The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLIX-B4-2026
XXV ISPRS Congress 2026 "From Imagery to Understanding", Commission IV, 4–11 July 2026, Toronto, Canada

Feature-Enhanced Visualization of 3D Point Clouds of Cultural Heritage in Transparent Virtual Reality

Taishi Matsuo[1], Satoshi Takatori[2], Liang Li[2], Satoshi Tanaka[2]

[1] Graduate School of Information Science and Engineering, Ritsumeikan University, Ibaraki, Osaka, 567-8570, Japan
is0636he@ed.ritsumei.ac.jp
[2] College of Information Science and Engineering, Ritsumeikan University, Ibaraki, Osaka, 567-8570, Japan
(stakator, liliang)@fc.ritsumei.ac.jp, stanaka@is.ritsumei.ac.jp

Keywords: Feature enhanced visualization, Transparent visualization, 3D Point cloud, Virtual Reality, Cultural heritage.

Abstract

While virtual reality (VR) has been increasingly adopted for the digital archiving of cultural heritage, most existing systems focus on visual appreciation rather than structural analysis. To address this limitation, this study proposes a transparent VR visualization system designed to enhance the recognition of structural features in 3D scanned point clouds of historic architecture. Using a large-scale point cloud dataset of the main hall of Tamaki Shrine, which is part of the UNESCO World Heritage site "Sacred Sites and Pilgrimage Routes in the Kii Mountain Range," the data were initially processed using Poisson disk sampling to optimize real-time rendering throughput while preserving geometric fidelity. Structural salience was subsequently quantified through principal component analysis (PCA), employing linearity for sharp-edge extraction and the change of curvature for soft-edge representation. To alleviate the occlusion inherent in opaque point cloud rendering, we implemented a custom alpha-blending shader in Unity. This enabled two types of transparent feature-enhanced visualization: binarization for highlighting sharp edges and opacity gradation for visualizing soft-edge regions. The developed system, operated with a Meta Quest Pro, provides distinct viewing and analysis modes. Experimental results demonstrate that combining feature enhancement with opacity control improves the visibility of internal depth relationships and point-density variations in complex wooden architecture, thereby supporting structural understanding that is difficult to achieve with conventional rendering.

1. Introduction

Historic cultural properties are constantly under threat from environmental changes, natural disasters, and age-related deterioration, making their preservation a critical global issue. Digital archiving has emerged as a vital initiative to protect and document these invaluable assets for future generations (Zorich, 2003, Koller et al., 2010). In recent years, advancements in three-dimensional (3D) measurement technologies, such as laser scanning and photogrammetry, have enabled the high-precision acquisition of large-scale point cloud data from historical sites (Remondino et al., 2009). Among these preservation efforts, digital archives utilizing virtual reality (VR) technology have been actively developed and widely adopted (Bekele et al., 2018). VR provides a highly immersive environment that allows users to intuitively understand the true scale and 3D structure of historical objects. However, the majority of existing VR applications are primarily designed for the visual appreciation and virtual tourism of cultural properties. Very few of these systems are tailored for professional or academic analysis (Van Dam et al., 2000), which requires a precise understanding of complex shapes and intricate architectural features.

To address this limitation, this study develops a transparent VR visualization system that enhances the recognition of structural features in 3D scanned point clouds of cultural heritage architecture. The key idea of our approach is to integrate transparent visualization into VR-based edge enhancement so that both sharp and soft structural features can be perceived more clearly. Specifically, sharp edges refer to distinct ridge lines and geometric creases, while soft edges represent areas with gradual changes in surface curvature. This system uses two different methods for visualization. First, binarization is utilized to extract and highlight only the sharp edges, defining clear architectural features. Second, an opacity gradation enables the continuous visualization of soft-edge regions, allowing for smooth and natural transitions between varying feature strengths. By intelligently integrating binary edge enhancement and soft-edge opacity gradation within a transparent VR environment, the proposed method significantly improves the visibility of point-density variation and intricate internal structural relationships within complex wooden architecture.

