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A Multi-scalar and Multi-modal Approach to Architectural Heritage Documentation: An Interactive Digital Representation of the St. Nicholas Chapel

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Abstract. The documentation, curation, and dissemination of endangered architectural heritage requires multidisciplinary expertise and imaginative engagements with heterogeneous formats and scales of analysis. Through a case study of a Carpathian-style chapel in Beaver, Pennsylvania, St. Nicholas Chapel, we explore how an architectural heritage building might be interactively documented in a way that situates it within long-standing architectural traditions while remaining attentive to its social and material specificity. We present a prototype of an interactive document showcasing a multi-modal and multi-scalar approach to architectural heritage that innovatively brings together data-intensive typological analyses, historical documentation, ethnographic interviews, geometric studies, and photogrammetry and LiDAR captures. The web-based document offers a highly detailed portrait of the St. Nicholas Chapel, inviting a broad audience of users to dynamically explore it through a combination of high-quality imaging and scanning methodologies, artificial intelligence (AI)-enabled geometric analyses, historical materials, and first-person accounts of its construction.

Keywords: Digital Cultural Heritage, Digital Heritage Storytelling, Carpathian Wooden Churches, Architectural Distant Reading, Interactive Digital Representation

1 Introduction

The documentation, curation, and dissemination of endangered architectural heritage pose complex challenges that require multidisciplinary expertise and innovative methodologies with heterogeneous formats and scales of analysis. In the present contribution, we propose a multi-modal and multi-scalar approach for the analysis and dissemination of historical architectural heritage utilizing high-quality imaging and scanning methodologies, as well as artificial intelligence analysis and reproduction techniques, alongside historical and ethnographic research. Closely examining an example from the endangered architectural heritage of Carpathian-style wooden churches, our goal is to provide an example of an enriched portrayal of an architectural heritage building. The final output consists of a prototype of an

innovative interactive digital document where these different resources are made accessible, enabling innovative storytelling and cultural engagement. Our work builds on recent architectural heritage scholarship aiming to combine the methodologies of *distant* and *close* reading of architectural data through the application of advanced computational analysis techniques. In particular, the use of emerging neural and geometric analysis methods to create lightweight representations of existing structures, and to analyze their morphological features. We draw on the terms architectural distant reading and close reading, which refer to a specificity of scale and cultural reach between an architectural style or cultural movement, and a single object or structure, respectively [1].

With the aim of holding these different scales of analysis together, this paper draws from two main sets of materials. First, an in-depth digital capture of a Carpathian-style wooden chapel in Pennsylvania, conducted by our team. The process combined different digital capture techniques, including geometric studies, photogrammetry and LiDAR captures, historical and archival documentation, and ethnographic interviews. Second, we draw from prior works employing deep learning (DL) techniques, of a dataset of 331 wooden folk churches dating from the 17th to the early 20th century in the central Carpathian region [2]. These two scales of analysis come together in a custom platform we designed to collect and integrate our close reading of St. Nicholas with pre-existing distant analyses of the typology it belongs to. Our aim is to showcase how advanced computational techniques for the capture and analysis of architectural heritage might converge into a compelling, interactive digital document accessible to a broad audience.

1.1 Case Study Context

Our case study focuses on a Carpathian-style wooden chapel in Beaver, Pennsylvania, USA built in the 1990s to serve the religious needs of a local Rusyn diaspora community. The building expresses the distinctive wooden architectural traditions particular to the historic "homeland" of the Rusyn's located within the Eastern Carpathian mountain region of present day Ukraine, Poland, and Slovakia. Built between the 17th and early 20th centuries, churches belonging to this tradition have been endangered by many factors [2]. In the last several years, the conflict between Russia and Ukraine has further endangered these unique structures, adding to the urgency of their documentation and care [3]. While some recent efforts have helpfully focused on digitally documenting instances of this traditional style [21], our case study takes a different approach. It illustrates on one hand how the long standing architectural tradition of Carpathian wooden churches played a role in helping communities of Rusyn migrants to establish themselves in a new, distant context, fostering a sense of belonging. On the other, by precisely tracing the architectural genealogy of St. Nicholas in this broader tradition, it illuminates the mobility of historical architectural styles, and their importance as cultural signifiers in a diaspora community that adopts them — while also keeping them in motion.

