The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-9-2025
30th CIPA Symposium “Heritage Conservation from Bits:
From Digital Documentation to Data-driven Heritage Conservation”, 25–29 August 2025, Seoul, Republic of Korea

Virtual and Augmented Reality as a Modern Way of Exploring and Analysing Historical Objects in High Quality

Karel Pavelka Jr.[1*], Tomáš Bouček[1], Almedina Rapuca[1]

[1] Czech Technical University in Prague, Faculty of Civil Engineering Faculty, Department of Geomatics, Czech Republic - (karel.pavelka, tomas.boucek, almedina.rapuca)@cvut.cz

Keywords: Virtual Reality, Augmented Reality, Documentation of Heritage, Retopology, Photogrammetry.

Abstract

This study explores the integration of modern visualization technologies, specifically virtual reality (VR) and augmented reality (AR) into the documentation and presentation of cultural heritage, using the Old Town Bridge Tower in Prague as a case study. The project demonstrates a complete digital workflow for creating optimized 3D models suitable for immersive applications, while preserving the historical integrity and detailed features of the original monument. A combination of laser scanning and photogrammetry was used to capture high-resolution geometric and textural data. The resulting dense 3D models were processed through retopology and texture mapping (including normal and ambient occlusion maps) to reduce polygon count and enhance real-time performance without sacrificing visual fidelity.
The optimized model was then integrated into Unreal Engine to create an interactive VR experience, complete with an educational virtual museum space inside the tower. Additionally, an augmented reality version was developed for mobile devices, allowing users to explore the digital twin of the structure via a QR code without the need for specialized hardware. This paper highlights the significance of using correct workflows in digitizing cultural heritage assets for immersive technologies, showcasing how accurate modelling, texture preservation, and optimization can lead to accessible, engaging, and realistic virtual representations of historical monuments. The entire project was created at the request of conservationists, investors, and experts in the documentation of historical buildings.

1. Introduction

In recent years, virtual reality (VR) and augmented reality (AR) have revolutionized the way we explore and analyze historical objects. These cutting-edge technologies provide users with an immersive and interactive experience, allowing them to examine high-quality 3D-scanned and digitally recreated artifacts like never before. By integrating VR and AR, museums, researchers, and history enthusiasts can engage with cultural heritage in a more inclusive, immersive and detailed manner (Agapiou et al, 2023, Barsanti et al, 2015, Abd-Elrahman, 2023). This approach not only enhances the study of historical objects but also makes them more accessible to a global audience, offering a new perspective on history through modern visual technology.

This study is intended to demonstrate the potential of modern visualization technologies on a historical object and to present a possible approach to reduce large 3D models for VR and AR, optimizing them without loss of quality.

Correct retopology of the object combined with texture calculation, not only diffuse texture (RGB) but also, for example, normal texture, ambient occlusion texture, and more.

1.1 Object

The historical building selected for this study is the Old Town Bridge Tower, located at the eastern end of the renowned Charles Bridge in Prague. Widely regarded as one of the most exquisite examples of Gothic gateway architecture in Europe, the tower stands as a masterpiece of medieval engineering and artistry. Constructed in the mid-14th century during the reign of Emperor Charles IV, the tower formed an integral part of the broader urban and architectural transformation of Prague, symbolizing the city's growing political and cultural significance within the Holy Roman Empire. The design of the tower is attributed to Petr Parléř, the imperial architect also responsible for the iconic St. Vitus Cathedral at Prague Castle, who brought to the project his deep knowledge of High Gothic design principles and an innovative approach to monumental architecture. More than merely a defensive fortification, the Old Town Bridge Tower served a ceremonial and symbolic function as the grand entrance to the city from the east, effectively acting as a triumphal arch for Czech monarchs. It marked the beginning of the Royal Route, the formal procession path that kings followed during their coronation ceremonies, stretching from the banks of the Vltava River through the Old Town and up to Prague Castle. The tower’s elaborate façade features intricate sculptural decoration, including statues of saints, coats of arms, and imperial symbols, all designed to convey both religious authority and royal legitimacy. Through its blend of military, architectural, and ceremonial significance, the tower encapsulates the political ideology and artistic ambition of Charles IV’s reign and continues to stand as a central monument in Prague's historic skyline, attracting scholars, tourists, and heritage professionals alike (Prague.eu, 2025).