The structure of this paper is as follows: Section 2 introduces the study site, Tamaki Shrine, and its point cloud data. Section 3 describes the preprocessing of the data and the methods used for feature extraction and enhancement. Section 4 details the configuration and implementation of the VR system. Section 5 presents the results of the system implementation, and Section 6 concludes the paper with suggestions for future work.

2. Study Site and Data Acquisition

2.1 Tamaki Shrine

In this study, we developed a VR system that utilizes a point cloud dataset acquired through 3D measurements of the main hall (Honden) of Tamaki Shrine, located in Totsukawa Village, Yoshino District, Nara Prefecture. Figure 1 shows the main hall of Tamaki Shrine. The shrine is situated near the summit of Mt. Tamaki and is an integral part of the Omine Okugakemichi, which is registered as a UNESCO World Heritage site under the "Sacred Sites and Pilgrimage Routes in the Kii Mountain Range." The shrine grounds contain many historically valuable buildings, as well as rocks and trees that have been objects of worship for centuries.

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLIX-B4-2026-753-2026

Figure 1. Main hall of Tamaki Shrine

The main hall's architecture style is characterized by its hip-and-gable roof style (irimoya), featuring both undulating gable (kara-hahu) and dormer gable (chidori-hahu). Digitally preserving this building is essential, especially given the harsh environmental conditions of its mountainous location, which accelerate natural deterioration. Furthermore, because the building is an irreplaceable cultural property, understanding its structure without physical interference is highly desirable. The dense and intricate nature of this wooden architecture makes it an ideal subject for our proposed VR visualization system aimed at structural analysis.

2.2 Point Cloud Data of Tamaki Shrine

The 3D measured point cloud data used in this study was acquired by combining terrestrial laser scanning and drone-based photogrammetry before the current renovation work began (Remondino, 2011). Figure 2 and 3 show the scanning process for Tamaki Shrine in progress. The total number of points in the point cloud data obtained by this combined scan is 123,413,414. Figure 4 shows the resulting point cloud of the main hall. While this massive amount of data accurately captures the minute geometric details of the heritage site, rendering over 120 million points directly in VR imposes a heavy computational load (Schütz et al., 2020). Therefore, downsampling, as explained in a later section, is necessary to maintain the frame rate while preserving important structural information.

3. Methodology: Feature-Driven Processing Pipeline

3.1 Preprocessing of Point Cloud Data

As mentioned in Section 2, rendering raw point cloud data with over 120 million points imposes a significant load on the VR system, resulting in a decrease in frame rate. In a highly immersive environment utilizing a head-mounted display (HMD), such frame rate degradation not only disrupts the visual experience but is also a primary cause of VR sickness (cybersickness) (Rebenitsch and Owen, 2016), making prolonged structural analysis impossible. To address this problem, we downsampled the point cloud data uniformly using Poisson disk sampling (PDS) (Bridson, 2007, Yuksel, 2015). PDS defines a minimum distance between any two points, ensuring that the point cloud data is downsampled uniformly across the entire 3D space. Using PDS, the raw point cloud data was downsampled to 8,178,301 points, striking a balance between maintaining fine structural details and ensuring a high, stable frame rate in the VR environment.

Figure 2. Terrestrial laser scanning of the shrine's main hall

3.2 Feature Extraction

Following the preprocessing, we extracted structural feature regions using a method based on principal component analysis (PCA) (Yamada et al., 2024, Dittrich et al., 2017). First, for each individual point $p^{(i)}$ in the point cloud, we define a local neighborhood by considering a small sphere centered on that point. A variance-covariance matrix is created from the 3D coordinates of the points within that spherical neighborhood. By performing eigenvalue decomposition on this matrix, its three eigenvalues ($\lambda_1 \geq \lambda_2 \geq \lambda_3$) are determined. These eigenvalues represent the variance of the local point distribution along its principal axes, mathematically capturing the local surface geometry. Feature values are calculated using these eigenvalues.