1.2 Outline

Our paper is structured as follows. In section 2 we provide a brief overview of the state of the art in digital cultural heritage, paying attention to contemporary digital

representation techniques. In section 3 we discuss the missing overlap of cultural heritage preservation and emerging computational analysis methods, identifying the gap that our implementation fills within these two realms. In section 4 we discuss the data collection techniques we employed, including the purpose and rationale behind each technique, and the utility of each technique in addressing specific documentation needs. In section 5 we discuss the process, challenges, and opportunities with integrating these techniques into a cohesive 3D representation of the St. Nicholas Chapel. The final section summarizes the findings and scope of this research, including limitations and next steps.

2 Related Works



Fig. 1. Previous works using computer vision techniques to reconstruct 3-D models of Carpathian churches from ground-based, drone, and satellite imagery (Images from [6]).

The field of digital cultural heritage (DCH) is rapidly evolving alongside the advancement of novel techniques and the increased accessibility of 3D capture and high-fidelity data collection technologies. However, the ability to combine, clean, and centralize the vast amounts of data created through separate processes is still in its infancy. Several consumer-grade hardware packages require the use of proprietary formats, and many of the most contemporary AI techniques for photo-realistic novel-view synthesis are undersupported by most technology stacks for web-based representation. Consequently, efforts to combine heritage data often remain soiled, limiting their impact beyond preservation circles [3]. This section presents recent case studies that informed our approach to conducting the analysis of the St. Nicholas Chapel and structuring the workflow for the data collection and dissemination platform.

As previously mentioned, due to the enormous discrepancy in the data that emerge from the processes of studying architectural buildings, experiments that combine distant and close reading methodologies are rare. While architectural studies traditionally prioritize close reading approaches, recent research shows a burgeoning interest in computational methods for analyzing extensive architectural datasets [1, 4, 5]. In this work, we draw in particular from recent work employing architectural distant reading techniques to extract subtle features of physical architecture of 331 Carpathian churches from photographs, online resources and archives [2, 6] [Fig. 1].

On the other hand, in terms of close architectural readings, recent efforts to digitize buildings, rooms, and artifacts for freely available virtual exhibitions have created a new venue for scholarship at the intersection of preservation and digital storytelling [7], with the purpose of curation and with a multifaceted excitement in the fields of lightweight digital representation of physical goods. Overall, one of the most popular methods is the 3D virtual reproduction of cultural heritage [8], also involving VR/XR applications, Web3D technologies, metaverse [9], and tools from video game design [10]. These experiments allow for a variety of potential enrichments in the ways of heritage fruition, such as the virtual visitation of sites with limited accessibility [11], or the augmentation of the experience through the visualization of different layers and temporal phases of an architectural object not necessarily visible to the naked eye [12, 13]. Projects such as the Brancacci VR project in Florence [14], the 3D reconstruction of Sala degli Stemmi at Pisa [15], and the Dame_Heritage [16] exemplify the increasing efforts in leverage restoration and diagnostic data to create multidisciplinary and multiscale virtual experiences. In the context of endangered built heritage, initiatives like #SaveUkranianHeritage [17] by the research collective SKEIRON and Heritage at Risk [18] in Algeria aim to digitize architectural and artistic heritage, preserving historical memory and promoting wider accessibility. In terms of dissemination tools, the choice is crucial and can range from open-source solutions such as the ATON project, to collaborations with private digital data collection platforms, such as Europeana and Google Cultural Institute's Arts & Culture [19].

These examples are significant as they assemble multidisciplinary datasets from the analysis of individual buildings or specific artistic elements. Some platforms extend their archive by collecting multiple buildings or different exhibitions. However, what remains lacking is the integration of the single building reproductions with broader contextual connections about stylistic, historical, and architectural milieus. This crucial connection is frequently overlooked, relegated to traditional textual tools, or omitted from the platform data altogether.

