Realistic and Interactive Virtual Museum Representation Using 3D Gaussian Splatting

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Abstract

This study presents the development of a virtual museum utilizing 3D Gaussian Splatting (3DGS), a novel real-time rendering technique, and evaluates its experiential quality and effectiveness in comparison with a conventional 360-degree panoramic image (360° image)–based system. While 360° images offer advantages such as high visual clarity and ease of implementation, they are inherently limited in terms of user mobility and interaction, which restrict their immersive potential. In contrast, 3DGS enables robust scene reconstruction even in complex exhibition environments, supporting free navigation and interaction, and is therefore considered a promising approach for immersive virtual experiences. Two systems are implemented based on identical exhibition content, and a comprehensive user evaluation is conducted incorporating both quantitative and qualitative methods. The results, measured through the Igroup Presence Questionnaire (IPQ) and additional user perception metrics, indicate that the 3DGS-based system achieves statistically significant higher scores across all IPQ items. Furthermore, participants report greater satisfaction, intention to reuse, preference for widespread use, and motivation to visit. Despite minor limitations in image sharpness and text readability, users generally perceive the visual quality of the 3DGS system to be acceptable—sometimes even impressive—and show a clear preference for its interactive and participatory features. These findings suggest that, with further advancements in rendering quality and optimization, 3DGS holds strong potential as a viable alternative for future virtual museum implementations.

1. Introduction

As demand grows for accessible and immersive cultural heritage experiences, virtual museums have become a key medium for digital cultural dissemination. Among commonly used methods, 360-degree panoramic images (360° images) are popular due to their low cost, ease of implementation, and ability to deliver high-resolution visuals of real museum spaces. Interactive elements, such as clickable Points of Interest (POIs), further enhance engagement.

However, 360° image-based systems limit user movement to fixed viewpoints, reducing spatial exploration. In contrast, 3D reconstruction methods like laser scanning and photogrammetry offer free navigation and greater immersion, but struggle with reflective surfaces and complex lighting.

3D Gaussian Splatting (3DGS) has recently emerged as a promising alternative. Using point-based rendering with Gaussian functions, it enables real-time visualization of complex scenes without mesh modeling. Its ability to achieve high visual fidelity with efficient rendering makes it well-suited for immersive virtual environments.

This study compares two virtual museum systems—one based on 3DGS and the other on 360° images—built using the same exhibition content. A user study was conducted using the Igroup Presence Questionnaire (IPQ) (Schubert et al., 2001) is used to quantitatively evaluate General Presence, Spatial Presence, Involvement, and Experienced Realism, along with additional indicators such as satisfaction, intention to reuse, preference for widespread use, and motivation to visit. Results show that the 3DGS-based system scores significantly higher across all metrics. Qualitative feedback also highlights greater immersion, interactivity, and freedom of navigation, underscoring the potential of 3DGS in future digital exhibition development.

2. Related Works

2.1 Evolution of Virtual Museums

The concept of virtual museums emerged in the 1960s through experimental information technologies and documentation systems. In the 1980s and 1990s, CD-ROM-based multimedia fostered the idea of digital museums, which evolved into online virtual museums with the rise of the World Wide Web in the mid-1990s (Povroznik, 2020). This development marks a gradual shift from technical experimentation to today's immersive, user-centered virtual museums.

This progression has increasingly focused on enhancing presence—the psychological sense of "being there." Interactive features such as 3D spaces, real-time navigation, and audiovisual elements promote a stronger sense of presence than static displays (Sylaiou et al., 2008), which correlates with higher emotional satisfaction (Sylaiou et al., 2010). VR exhibitions further foster multi-layered presence through elements like human, content, interaction and socialising (Zhou, 2019).

Two major trends define this evolution: enhanced visual realism and dynamic user interaction. Visual vividness improves spatial presence and user engagement (Huang et al., 2010), supported by technologies like photogrammetry, laser scanning, and 3D modeling. Real-time rendering and lighting also enhance realism and the appeal of VR-based exhibitions (Shi Ke et al., 2023).