In this study, we adopted *linearity* from Eq. (1) and *change of curvature* from Eq. (2) as feature values. Linearity is a feature value effective for extracting the ridge and contour lines of an object, while change of curvature is effective for extracting the angular parts of an object:

$$L_\lambda = \frac{\lambda_1 - \lambda_2}{\lambda_1} \tag{1}$$

$$C_\lambda = \frac{\lambda_3}{\lambda_1 + \lambda_2 + \lambda_3} \tag{2}$$

where L_λ, C_λ = feature value
$\lambda_1, \lambda_2, \lambda_3$ = eigenvalue

Figure 3. Photogrammetry using a drone to capture high-altitude geometric details of the roof

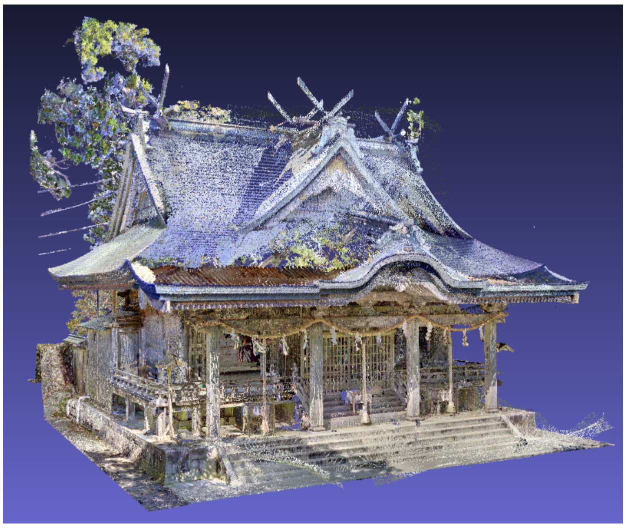

Figure 4. Point cloud data of the main hall of Tamaki Shrine

3.3 Feature Enhancement

The calculated feature values are then used to define and visually enhance feature regions. In this study, we performed two types of feature enhancement: binarization, which regards areas where the feature value is greater than a preset threshold f_{th} as feature regions, and an opacity gradation, which defines two thresholds $(f_{\mathrm{th}}, F_{\mathrm{th}})$ and varies the point proliferation rate in the range $f_{\mathrm{th}} < f < F_{\mathrm{th}}$ with the maximum proliferation rate in the range $F_{\mathrm{th}} \leq f$. Here, the maximum proliferation rate is $A_{\max}$ and the minimum is $A_{\min}$. The proliferation rate function for binarization is shown in Eq. (3), and the function for the opacity gradation is shown in Eq. (4). Here, $A(f)$ is used not only to control point density through upsampling but also as the opacity-control function in transparent VR rendering.

$$A(f) = \begin{cases} A_{\max} & (f_{\mathrm{th}} < f) \\ 0 & (f \leq f_{\mathrm{th}}) \end{cases} \tag{3}$$

$$A(f) = \begin{cases} A_{\max} & (F_{\mathrm{th}} \leq f) \\ \frac{A_{\max} - A_{\min}}{(F_{\mathrm{th}} - f_{\mathrm{th}})^d}(f - f_{\mathrm{th}})^d + A_{\min} & (f_{\mathrm{th}} < f < F_{\mathrm{th}}) \\ A_{\min} & (f \leq f_{\mathrm{th}}) \end{cases} \tag{4}$$

where
$A(f)$ = point proliferation ratio
$A_{\max}$ = maximum proliferation rate
$A_{\min}$ = minimum proliferation rate
f = feature value
$F_{\mathrm{th}}, f_{\mathrm{th}}$ = threshold
d = exponent to control the speed of gradation

Equation (3) represents conventional binary feature extraction, which is applied to transparent virtual reality in this study. Equation (4) represents feature extraction that expresses soft edges around sharp edges using opacity gradation, which allows the visualization to incorporate detailed information that has been ignored in conventional binary feature extraction. Figure 5 shows the graph of Eq. (4).