3 Our Approach

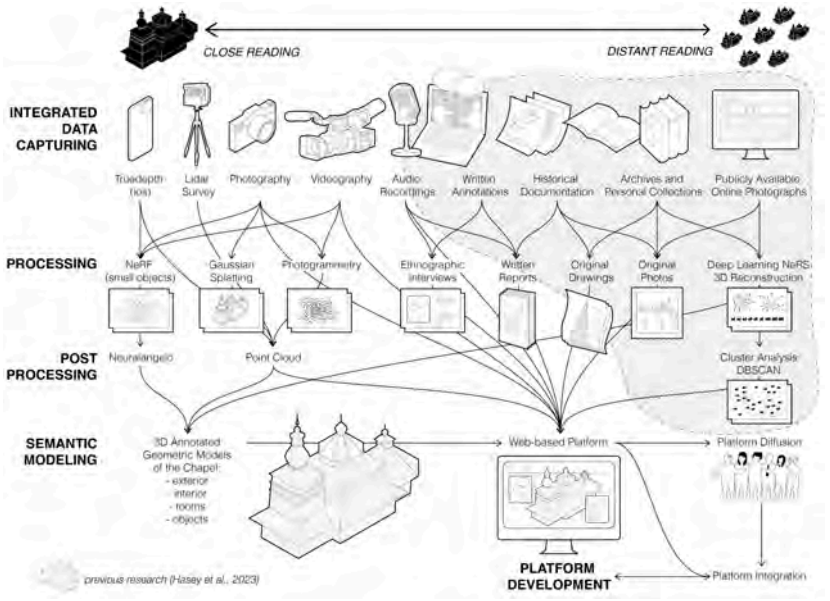


Fig. 2. Methods and pipeline for the capture, processing, and modeling through a variety of systems leading to the prototype.

Our approach seeks to bring together different styles of analysis and data, as well as to demonstrate an integrative environment where these are located. The diagram above [Fig. 2] summarizes the main elements of this approach, including different stages of capture and analysis. For example, the creation of a large database obtained by experimenting with different traditional and innovative techniques, the processing methods to obtain legible information, and the integration to generate the multimodal, interactive digital representation of the chapel.

4 Data Collection and Processing

In this chapter, we discuss the data collection process combining a close reading physical capture of a Carpathian-style chapel, with a distant reading overview of this style of architectural heritage using ethnographic interviews and data scraping. The following techniques are chosen and explored either due to their traditional use in historical preservation, or for their promise in alleviating issues, or expanding the utility of these techniques: ethnographic interviews with administrative staff and architectural historians, extensive on-site 3D data collection using a LiDAR scanner, extensive 2D data collection using high-resolution photography and videography. Finally, the captured data was utilized to reconstruct the chapel using several techniques, and at the building, room, and object scale.

4.1 LiDAR Scanning



Fig. 3. Mobile application interface to control Matterport Scanner, screenshot showing 70 scanning locations in an S-shape route on the main floor. Section perspective of the aligned interior scans of the whole building.

Light Detection and Ranging (LiDAR) technique captures 3D point clouds with high accuracy. It measures the time for the laser to be reflected from the target points on objects back to the receiver in a technique known as digital time of flight (ToF). It is common practice to use LiDAR to survey accurate geometries of physical structures, and further combine them with photogrammetry results. However, these scanners are also sensitive to bright sunlight and reflective surfaces, creating a short window for capture on days with direct sun exposure. Therefore, we chose LiDAR to obtain dense and accurate point clouds of the interior spaces only, and not outdoor detail that can be subject to bright light and includes high roofs that can extend beyond the functional range of the device.

We adopted a Matterport Pro 2, a consumer-grade terrestrial scanner that captures points in a small error of 1% of the distance within 8 meters and can be conveniently controlled using a mobile application. Since the point cloud files were heavy, we scanned each floor of the chapel individually and aligned them in post-processing. To ensure maximum coverage, we pre-planned an S-shape route passing through every other row of benches and scanned right in front of each icon and the iconostasis to obtain highly accurate details [Fig. 3].

4.2 3D Data Reconstruction From Images

Photogrammetry is a well-studied and proven technology for creating 3D geometry utilizing sequences of images, or frames from a video clip. There are several ways to implement this technology, but the best results often come from dedicated software that is capable of creating structure from motion, densifying point clouds, and meshing the results into 3D geometry. In this study, we implemented Agisoft Metashape under sequential and estimated, interpolated, and extrapolated processing pipelines from complete datasets as well as selections for objects of particular interest [Fig. 4]. Using specific lenses and lighting, a sequence of images or video can be 3D

projected and calibrated with simple measurements. A Canon 1D Mk.III with 40mm prime lens was used for this technique as the primary camera.