Figure 1. Old Town Bridge Tower

1.2 Documentation methods

A combination of photogrammetry and laser scanning is used to create 3D models for VR and AR. Photogrammetry processes high-resolution images to capture texture and colour, while laser scanning provides accurate geometric data (Raeva et al, 2023). Once the raw 3D data is acquired, the models are optimized and reconstructed (retopology) to ensure quality and performance in VR and AR environments. This process includes polygon reduction, texture enhancement and real-time rendering adjustments. Special attention in this paper is paid to preserving intricate details, allowing users to examine artifacts in detail.

The documentation project of the Old Town Bridge Tower on Charles Bridge in Prague provided exclusive data of one of the most important Czech monuments. This combination of methods ensures high geometric accuracy and realistic textures, allowing for a faithful digital reconstruction of this historic building.

2. Methodology

The creation and conversion of a 3D model for VR and AR is a complex process that ensures data is transformed into immersive visualization technologies while maintaining the highest level of detail (Pavelka et al, 2025). The creation and conversion process of a detailed 3D object model (Cipriani et al, 2019) can be divided into 3 basic steps:

a) Data collection and processing - high quality data is acquired using photogrammetry and laser scanning to capture geometric accuracy and detailed textures. The collected data is refined and integrated using tools such as RealityCapture or Agisoft Metashape to create a 3D model with high geometric and textural resolution.
b) Optimization for VR/AR - Optimization of 3D models for VR and AR includes polygon reduction to improve performance without losing essential detail, texture enhancement to refine surface detail and resolution, and real-time rendering preparation to ensure smooth interaction. These steps balance high-quality visual effects with efficient system performance, enabling smooth and immersive experiences.
c) VR/AR conversion and visualization - The optimized model is converted to VR using game engines such as Unreal Engine or Unity to create realistic environments and support VR peripherals. For AR, frameworks such as ARKit, ARCore, or WebAR are used to deploy models to mobile devices to ensure high-quality visualization experiences.

2.1 Data collection and processing

A combination of photogrammetry and laser scanning is used to create 3D models for VR and AR. Photogrammetry processes high-resolution images to capture texture and colour, while laser scanning provides accurate geometric data (Raeva et al, 2023). Once the raw 3D data is acquired, the models are optimized and reconstructed (retopology) to ensure quality and performance in VR and AR environments. This process includes polygon reduction, texture enhancement and real-time rendering adjustments. Special attention in this paper is paid to preserving intricate details, allowing users to examine artifacts in detail.

Using GNSS and a total station, a point field was surveyed and aligned for georeferencing all laser scanning and photogrammetric imaging data. The exterior and interior of the tower were scanned, and georeferenced scans (RTC360) were used as a fixed reference for subsequent processing together with photogrammetric aerial and ground images. A total of 225 scans and 6,264 photographs were taken, of which 2,610 were taken from a drone (DJI Matrice 300) and 884 were taken by hand (Canon Mark II). A total of 2,770 photographs were taken inside the tower.

Figure 2. DJI Matrice 300 and Leica RTC 360

The data was processed using Groma v13.1.10, Leica Cyclone Register 360 PLUS v2024.0.1, and RealityCapture v1.4.1 software.

GNSS points were calculated as the average of two measurements taken by the Groma program. The average deviation between stages was 10 mm in position and 7 mm in height. The largest deviation between stages was 22 mm in position and 15 mm in height. For greater accuracy, the GNSS points were also measured using a total station and included in the overall adjustment of the survey network. The point field was calculated in the Groma program using the network adjustment tool. The aligned network was calculated with a mean positional deviation of 2.1 mm and a mean height deviation of 0.4 mm. The scans were registered in the Leica Cyclone Register 360 PLUS program. The positions of the exterior and interior scans were calculated and aligned together. The point cloud was used to georeference the laser scanning data registration project. Table 1 shows an overview of the average and maximum registration deviations achieved in the local system, as well as the average and maximum deviation achieved at identical points.

registration deviations		georeference deviations	
average [mm]	largest [mm]	average [mm]	largest [mm]
2	8	3	5

Table 1. Registration and georeference deviations

The exported georeferenced scans were imported into RealityCapture. The photogrammetric data was aligned with the scans and used to complete the geometry and texturing of the scanned data. A separate project was created for the exterior and interior of the tower. Both projects were based on fixed scans in the same coordinate system. The final outputs were exported from Reality Capture in the form of a 3D point cloud and a 3D mesh model and high-resolution orthogonal views (for further analysis). The orthophotos are of the highest possible quality, with a resolution of 1 mm/pixel. The orthophotos are of the highest possible quality, with a resolution of 1 mm/pixel. These precisely processed orthophotos served as the basis for detailed vector drawings, including detailed joint patterns, which this quality made possible. Vector drawings are processed in up to 17 different layers and, thanks to the detail of the orthophoto, contain everything from joint patterns and objects on the facade to Lewis holes and mason’s marks.