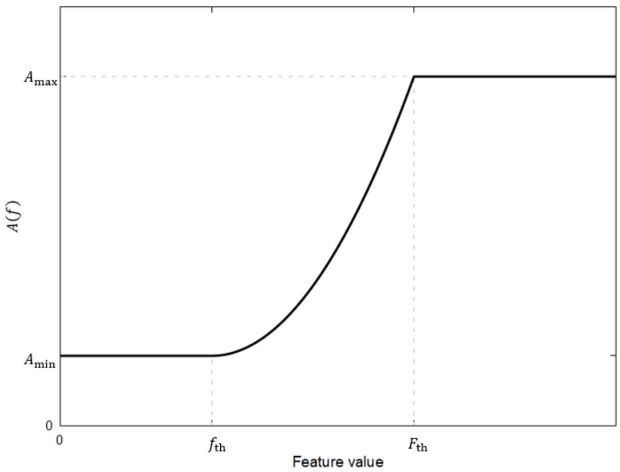

Figure 5. Proliferation rate function $A(f)$ defined for feature-based opacity gradation

4. VR System Architecture and Implementation

4.1 Overview of the VR system

Figure 6 shows an overview of the VR system developed in this study. The system consists of two modes: one for viewing and the other for analysis.

In the viewing mode, users can experience the original point cloud of the Tamaki Shrine’s main hall at a real-world scale,

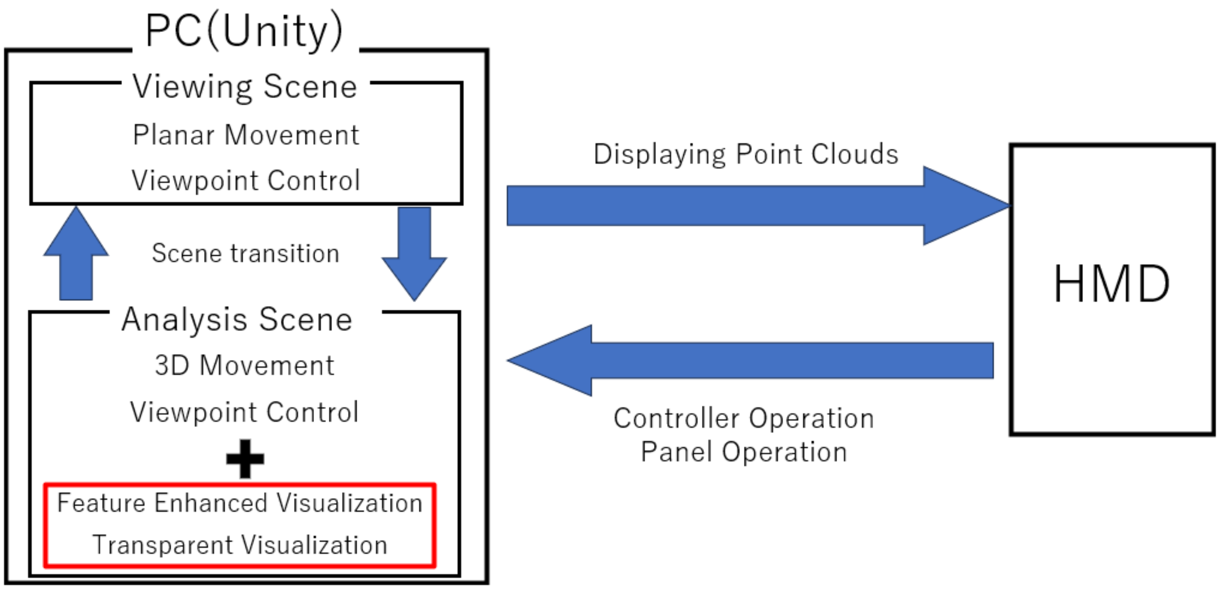

Figure 6. Overview of the VR system

providing a highly immersive experience as if they were actually standing there. On the other hand, in the analysis mode, users can view the feature-enhanced data where structural characteristics are highlighted. This mode allows for free 3D movement, enabling users to perceive complex wooden joints and roof structures from arbitrary angles that are physically impossible in the real world, such as aerial perspectives.