User interaction plays a central role in immersive experiences, as active navigation fosters deeper presence than passive viewing (Huang et al., 2010). In VR, users engage with artifacts through hand-tracking or controllers, and experience sensory input via haptics or treadmills (Chrysanthakopoulou et al., 2021; Wang et al., 2023). Multi-user features enhance immersion and engagement, especially among Gen MZ (Lee et al., 2022). Furthermore, biometric and cognitive studies show virtual museums can surpass physical visits in delivering information and stimulating the senses (Melendreras Ruiz et al., 2024).

2.2 Development of Virtual Museums Using 360-Degree Panoramic Images

The use of 360° images is one of the most widely adopted methods for constructing virtual museums (Tjahjawulan and Sabana, 2015; Koeva et al., 2017; Bocconcino et al., 2024). By placing panoramic cameras at selected points, these systems capture the surrounding environment in a single shot and deploy the images on web-based or VR platforms. Although they do not reconstruct actual spatial geometry, they allow users to move between viewpoints and simulate a sense of 3D immersion.

This method is favored for its low cost, ease of use, and fast deployment compared to advanced 3D reconstruction techniques. The rise of consumer-friendly 360° capture devices—such as Matterport, Ricoh Theta, and Insta360—has further accelerated its adoption. Some platforms also support automated stitching and navigation route generation, simplifying the virtual tour creation process for non-experts.

Interactive elements like hotspot navigation and exhibit-based POI markers enhance engagement, enabling users to explore content beyond passive viewing. As a result, 360° image-based systems have been widely used in cultural heritage, art galleries, and exhibition halls for digital archiving and remote access—especially during the COVID-19 pandemic.

However, their reliance on fixed capture points limits user freedom in navigation and close inspection. Recent developments in 3D reconstruction are addressing these limitations by offering more immersive and flexible spatial representations.

2.3 Advancement of Image-Based 3D Reconstruction Technologies

Recent advancements in 3D reconstruction technologies have been driven by improvements in image acquisition devices and the diversification of user-oriented workflows. A variety of sensors—including DSLR cameras, RGB-D cameras, LiDAR, 360° images, and SLAM-based mobile devices—enable accurate data collection in diverse environments. Among them, image-based 3D reconstruction has gained popularity for its high-resolution outputs, cost-effectiveness, and ease of use. Experts often use precise Structure-from-Motion and Multi-View Stereo (SfM-MVS) pipelines, while general users increasingly rely on smartphone apps or cloud platforms, promoting broader adoption in fields such as digital heritage, XR, and the metaverse.

SfM-MVS, based on RGB images, remains a widely used pipeline in museum and heritage documentation. This method involves camera pose estimation and sparse point cloud generation through SfM, followed by dense reconstruction using MVS, and finally the creation of textured meshes (Debevec et al., 1996; Pollefeys et al., 2004; Seitz et al., 2006; Schönberger and Frahm, 2016). While it provides high geometric accuracy, it struggles to handle reflective or transparent surfaces and complex lighting conditions, and its substantial computational demands and slow rendering performance further limit its applicability in practical scenarios.

To overcome such limitations, Neural Radiance Fields (NeRF) have recently garnered attention. NeRF learns a volumetric scene representation from densely overlapping multi-view images, enabling view-dependent effects (Mildenhall et al., 2020). However, its high computational requirements present challenges for real-time applications, limiting its practical deployment.

3DGS offers a promising alternative, representing scenes with thousands of 3D Gaussian primitives that encode position, covariance, color, opacity, and view-dependent radiance (Kerbl et al., 2023). It enables real-time rendering of complex visual properties such as transparency and reflectivity. Studies report that 3DGS outperforms NeRF and traditional photogrammetry in texture fidelity, lighting quality, and rendering speed (Basso et al., 2024; Clini et al., 2024; Previtali et al., 2024). It performs robustly in both indoor and outdoor environments (Fang et al., 2025; Cai et al., 2024), though issues such as sensitivity to camera tilt (Sathyan and Kinsman, 2024) and lack of geospatial metadata (Previtali et al., 2024) remain. Despite these, 3DGS shows strong potential for real-time immersive visualization (Chen et al., 2024).