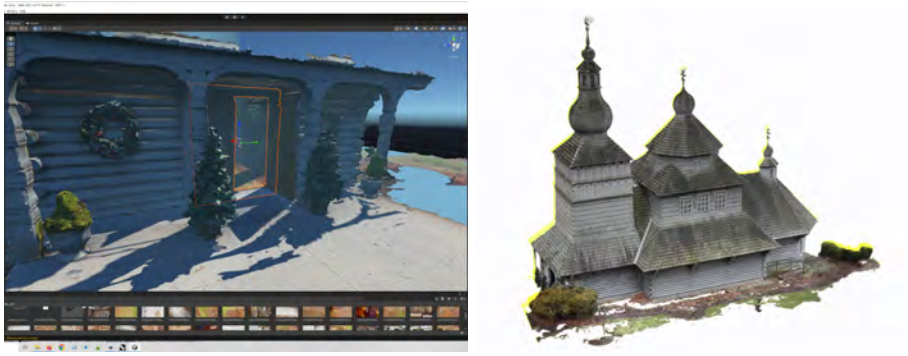


Fig. 4. Process capture from the photogrammetry pipeline and a Unity viewer (left) with the cleaned and edited final production model (right).

Neural Radiance Fields (NeRF) [20] is an emergent artificial intelligence (AI) representation of 3D scenes. It works on videos recording the 3D space and learns a fully-connected deep neural network to produce views that have never appeared in the videos, a technique known as novel view synthesis. Specifically, the neural network predicts the volume density and view-dependent emitted color radiance of every generated 3D point-of-interest in order to render the scene from a given viewing direction. Without the need for specialty equipment as in LiDAR scanning, we used Instant-NGP [21] to render photo-realistic views taking the same video input format as photogrammetry but handling shiny and transparent materials better. A Structure-from-Motion (SfM) technique [22] was first used to obtain camera extrinsics and salient point correspondences across video frames. Then a NeRF model representing each scene was trained in minutes, much faster than when compared to the hours required by photogrammetry methods. However, we noticed that the renderings looked better near seen views from the training dataset, and could be vague at novel views far away from the seen ones, usually coming with cloud-like artifacts. Another note is that the results from NeRF are renderings of the 3D scene. In other words, it has no geometric information beyond the underlying points themselves.



Fig. 5. Video frame (left) and NeRF novel view synthesis (right) for the incense in the sanctuary, which has shiny surfaces and thin chains.

Gaussian Splatting is a reversed ray-traced rendering technique for 3D scene reconstruction that is loosely related to NeRF. This technology is unique from other neural techniques as the color and size of each Gaussian are precomputed during training, allowing the scene to be more efficiently rendered during playback. The actual convergence time is relatively quick, and like NeRF, can create near-photorealistic scenes when viewed from reasonable angles. For our prototype, we employed two techniques for Gaussian Splatting creation - the first is from the inaugural paper by Kerbl et al., which provides the groundwork for this technique as well as a lightweight rendering engine for preliminary viewing of the processed scenes [23]. A subsequent implementation [24], called Splatfacto-big, is a recently released project that attempts to further reduce the rendering overhead of viewing scenes after initial training, and provides a higher density of Gaussians for a higher perceived resolution [24]. This format excels in rendering photorealistic representations of large areas such as rooms, furniture, or outdoor scenes, and is increasingly supported by interactive web viewing platforms.

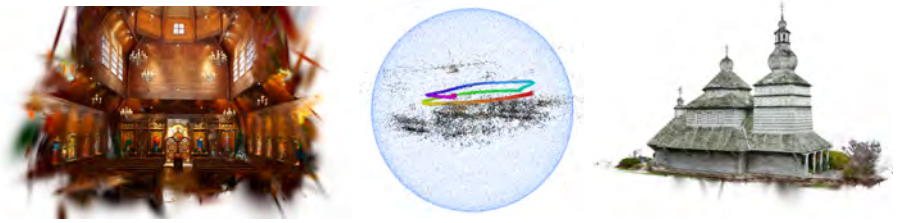


Fig. 6. Final result of an interior scene (left), COLMAP SfM (middle), and final result of an exterior scene (right).