Furthermore, users can smoothly transition between these two modes and interact within each environment using an HMD and its accompanying controllers. The scene transition and display settings are managed via a virtual UI panel operated by the controllers, allowing for an immediate comparative analysis between the realistic appearance and the extracted structural features.

4.2 Implementation of the VR system

We developed the VR system using the Unity game engine (version 2022.3.52f1), which provides robust support for VR applications and high flexibility through C# scripting. For the hardware setup, a Meta Quest Pro was used as the HMD, and its accompanying controllers were used for spatial navigation and UI operations within the VR system.

A significant technical challenge in point cloud visualization is depth perception and transparent shading (Zhang and Pajarola, 2006, Tanaka et al., 2016). There is a critical issue where simply loading the massive feature-enhanced data into Unity and displaying it with standard opaque materials causes severe visual clutter. The overlapping points occlude each other, making it extremely difficult to perceive changes in point density and the target object’s internal depth. Therefore, we aimed to improve the visibility of the internal spatial layout and make changes in point density easier to recognize by controlling the object’s opacity.

Specifically, we implemented a custom alpha-blending shader in Unity. The conventional opaque visualization extracting edges including soft-edge regions is shown in Figure 7. In this opaque visualization, fine internal details and structural depth are lost due to occlusion. In contrast, the transparent visualization based on the change of curvature combined with our custom alpha-blending shader is shown in Figure 8. By rendering the points transparently, the occlusion problem is resolved, and the intricate 3D structure of the complex wooden architecture becomes clearly visible and analyzable.

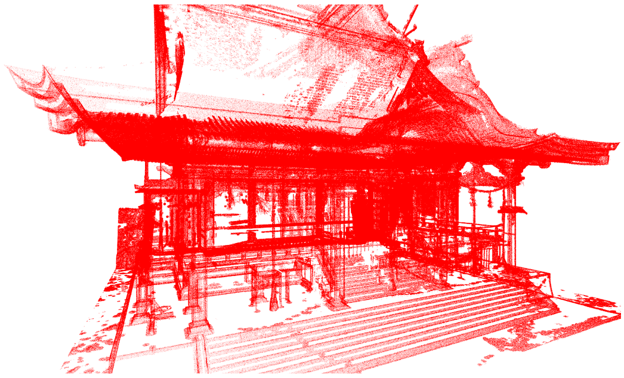

Figure 7. Opaque visualization (conventional method) extracting edges including soft-edge regions, based on change of curvature as the feature value.

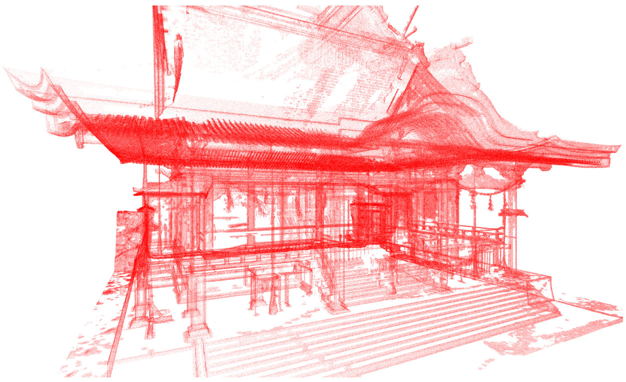

Figure 8. Transparent visualization using opacity gradation for soft edges, based on the change of curvature as the feature value.