In this study, the 3DGS technique is applied to reconstruct a museum interior with high visual fidelity and to implement a multi-user virtual environment supporting avatar navigation. A comparative user study is conducted between systems based on 3DGS and 360° images to comprehensively evaluate the user experience associated with each approach.

3. System Development

This section outlines the development of two virtual museum systems based on different approaches—360° images and 3DGS—using the interior of a university museum as the target environment. Each system is constructed through three main stages: image acquisition, post-processing, and system implementation. The resulting environments serve as the basis for comparative user evaluation. The computer specifications used for the post-processing and system implementation stages are presented in Table 1.

Types	Specifications
Processor	12th Gen Intel® Core™ i9-12900K 3.20GHz
RAM	128GB
System Type	64bit
OS	Windows 11 Pro
GPU	NVIDIA GeForce RTX 3090 Ti

Table 1. Computer Specifications.

3.1 System Development Using 360-Degree Panoramic Images

3.1.1 Image Acquisition: 360° images are captured at 11 key locations throughout the museum using an Insta360 Titan camera, with capture points strategically placed in front of exhibit cases along the anticipated user navigation path. Remote control is achieved via a dedicated mobile application, with automatic exposure and white balance settings applied to optimize image quality under varying lighting conditions. Captured images are taken without including the photographer.

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Figure 1. 360° image acquisition using Insta360 Titan.

3.1.2 Post-Processing: The eight fisheye images captured by the Insta360 Titan are stitched into seamless panoramic views using Insta360 Stitcher software. This process corrects parallax and lens distortion to generate a continuous 360° image for each viewpoint. The final outputs are exported at the maximum resolution of 11K (10,560 × 5,280 pixels) and saved in high-quality .jpg format, which is suitable for use as visual content in the virtual environment.

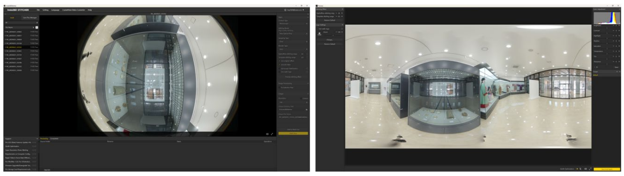

Figure 2. 360° image stitching using Insta360 Stitcher.

3.1.3 System Implementation: In the Unity 6-based virtual scene, 360° images are mapped onto spherical objects. Users can pan the view with mouse drag and zoom using the scroll wheel. Hotspot interactions enable navigation between viewpoints via mouse clicks, while exhibit information is accessed through overlay UI panels triggered by clicking on POIs near display cases. In Unity Editor Play Mode, average memory usage and FPS over one minute are measured at 639.31 MB and 456.43 FPS, respectively, using a custom script.

Figure 3. 360° image-based system development using Unity 6.

3.2 System Development Using 3D Gaussian Splatting

3.2.1 Image Acquisition: Multi-view images for 3DGS training are captured using a Canon R5 camera equipped with an RF 15–35mm F2.8 L IS USM zoom lens. To maximize information per frame and facilitate overlap and alignment between images, the lens is set to its widest focal length of 15mm. The camera is operated in manual mode with the white balance fixed at 5200K to ensure consistent color temperature across the image set. Exposure settings are adjusted to suit the museum's lighting conditions, targeting an EV close to 0 with aperture F8, ISO 200, and shutter speed 1/30 sec.

Image acquisition is conducted along a linear path in front of each display case, at a typical human eye-level viewpoint, with uniform half-step spacing between shots. Special attention is paid to capturing all images without noticeable horizontal or vertical tilt, as tilted inputs can lead to distorted or suboptimal reconstruction results in 3DGS. Additional images are captured to cover any missing regions identified in the initial 3DGS outputs. In total, 1,449 high-resolution images (8,192 × 5,464 pixels) are collected.