Figure 3. Detail of ortophoto and vector drawing

Figure 4. Mesh model

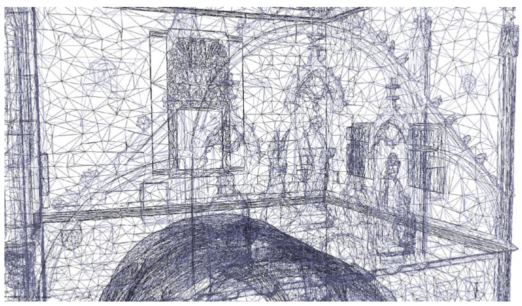
The 3D mdesh model of the outdoor area contains 47 mil. polygons polygons, while the indoor area contains 49 mil. polygons.

2.2 Optimalization for VR/AR

Displaying a 3D model with tens of millions of polygons is not feasible in VR or AR environments. To make such models usable, it's necessary to reduce their complexity by decimating them into versions with millions or even hundreds of thousands of triangles. The exact number depends on the object's size and complexity. For smaller elements, such as columns, arches, or statues, models with just a few tens of thousands of triangles are typically adequate. This optimization process is known as retopology.

At the core of retopology are two basic concepts: a high-polygon model, which is the original, highly detailed version, and a low-polygon model. Since game engines are optimized for more efficient rendering of low-polygon models, virtually all 3D objects must undergo retopology. In this context, the key goal, especially when working with historical artifacts, is to preserve surface details and fidelity (Barsanti, S.G. et al., 2015b).

a)



b)

Figure 5. Polygon structure a) high-poly exterior model (47mil. polygons), b) low-poly model (200.000 polygons)

The entire model was divided into interior and exterior for easier work due to the size of the data and its optimization.

The object was retopologies in RealityCapture, followed by the calculation of normal, diffuse, and ambient occlusion textures. Low poly 3D model of exterior has 200.000 polygons; interior has also 200.000 polygons.

2.3 Textures

Textures play a crucial role in shaping the visual appearance of surfaces when creating 3D models for VR. Various types of textures can be applied to achieve the desired visual effect. These textures are mapped onto the 3D surface using a system called a UV map. UV coordinates, U representing the x-axis and V the y-axis are used to project a two-dimensional (2D) image onto the three-dimensional (3D) geometry of a model. This mapping defines how the 2D texture wraps around and adheres to the 3D object.

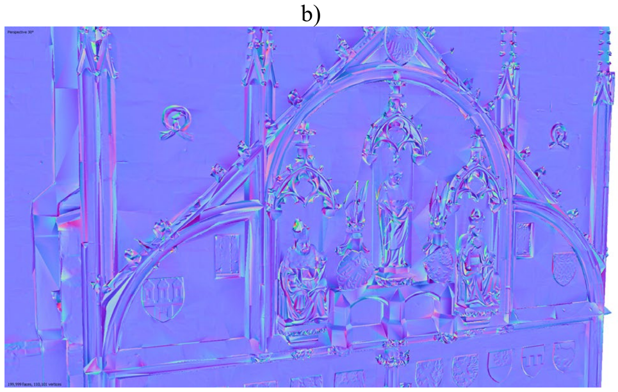
It’s important to distinguish between a texture and a map. A *texture* is a general term for any image applied to a 3D model, commonly in formats like JPG or PNG. A *map*, on the other hand, is a specific type of texture used to influence particular properties of the model—such as reflectivity, surface detail, or how it interacts with light. A common example of this is the normal map, which simulates fine surface detail without adding extra geometry. And it is exactly this map that we will be working with in this study (Roberts, S. et al., 2021).

For virtual or augmented reality displays, low-poly models are preferred due to performance constraints. However, this simplification often results in the loss of detailed surface features, such as fine roughness or geometry variations. To preserve the visual richness of the original high-poly model, a normal map is generated and applied to the low-poly version. This map uses RGB values to represent XYZ directions within a 0–1 range, effectively simulating surface details without adding geometric complexity.