5. Experimental Results and Discussion

In this study, we applied binarization with linearity as the primary feature to highlight prominent structural edges, enabling clear visualization of the overall structure. In addition, opacity gradation was introduced for soft-edge regions by using the change of curvature as the feature value, allowing finer structural details that are not included in sharp edges to be visualized. The result of binarization based on linearity is shown in Figure 9, while the result of opacity gradation based on the change of curvature is shown in Figure 10.

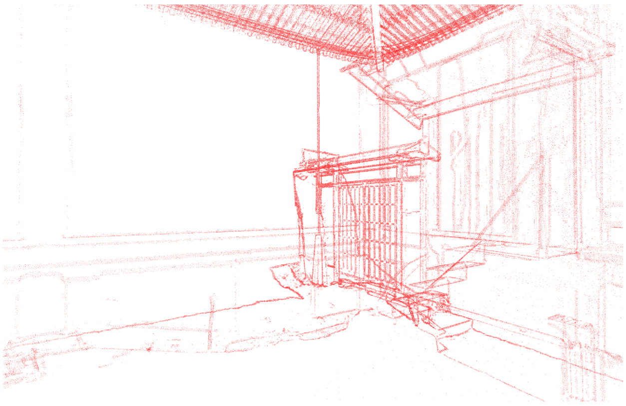

Figure 9. Transparent visualization of the inner scene using binary edge extraction based on linearity as the feature value.

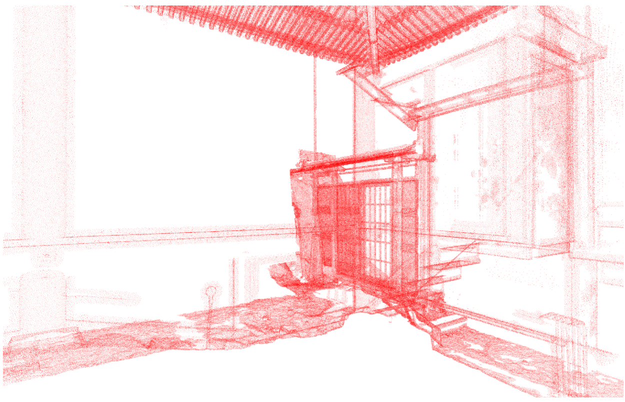

Figure 10. Transparent visualization of the inner scene using opacity gradation for soft edges based on change of curvature as the feature value.

The binary visualization clearly highlights prominent structural edges and supports understanding of the overall structural configuration, whereas the opacity-gradation visualization preserves softer feature transitions and reveals finer structural details, making the internal depth relationships easier to perceive. These results indicate that the proposed transparent VR visualization is effective for understanding the complex internal structure of wooden architecture.

Furthermore, to make the spatial distribution of the extracted features more intuitive, we implemented an overlaid visualization that combines the original point cloud with the feature-enhanced point cloud. By displaying the original building structure together with the highlighted feature regions, users can immediately identify the locations of prominent structural elements. Figure 11 shows the result of this overlaid visualization, which effectively bridges the gap between overall architectural appreciation and detailed structural analysis.

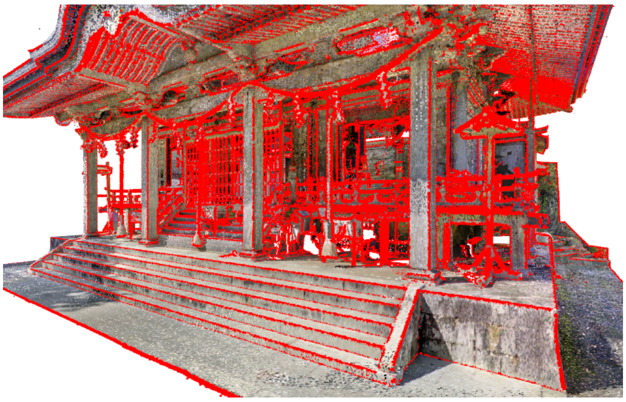

Figure 11. The result of overlaying the original point cloud data with the feature-enhanced data.