3.2.2 Post-Processing: SfM-based image alignment is performed using RealityCapture. Any disconnected components in the alignment are manually corrected using control points, resulting in successful alignment of 1,419 out of 1,449 images. According to the alignment report, the mean error is 0.685261 pixels. Generally, a mean error below 1 pixel is considered as indicative of high-quality alignment. Real-world scale is applied using the Define Distance function, based on physical measurements taken on-site with a tape measure. This process generates camera poses and a sparse point cloud scaled to real-world dimensions, which are then used to extract the necessary camera parameter files for 3DGS training.

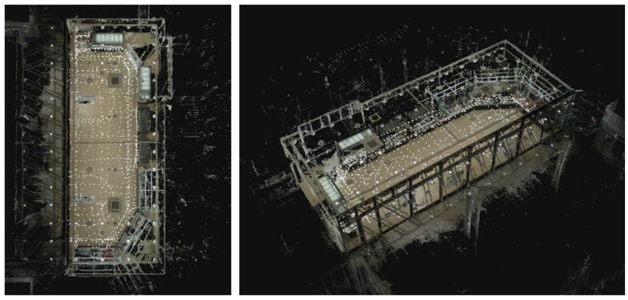

Figure 4. Camera alignment using RealityCapture.

The sparse point cloud is exported in .ply format and the camera parameters in .csv format, all saved within the same directory as the image set. Unaligned images are removed prior to training. The dataset folder is then imported into Postshot, a tool designed to facilitate 3DGS training from either image-based or video-based input. It supports various input types and automates the training pipeline using externally generated camera poses and point clouds. In this study, the image set, sparse point cloud, and camera parameters generated via RealityCapture are used as input. All images in the folder are included for training, which is set to terminate at 300k steps. The training process iteratively optimizes the parameters of the initial Gaussian splats—including position, scale, color, opacity, and orientation—to minimize the difference between the rendered views and the original images. The trained result is exported as a .ply file containing the Gaussian point cloud, which is then used as the visual content in the system implementation phase.

Figure 5. Gaussian point optimization using Postshot.

Figure 6. Comparison between photogrammetry and 3DGS results.

For reference, a photogrammetry-based 3D model is also generated using the same aligned camera data from RealityCapture. The mesh is reconstructed at the "Normal Detail" level and textured at 16K resolution. Comparative analysis shows that the photogrammetry model suffers from significant reconstruction failures, particularly in uniform color regions and glass surfaces due to insufficient feature points, and shows limitations in rendering reflections. In contrast, 3DGS produces a more complete and visually consistent result, demonstrating greater robustness under these conditions.

3.2.3 System Implementation: The trained 3DGS scene is implemented in Unity 6 using the UnityGaussianSplatting plugin (Aras-P., 2023), which enables efficient visualization of Gaussian point data. After generating the scene using 3DGS, collider objects are added to the environment to enable free avatar movement and exploration. Users navigate the environment using keyboard arrow keys and mouse input, and access exhibit information by clicking on POIs placed near display cases. A multiplayer environment is implemented using the Photon Fusion networking framework, allowing multiple users to explore the virtual museum space simultaneously in a shared, interactive setting. Based on a custom script, the average memory usage and FPS during one minute of runtime in Unity Editor Play Mode are measured as 682.12 MB and 24.93 FPS, respectively.

Figure 7. 3DGS based system development using Unity 6.

4. Evaluation

4.1 Evaluation Items and Measurement Methods

For the quantitative evaluation of user experience, the standardized IPQ is employed. The IPQ is a widely validated instrument designed to assess users’ sense of presence in virtual environments, and it continues to be actively used in a variety of recent studies. The questionnaire consists of 14 items across four subscales: General Presence, Spatial Presence, Involvement, and Experienced Realism. Each item is rated on a 7-point Likert scale, and recent research recommends using a bipolar scale ranging from -3 to +3 (Tran et al., 2024). Following this guideline, the full item list of the official IPQ is utilized in this study, and user responses are collected using the -3 to +3 scale (-3 = Strongly Disagree, 3 = Strongly Agree).