4.3 Ethnographic Interviews

In addition to acquisition and reconstruction techniques, ethnographic interviews have been conducted to enhance the historical narrative of the chapel. Through this process we attempted to uncover cultural information that might not directly emerge from the pure technical analysis of the architectural object. During the surveys and data capturing sessions, significant background information about the chapel was gained by engaging in dialogue with locals. During an interview with a member of the organization that had promoted the construction of the chapel we learned surprising insights into the design development process of the project: “We did have like 3 structures that we initially took the idea of the design from. The tower section from the wooden church in Bardejov. [...] Then, in the middle section was from Nová Sedlica Church, which I think is St. Michael's Church. Then, the Altar section was from St. Nicholas Church in Zboj. So, we used those as models for those 3 different sections of the church.” Insights like this allowed for a cross referencing with the information uncovered by previous scholarship through neural cluster analysis [6]. In addition, relevant information was found pertaining to construction choices and deviations from the Eastern European tradition:

It was his (the craftsman) idea to use half logs. So those logs are all flat on the backside because we had to use modern-day construction code; we couldn't do what they did over there. With the logs they used, they would just start leaning them in so the upper part of the charts would get a little bit narrower at the top. The weight of all the walls would hold them together, and that's how they were able to attain that height with the logs. But we had to use the building codes in America. So that's why when you come inside and then you see those big, long arches that seem to be built of wood, but they're actually holding up a lot of the construction on the inside." Remarkable were also the details about hidden structures invisible in the previous capture process: "You know the tower section, the cinder block is constructed with a steel frame and then covered with the wood. It is definitely not as it would have been built in the old country. On the inside, those are all stud walls and then with the help of those interior arches that would enable them to build the height that they wanted but also to maintain that integrity of using wood all the way through the structure on the inside.

4.4 Historical documentation

The historical documentation includes the more 'traditional' architectural research material that was sourced by the working group. This includes the original drafted architectural drawings, and the photographic and written archive of traditional churches that was compiled as reference imagery for the construction of the American chapel.

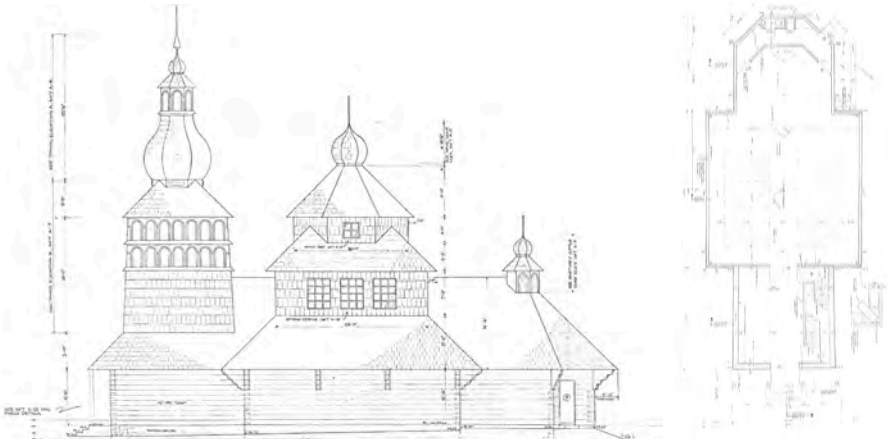


Fig. 7. Pictures of the St. Nicholas Chapel's original drawings (source: Archives of the Greek Catholic Union, 1991)

5 Interactive Storytelling Prototype

The materials described above create a significant cultural dataset on the St. Nicholas Chapel that can be shared and enabled for many different applications. Drawing from this dataset, we prototyped an interactive, online document bringing together the multi-scalar and multi-modal analyses described above to a broad audience.

The prototype aims at presenting a comprehensive portrait of the chapel using various media and allows users to dynamically explore which acts as a repository for the information captured and created in section 4. The website thus functions as a hub for supplemental and continued reading about cultural heritage, and, potentially, as a link aggregator for similar projects. To achieve this, the document is composed of three main sections, *History, Tour,* and *Video.* As shown in the information architecture diagram [Fig. 8], users can choose to explore the chapel at different scales, with the option to jump to other sections at all times. Alternatively, when the website opens, users have the ability to follow the pre-prescribed linear order by scrolling through the page. *History* offers a distant reading of the cultural and architectural history, and the *Tour* of the Chapel allows the user to enter an explorable 3D model of the interior space. Finally, the *Video* experience concludes with a pre-recorded summary of the stories of the chapel.

