the processing stage also aimed to preserve spatial continuity between exterior and interior spaces, which was essential for the design of the interactive experience. Since the reconstructed environment functions as the navigable space of the serious game, discontinuities or inconsistent transitions between acquisition modalities would directly affect the interpretability and immersion of the experience.

The final model represents the site in its current observable condition, including visible degradation and inaccessible areas. The pipeline preserves these absences as part of the documentary state of the heritage asset, leaving missing portions unreconstructed. Figure 3 shows the photogrammetric reconstruction imported into the Unity environment, where the surveyed geometry defines the navigable spatial structure of the serious game prototype.

4 Serious Game Design

The serious game was designed as an interpretative layer built directly on top of the surveyed 3D model. The experience preserves the present state of the site and introduces historical information through localized narrative and interactive elements, without simulating hypothetical past configurations. This choice derives from the limited and fragmented documentary record available for the monument. While historical sources describe the evolution of the complex across different periods, they do not provide sufficient evidence to support a fully reliable geometric reconstruction of its past configurations. Consequently, the game design adopts a layered narrative approach in which historical content is superimposed onto the surveyed geometry without altering its documented state. The resulting experience combines spatial exploration, contextual storytelling, and interactive interpretation while maintaining consistency with the available documentary evidence.

4.1 Design Principles and Constraints

The design of the serious game was guided by the principle that historical interpretation should remain visually and conceptually distinguishable from documented reality. For this reason, the surveyed 3D model is not altered to simulate hypothetical past configurations of the monument. Instead, the current observable state of the site remains continuously visible throughout the experience. Historical information is introduced through localized holographic overlays, textual fragments, and contextual multimedia elements positioned within the reconstructed environment. These elements act as interpretative layers associated with specific locations and time periods, allowing users to explore the historical evolution of the complex without replacing the surveyed geometry with speculative reconstructions.

This approach also supports transparency in the communication of uncertainty. Areas for which limited or fragmented documentation is available are intentionally left unresolved, avoiding the risk of presenting conjectural content as documentary evidence. The game therefore operates not as a simulation of a lost historical state, but as an interactive framework for contextualizing and interpreting the existing architectural remains.

4.2 Narrative Structure and Interaction Design

The interactive experience is structured around the free exploration of the reconstructed environment. Players navigate the complex in first person, progressively accessing contextual information associated with specific architectural spaces and historical phases of the site. The game adopts an environmental storytelling approach: historical interpretation emerges through spatial exploration rather than through a predetermined narrative order. Holographic elements, archival references, audio narration, and multimedia content are distributed throughout the environment and activated by proximity or direct interaction, encouraging exploratory engagement with the monument. Each interpretative unit is associated with a documented historical phase and anchored to a specific location within the surveyed geometry. When the user reaches the corresponding hotspot, the related holographic overlay appears within the reconstructed environment without modifying the underlying geometry (Fig. 4). The narrative progression

(a) Narrative node activation. (b) Holographic figures.

Fig. 4: Example of narrative interaction within the serious game environment.

therefore reflects the structure and granularity of the available documentary record.

4.3 Documented Events and Interpretive Variability

A central interaction principle of the proposed design is the distinction between documented events and their interpretation. The events associated with each narrative unit are treated as fixed: users cannot alter the historical record, and each interaction ultimately converges toward the documented outcome. The variability of the experience therefore does not derive from alternative historical developments, but from the interpretative perspective through which the event is contextualized. Different interaction paths expose different subsets of the available documentary material, including archival references, chronicle excerpts, and narrated fragments, without any perspective claiming privileged access to historical truth. The system therefore allows interpretative variability while preserving the stability of the documented event itself.

This design reflects a broader historiographical principle: historical events may admit multiple coherent interpretations even when the underlying documentary evidence remains unchanged. Within the proposed framework, user agency is consequently restricted to interpretation rather than event modification. This constraint is consistent with the documentary principle that motivates the entire system. As the acquisition pipeline limits the 3D reconstruction to the observable state of the site, and the virtual assistant restricts generative outputs to curated documentation, the narrative layer similarly constrains the space of possible interaction. The three components therefore implement different forms of the same documentary principle: the system never asserts more than the available sources can support.

5 Generative AI Components

Generative AI technologies were employed as supporting components within the project pipeline, primarily to enhance interaction, accessibility, and content production. Their integration, however, was intentionally constrained in order to preserve consistency with the documented historical record of the site. Within the proposed framework, generative AI is treated as an interpretative interface to documented knowledge rather than as an authoritative generator of historical content. Accordingly, the project adopts a grounded approach in which generated outputs remain explicitly linked to curated documentary material. This constraint is particularly relevant in the context of cultural heritage communication, where plausible but unsupported content may compromise the reliability of the user experience.

The proposed framework integrates generative AI in two main forms: a retrieval-augmented virtual assistant designed for interactive cultural dissemination, and a set of generative media tools employed during the prototyping and production stages of the experience.