The normal map creates the illusion of depth and texture, allowing the low-poly model to visually match the high-poly one while maintaining a significantly smaller file size. When no texture data is available for a model, artificial intelligence can be used to generate high-quality textures based on user input. These AI-generated assets can include not only base color textures, but also normal maps, ambient occlusion maps, and more customized to meet specific visual requirements. (Adobe, 2025). Ambient Occlusion (AO) is a shading technique that enhances realism by simulating how ambient light is blocked in areas where surfaces are close together, such as crevices, corners, and holes. By estimating the amount of ambient light reaching each point on a surface, AO darkens occluded areas, creating subtle soft shadows that add depth and a more lifelike appearance to the scene (Unity, 2025).

a)

b)



c)

Figure 6. Computed textures on 3D model – a) diffuse texture (RGB), b) occlusion map, c) normal texture

2.4 Game engine

Unreal Engine, along with Unity, is one of the most widely used commercial game engines in the world, known for its powerful rendering capabilities and versatility across a wide range of platforms. Developed by Epic Games, Unreal Engine offers a robust and feature-rich environment that is particularly well-suited for creating immersive virtual reality (VR) applications. Its high-fidelity graphics, real-time performance optimization tools, and support for both PC and mobile VR platforms make it a top choice among developers aiming to build cutting-edge, interactive VR experiences.

One of the key advantages of Unreal Engine is its innovative visual scripting system known as Blueprints. This system allows developers to create complex game logic and interactions without writing traditional code. Blueprints use a node-based interface, enabling users to visually connect events, functions, variables, and components in a way that is both intuitive and powerful. The following figure (Figure 6.) shows a workflow chart of the entire process, from object selection to integration into VR or AR.

https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-1161-2025 | © Author(s) 2025. CC BY 4.0 License.

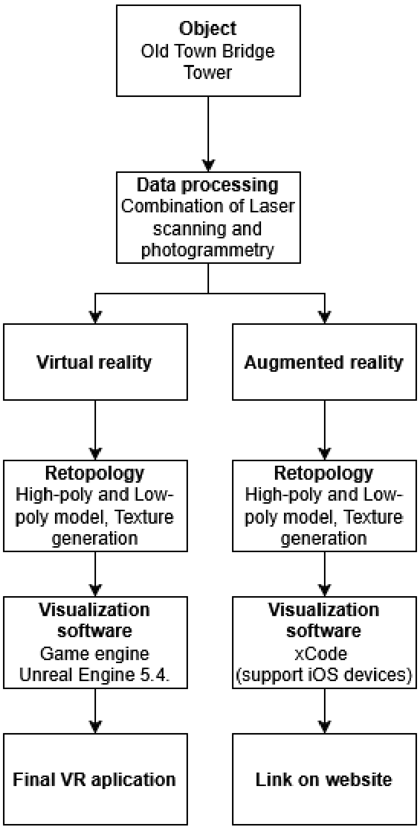


Figure 7. Workflow chart

A low poly model of the Old Town Bridge Tower was uploaded to the Unreal engine, including all calculated textures. A material was then created from the textures and applied to the 3D model. On the first floor, where the treasure was found, a small museum documenting the tower has been created.

3. Results

The outer and inner part of the tower was scanned, aligned and georeferenced based on geodetic measurements and was used as a solid skeleton of the building. The scans were combined with aerial and ground photogrammetric images for a detailed reconstruction. This approach preserved even the smallest architectural details and ensured an accurate digital representation of the Old Town Bridge Tower. The integration of laser scanning and photogrammetry ensured precise geometric accuracy and high-resolution textures, making the model suitable for VR and AR applications.

3.1 Documentation

The first output was documentation for repair work on the tower and complete documentation of its initial condition. Orthophotos of all walls with a detail of 1 mm/pixel were processed, which were then used as a basis for detailed vectorization. The Old Town Bridge Tower was documented both from the exterior and interior, including all details. In the future, the statues will be cut out and become separate models for detailed analysis.

3.2 Virtual reality

A VR application has been developed using the Unreal Engine (Unreal engine, 2025), allowing users to explore the historic Old Town Bridge Tower in an immersive virtual environment. Users can walk through the tower, navigate around it, or even fly around for a unique aerial perspective. The second floor of the tower has been transformed into a small interactive museum, where visitors can learn about the rich history of Old Town Bridge Tower and the iconic Charles Bridge. The museum features detailed historical exhibits, interactive elements, and multimedia content, offering an engaging and educational experience for history enthusiasts and virtual tourists alike.

3.3 Augmented reality

Another output of the project is a decimated and optimized 3D model designed for use in AR applications on iOS tablets and mobile devices. AR is a highly popular modern visualization technology that, unlike VR, does not require expensive hardware. No VR headset or high-performance computer is needed users can simply view the 3D model using a smartphone or tablet. The optimized 3D model can be accessed via the following QR code, allowing users to explore it directly on their mobile devices.

The process of optimizing a 3D model for augmented reality is largely similar, but we need to reduce the 3D model and texture even more, because this AR model will primarily be displayed on smartphones or tablets, which do not have as much hardware power as computers.