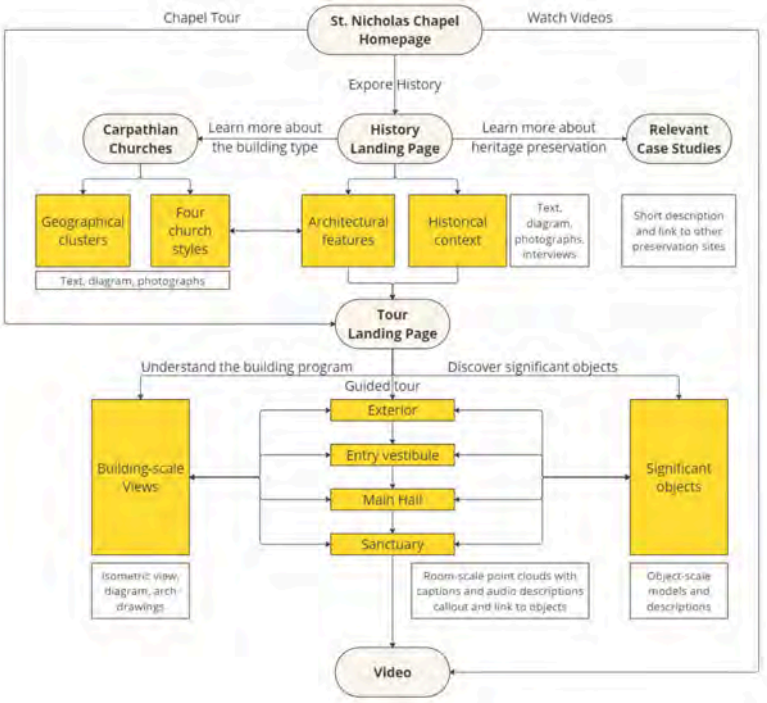


Fig. 8. Information architecture diagram of the interactive, web-based document (left). Linear presentation if scrolling through the webpage (right).

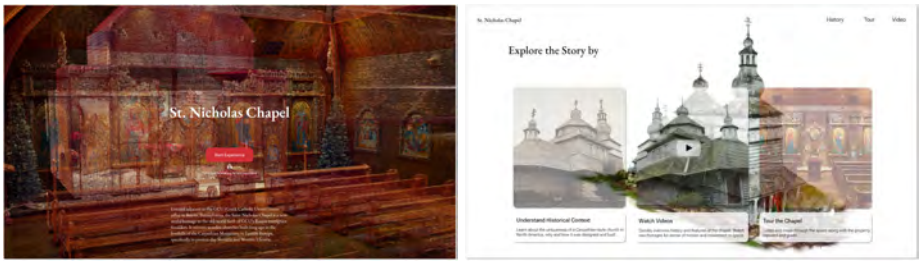


Fig. 9. The landing page (left) and the main navigation page (right) of the website.

The *History* chapter starts with a distant reading contextualizing St. Nicholas Chapel among 331 Carpathian wooden churches on their latent representation space. Each 3D model of each church was encoded to a vector using deep learning, providing a novel way of categorizing each structure based on semantic traits [2]. Clusters in this illustration indicate the four primary styles that they belong to. Clicking on each cluster directs users to more descriptions about the selected style, accompanied with images and drawings. St. Nicholas Chapel is highlighted on the latent space diagram, and can be expanded to show its architectural features and Carpathian traits. Annotations and audio clips from ethnographic interviews depict how the chapel was designed to be reminiscent of where people would have worshiped when they were living in the Carpathian Mountains. Looking forward to digital cultural heritage preservation, users are linked to other projects with similar preservation goals.