5.1 Grounded Virtual Assistant

The interactive experience includes a virtual assistant designed to provide contextual historical information during navigation of the site. The assistant is based on a RAG architecture [8], in which the language model, instantiated through the OpenAI ChatGPT API [14], accesses a curated corpus composed exclusively of site-specific documentation, historical references, and bibliographic material. The system is explicitly constrained to produce responses grounded in the retrieved documentary sources and to decline queries not supported by the available corpus. The objective of this design is to reduce the risk of unsupported or hallucinated historical claims while preserving natural and interactive access to the documented knowledge associated with the site. Retrieved passages therefore act as the primary contextual basis for response generation, promoting consistency between the assistant output and the curated historical material. Within the virtual environment, the assistant functions as an interactive interface for accessing the documentary corpus during the user experience.

5.2 Generative AI for Multimedia Content Production

Generative AI techniques were employed during the prototyping and multimedia production stages of the project to support the creation of audio narration and visual content within the virtual experience. In particular, neural text-to-speech systems were explored for the generation of contextual narrations and character-associated voices, providing an additional acoustic layer accompanying the holographic overlays during spatial exploration. In our implementation, we employed ElevenLabs [6] as an example of a neural voice synthesis platform capable of generating expressive multilingual narration from textual scripts.

Similarly, generative video models were investigated for the rapid prototyping of conceptual scenes, narrative transitions, and interaction dynamics prior to their integration into the real-time environment. For this purpose, we experimented with Meta AI [10] tools during the early design stages to support the visualization of

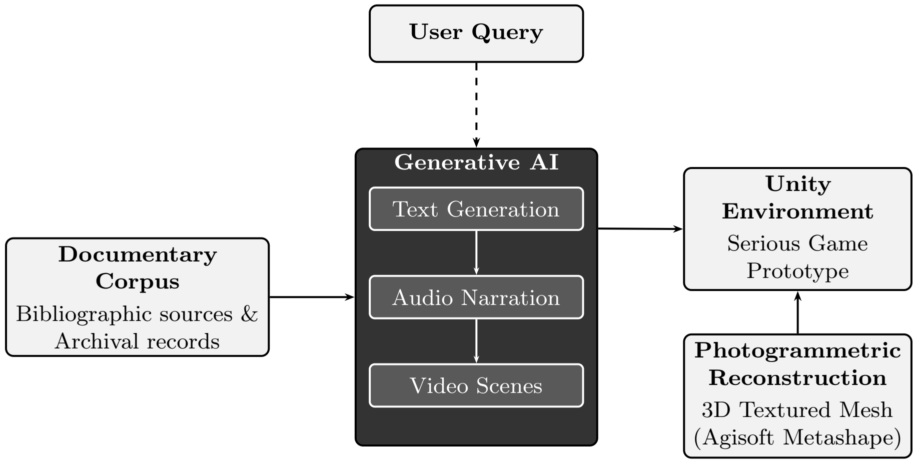


Fig. 5: The Generative AI Pipeline

interaction concepts before the final photogrammetric assets were fully processed and optimized for real-time rendering.

6 Implementation

The interactive prototype was implemented in Unity, chosen for its native FBX import path and for the possibility of targeting multiple platforms (PC, mobile, and standalone VR) from a single code base. It is developed as a first-person navigable environment built directly on the integrated photogrammetric reconstruction of the site. As shown in Fig. 5, the Unity environment constitutes the convergence point of all system components described in this work: the photogrammetric reconstruction provides the navigable spatial substrate, the generative AI pipeline contributes narrative text, audio narration, and video content, and the grounded virtual assistant provides interactive access to the documentary corpus. These components are integrated into a unified interactive framework that supports spatial exploration of the heritage site, activation of holographic narrative overlays anchored to the surveyed geometry, and conversational interaction constrained to the available historical documentation.

The reconstructed environment was optimized for real-time navigation while preserving the spatial continuity and visual characteristics necessary for architectural interpretation. The current implementation represents a functional proof of concept aimed at evaluating the feasibility of evidence-constrained interactive heritage communication based on photogrammetry, serious game design, and generative AI.

7 Conclusions

The proposed framework explores the integration of photogrammetric reconstruction, serious game design, and generative AI for the valorization of non-visitable cultural heritage under explicit documentary constraints. The central methodological choice of the project is to preserve the distinction between documented evidence and interpretative content across all components of the system. This approach is particularly relevant for minor heritage sites, where incomplete documentation and limited accessibility often make fully reliable historical reconstruction impossible. Instead of compensating for these absences through speculative visualization, the framework treats uncertainty and incompleteness as part of the communicative condition of the site itself.

The current work represents a preliminary prototype, and its contribution lies in the design strategy rather than in its empirical validation. The design strategy described above is largely independent of the specific site. What transfers to other contexts is the strategy itself and its three instantiations: a multi-modal acquisition pipeline for partially inaccessible sites, a narrative layer in which user agency is restricted to interpreting documented events, and a retrieval-augmented assistant confined to a curated corpus that declines unsupported queries. These components are agnostic to the particular monument. What is necessarily site-specific is the documentary substrate on which they operate: the curated corpus, the historical phases of the complex, and the reconstructed 3D assets. Porting the framework to a new site therefore amounts to replacing this substrate while preserving the underlying constraint, rather than redesigning the system.

Future developments will include formal user evaluation, analysis of user engagement and learning outcomes, and the extension of the framework to additional heritage contexts characterized by similar conditions of limited accessibility and fragmented documentation.

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