6. Conclusion

While conventional VR archives primarily focus on the visual appreciation of cultural properties, this study developed a novel transparent VR visualization system aimed at structural analysis. We utilized a 3D-measured point cloud of the main hall of Tamaki Shrine. To overcome the rendering load issues associated with massive point cloud data, the data were downsampled, and feature enhancement was performed using principal component analysis. The system successfully visualizes structural characteristics using two methods: binarization based on linearity for sharp edges and opacity gradation based on the change of curvature for soft edges. By displaying the feature-enhanced data transparently, the visibility of changes in point density and internal depth relationships was significantly improved. Furthermore, overlaying the original point cloud with the enhanced data allowed an immediate and intuitive understanding of feature locations within the building.

For future work, we plan to expand our feature extraction methods. Currently, the visualization relies only on geometric shape features derived from spatial coordinates. Since the original data also contains color information, we aim to pursue visualization techniques that extract and highlight color boundaries. Additionally, we consider integrating omnidirectional walking devices to enhance the user experience. By incorporating physical walking actions into the VR environment, the system may become highly immersive, enabling more intuitive spatial cognition of the scale and shape of historical architecture (Slater et al., 1995).

References

Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S., Gain, J., 2018. A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH)*, 11(2), 1–36.

Bridson, R., 2007. Fast Poisson disk sampling in arbitrary dimensions. *SIGGRAPH sketches*, 10(1), 1.

Dittrich, A., Weinmann, M., Hinz, S., 2017. Analytical and numerical investigations on the accuracy and robustness of geometric features extracted from 3D point cloud data. *ISPRS J. Photogramm. Remote. Sens.*, 126, 195–208.

Koller, D., Firischer, B., Humphreys, G., 2010. Research challenges for digital archives of 3D cultural heritage models. *Journal on Computing and Cultural Heritage (JOCCH)*, 2(3), 1–17.

Rebenitsch, L., Owen, C., 2016. Review on cybersickness in applications and visual displays. *Virtual reality*, 20(2), 101–125.

Remondino, F., 2011. Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote sensing*, 3(6), 1104–1138.

Remondino, F., Girardi, S., Rizzi, A., Gonzo, L., 2009. 3D modeling of complex and detailed cultural heritage using multi-resolution data. *Journal on Computing and Cultural Heritage (JOCCH)*, 2(1), 1–20.

Schütz, M., Stefan, O., Wimmer, M., 2020. Fast out-of-core octree generation for massive point clouds. *Computer Graphics Forum*, 39number 7, Wiley Online Library, 155–167.

Slater, M., Usoh, M., Steed, A., 1995. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 2(3), 201–219.

Tanaka, S., Hasegawa, K., Okamoto, N., Umegaki, R., Wang, S., Uemura, M., Okamoto, A., Koyamada, K., 2016. See-through imaging of laser-scanned 3D cultural heritage objects based on stochastic rendering of large-scale point clouds. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 3, 73–80.

Van Dam, A., Forsberg, A. S., Laidlaw, D. H., LaViola, J. J., Simpson, R. M., 2000. Immersive VR for scientific visualization: A progress report. *IEEE Computer Graphics and Applications*, 20(6), 26–52.

Yamada, Y., Takatori, S., Adachi, M., Hasegawa, K., Li, L., Pan, J., Thufail, F. I., Yamaguchi, H., Tanaka, S., 2024. High-visibility edge-highlighting visualization of 3D scanned point clouds based on dual 3D edge extraction. *Remote Sensing*, 16(19), 3750.

Yuksel, C., 2015. Sample elimination for generating poisson disk sample sets. *Computer Graphics Forum*, 34number 2, Wiley Online Library, 25–32.

Zhang, Y., Pajarola, R., 2006. Single-pass point rendering and transparent shading. *PBG@ SIGGRAPH*, 37–48.

Zorich, D. M., 2003. *A Survey of Digital Cultural Heritage Initiatives and Their Sustainability Concerns. Managing Economic Challenges.* ERIC.