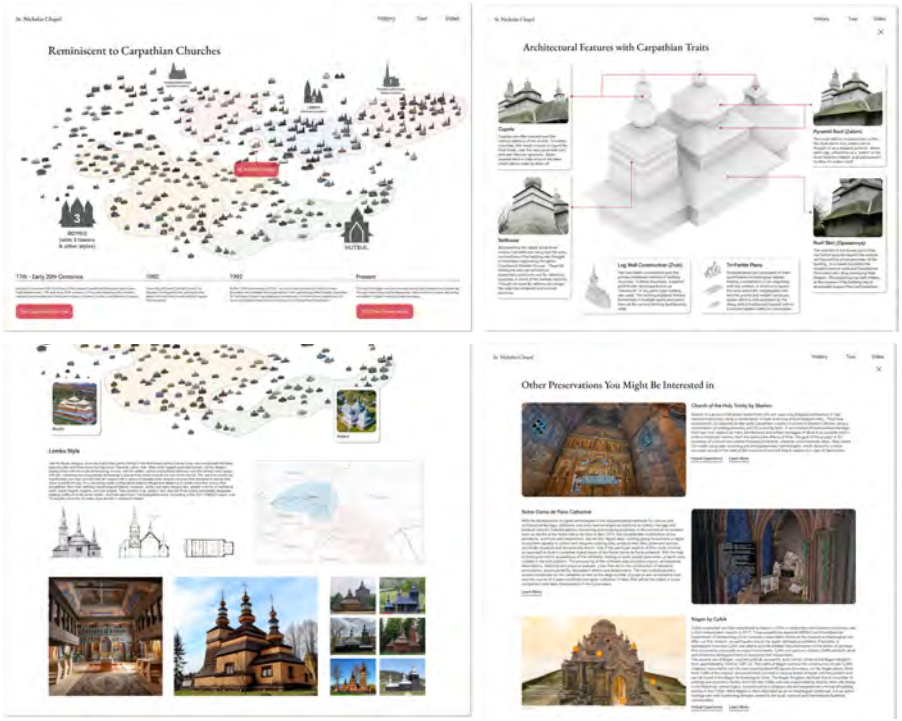


Fig. 10. Landing page for *History* chapter (top-left), architectural features with Carpathian traits (top-right), more information about the Lemko Style (bottom-left), and a selection of Other Preservations with similar goals (bottom-right).

To closely read the chapel, users can choose to tour on the building-scale, room-scale, and object-scale, with connections between them. Each major component is accompanied by audio descriptions and captions. Building-scale information includes the original architectural floor plan and elevation drawings, and a reconstructed mesh of the interior volume. Individual rooms are called out and linked to the 3D tour at each corresponding location. Upon entering a room, the user can freely move around or click arrows to move along a prescribed tour path. Audio clips from the ethnographic interviews explain the function of major spaces, and provide additional context for objects and interesting architectural features. Significant objects are highlighted during the tour and illustrated with further details using various media, including photographs, videos, NeRF and Gaussian Splatting renderings, and photogrammetrically reconstructed models.

Lastly, a summary video provides a pre-captured walkthrough, historical context, and specific information about architectural features. The walkthrough utilizes captured footage of the exterior and interior space and includes a recorded selection of the multi-media representations created for the St. Nicholas Chapel.

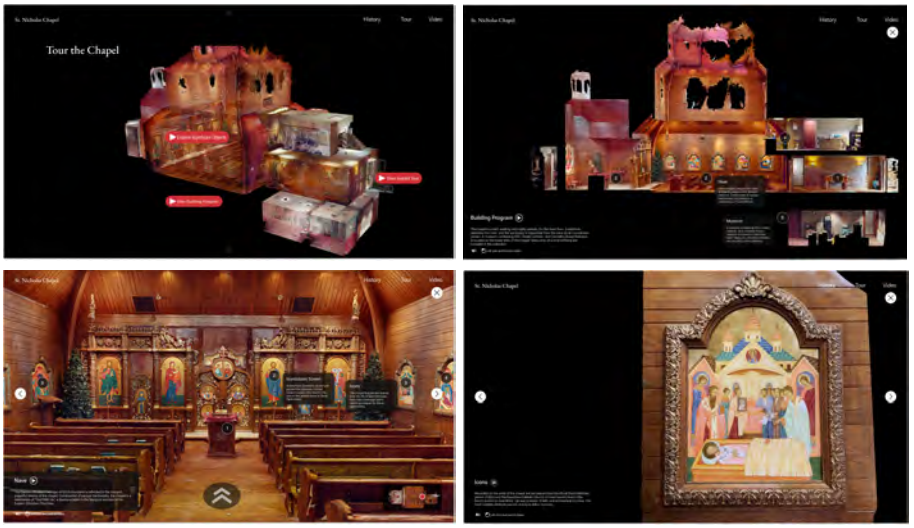


Fig. 11. Whole-building model to navigate the multi-scale tour (top-left). Interconnected building-scale (top-right), room-scale (bottom-left), and object-scale (bottom-right) tours.

6 Conclusions

Through the case study of St. Nicholas Chapel, this paper demonstrates an approach to the holistic documentation, analysis, and dissemination of an endangered architectural heritage building. It shows how diverse methodologies, including high-resolution intensive data collection, historical documentation, ethnographic research, and distant readings of an architectural tradition based on advanced computational analysis, can converge into a cohesive multi-modal and interactive document. These findings not only contribute to the broader field of architectural heritage preservation, but also address the urgent need for leveraging emerging digital technologies in at-risk areas. The proposed interactive digital representation offers global audiences unprecedented access to explore and experience St. Nicholas Chapel, preserving the structure in the conservationist zeitgeist, while also highlighting its place within the Carpathian wooden church-building tradition. This project underscores the importance of interdisciplinary collaborations and methodological exploration for the purpose of safeguarding and disseminating architectural heritage. In addition, our study contributes to the understanding and appreciation of Carpathian-style churches, which is especially urgent given the ongoing war between Russia and Ukraine. We hope that it helps to draw the attention of other scholars and the public to this unique, and endangered, architectural tradition.