Figure 8. QR code for iOS devices

Figure 9. Demonstration of the digital twin of the Old Town Bridge Tower in Prague near the Charles Bridge

4. Conclusion

Modern visualization technologies such as virtual reality (VR) and augmented reality (AR) offer groundbreaking possibilities for presenting, interpreting, and analyzing historical objects and cultural heritage artifacts. These immersive technologies allow users to experience historical objects in a completely new way—enabling interaction, detailed exploration, and contextual placement that would be difficult or impossible in traditional museum or academic settings. When combined with a suitable digital workflow, these technologies can bridge the gap between physical history and digital innovation. However, the main outputs for conservationists are accurate vector drawings based on a detailed orthophoto with a quality of 1 mm/pixel, which was generated from different viewing depths and therefore contains all the important information. A key component of successfully integrating historical objects into VR or AR environments is the accuracy and efficiency of the 3D digitization process. With the right workflow, which typically involves high-resolution 3D scanning, photogrammetry, retopology, texture work, and optimization, it is possible to faithfully preserve complex surface details such as inscriptions, wear marks, or material textures while ensuring that the model is optimized for real-time rendering. This balance between visual fidelity and performance is essential for seamless integration into platforms such as Unreal Engine, which powers many cutting-edge VR and AR applications. By following best practices in asset creation and optimization, historical artifacts can be rendered in real time with a high degree of realism, allowing researchers, students, and the public to interact with them in ways that were previously unavailable. In addition to increasing engagement and educational value, VR and AR also support remote access, digital preservation, and collaborative research. These technologies are therefore a powerful tool for cultural heritage institutions, museums, and researchers seeking to digitize and disseminate our shared history in immersive, interactive formats.

Acknowledgements

Internal grant of the CTU in Prague SGS25/046/OHK1/1T/11

References

Adobe. What is normal mapping? Available at: https://www.adobe.com/products/substance3d/discover/normal-mapping.html [Accessed 19 Jun. 2025].

Abd-Elrahman, A. et al. 2023. Virtual Reality (VR) Assisted Geomatics Lab Development, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-1/W2-2023, pp. 933–938. https://doi.org/10.5194/isprs-archives-xlviii-1-w2-2023-933-2023

Agapiou, A., Skarlatos, D. 2023. Geomatic Sensors for Heritage Documentation: A Meta-Analysis of the Scientific Literature,' Heritage, 6(10), pp. 6843–6861. https://doi.org/10.3390/heritage6100357

Barsanti, S.G. et al. 2015. 3D Visualization of Cultural Heritage Artefacts with Virtual Reality devices, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5/W7, pp. 165–172. https://doi.org/10.5194/isprsarchives-xl-5-w7-165-2015

Cipriani, L., Bertacchi, S., Bertacchi, G. 2019. An Optimised Workflow for the Interactive Experience with Cultural Heritage Through Reality-Based 3D Models: Cases Study in Archaeological and Urban Complexes, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W11, pp. 427–434. https://doi.org/10.5194/isprs-archives-xlii-2-w11-427-2019

Nanite virtualized geometry in Unreal engine | Unreal engine 5.5 documentation | epic developer community (no date) EPIC Unreal Engine. Accessed: 18 February 2025. https://dev.epicgames.com/documentation/en-us/unreal-engine/nanite-virtualized-geometry-in-unreal-engine

Pavelka, K., Jr.; Pavelka, K.; Běloch, L. 2025. A Reconstruction of the Shrine of the Prophet Nahum: An Analysis of 3D Documentation Methods and Data Transfer Technology for Virtual and Augmented Realities. Appl. Sci., 15, 1000. https://doi.org/10.3390/app15021000

Prague.eu. (n.d.). *Staroměstská mostecká věž*. Available at: https://prague.eu/cs/objevujte/staromestska-mostecka-vez/ [Accessed 19 Jun. 2025].

Raeva, P., Pavelka, K. and Pavelka, K., Jr. 2022. Gathering Geodata for HBIM and Analysis on Preserving a Caravanserai in Koysenjaq, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVI-5/W1-2022, pp. 185–192. https://doi.org/10.5194/isprs-archives-xlvi-5-w1-2022-185-2022

Roberts, S. et al. (2021) How to use textures, Free Assets Unity. Available at: https://web.archive.org/web/20210924034033/https://freeassetsunity.com/how-to-use-textures/ (Accessed: 18 February 2025).

Unity Technologies. (n.d.). *Baked ambient occlusion*. In *Unity Manual*. Available at: https://docs.unity3d.com/Manual/LightingBakedAmbientOcclusion.html [Accessed 19 Jun. 2025].