6.1 Limitations

Throughout the progress of this study, numerous unforeseen challenges emerged, spanning from global conflicts to weather-related obstacles. The ongoing Russo-Ukrainian war significantly hindered our ability to visit and digitize similar

religious structures at the highest risk for loss, thereby narrowing the original scope of capturing these structures to legal and logistical uncertainty.

The footage acquisition process for the Pennsylvania chapel served as a valuable trial run of our methodologies, shedding light on the intricate details involved in gathering clear data for diverse styles of reconstruction techniques. However, challenges arose when attempting to integrate datasets due to varying weather conditions and lighting, as well as differences in pixel densities and in the orientation of photographs from disparate camera models.

Upon photographic normalization (exposure and white balance equalization), we encountered significant computational hurdles in rapidly converting and training multiple neural reconstruction or photogrammetric techniques. For instance, generating textures or geometry from several of the chosen methodologies requires high amounts of VRAM, thereby limiting the effectiveness of training on consumer-grade graphics cards. While virtual services exist, these systems can themselves be cost prohibitive. To address this, future iterations may require substantial investments in rendering hardware or cloud based virtual machines to enable parallel processing of multiple tests concurrently.

Finally, while several techniques showcased remarkable advancements in photorealistic visualization or in computational efficiency, each brought its own set of challenges and limitations. In particular, capturing reflective or semi-transparent surfaces continued to produce artifacts and voids in geometry, and techniques that are capable of rendering reflective surfaces had other issues in producing watertight geometry at all.

Factors such as environmental conditions during scanning, limitations of the equipment used, or challenges in processing large datasets could introduce inaccuracies or artifacts into the final digital representation. Regardless of equipment, light overcast weather without rain or severe sunlight offers researchers comfort and more average exposure of imagery for uniform results. As this case study suggests, an approach to capture must take into consideration the specific characteristics of a site. With this, the use of cross-polarizers and a ring flash can help to overcome environmental factors and reflections allowing post relighting and consistent stitching. In addition, the utilization of geospatial information can further increase the accuracy of a project. While costly and complex, drones offer a happy compromise in accuracy, perspective, and ease of integration with multiple sensor types.

6.2 Transferability and scalability

The multi-scalar and multi-modal approach illustrated in this article is broadly applicable to other studies of architectural heritage. Integrating analyses at different scales, and through various mediums, can create comprehensive and engaging architectural narratives. For example, the web-based 3d diagnostic reconstruction of the Brancacci Chapel [14] could be enhanced by a “distant reading” situating its frescoes within the broader context of the Italian Renaissance landscape, highlighting other relevant references and their relative states of preservation [14]. Furthermore, projects such as SKEIRON’s digitization of endangered heritage sites [17] could be greatly enriched by incorporating additional multi-modal layers such as historical archival documents, ethnographic interviews with relevant actors. Our work does not

intend to affix one specific workflow or standalone system, but to serve as a proof of concept for an integrative disposition for a variety of modes of architectural heritage analysis in architectural heritage documentation. Accordingly, while not directly scalable as a technical platform, our approach is transferable to other projects and case studies, and has the potential to allow for deeper, more nuanced understandings of architectural heritage.

6.3 Next Steps

Future experiments using emerging techniques will focus on reconstructing geometries that are both photorealistic and watertight. To further enrich the models, we aim at integrating semantic information into the template of the Heritage Building Information Modelling (HBIM) for conservation and analytical purposes. Additionally, the collected information could potentially be structured to jointly form a global cultural heritage database with other preservation cases — providing a path towards future scalability.

In future research, the specific combination of acquisition and analysis techniques should be tailored to respond to the unique characteristics of the object of study and the specific composition of the project team. This adaptability is crucial, as performing these analyses requires a diverse range of tools and technical skills, from ethnography to advanced capture techniques and digital modeling. This also would encourage collaboration among specialists from different fields, enhancing the overall depth of the heritage study.

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