Items	Questions
G1	In the computer generated world I had a sense of "being there"
SP1	Somehow I felt that the virtual world surrounded me.
SP2	I felt like I was just perceiving pictures.
SP3	I did not feel present in the virtual space.
SP4	I had a sense of acting in the virtual space, rather than operating something from outside.
SP5	I felt present in the virtual space.
INV1	How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?
INV2	I was not aware of my real environment.
INV3	I still paid attention to the real environment.
INV4	I was completely captivated by the virtual world.
REAL1	How real did the virtual world seem to you?
REAL2	How much did your experience in the virtual environment seem consistent with your real world experience?
REAL3	How real did the virtual world seem to you?
REAL4	The virtual world seemed more realistic than the real world.

Table 2. Items and questions for IPQ metrics.

In addition to presence measurement, a supplementary questionnaire is developed to assess overall user perceptions of each system. These additional items are designed to capture intuitive and attitudinal responses not covered by the IPQ. The questionnaire includes items related to satisfaction, intention to reuse, preference for widespread use, and motivation to visit. To ensure ease of response and consistency in interpretation, these items are rated on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).

Items	Questions
satisfaction	I was satisfied with the experience.
intention to reuse	I would like to use this system again in the future.
preference for widespread use	I hope this system will be widely used for building virtual museums.
motivation to visit	After this experience, I feel more motivated to visit a real museum.

Table 3. Items and questions for overall user perception metrics

Furthermore, participants are invited to provide open-ended responses describing any perceived strengths, weaknesses, or additional feedback based on their experience with each system. This qualitative component aims to supplement the quantitative data by capturing user insights and reactions that may not be reflected through structured survey items.

4.2 Evaluation Procedure

The user evaluation is conducted over seven weekdays between March 27 and April 4, 2025, excluding weekends. A total of 30 participants take part in the study, the majority of whom—except for three—have prior experience with virtual museums based on 360° images. Prior to the evaluation, all participants are thoroughly briefed on the purpose of the study, the two virtual museum systems, usage instructions, and relevant precautions. The computer used for the experiment is connected to a local area network via wired LAN to ensure stable performance for the multiplayer functionality of the 3DGS-based virtual museum.

Each participant experiences both systems: the 360° image-based virtual museum and the 3DGS-based virtual museum. The exploration in both systems begins at the virtual museum entrance and follows a linear path along the exhibition displays. To minimize order effects, participants are randomly divided into two groups. One group experiences the 360° image-based system first, while the other begins with the 3DGS-based system.

Distinction		Number of Participants (%)
Gender	Male	6 (20%)
	Female	24 (80%)
Age	20's	24 (80%)
	30's	6 (20%)
Pre-experience of 360° Image-Based Virtual Museum	O	27 (90%)
	X	3 (10%)

Table 4. Participant demographics.

After completing both experiences, participants fill out a questionnaire designed to compare and analyze their perceptions of the two systems. The entire session, including both experiences and the survey, lasts approximately 20 to 30 minutes per participant. As a token of appreciation, each participant receives a gift voucher worth approximately 5 USD. The collected data are analyzed using IBM SPSS Statistics 26.

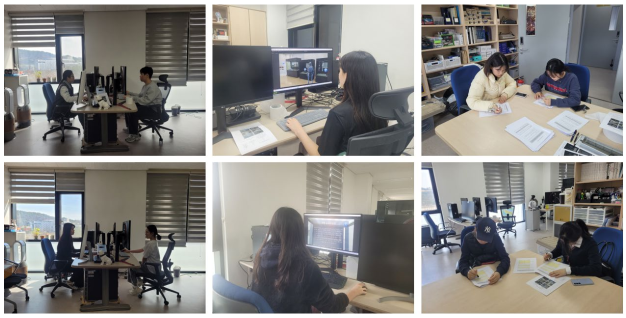

Figure 8. System evaluation activities.

4.3 Quantitative Analysis

4.3.1 Analysis of IPQ Responses

4.3.1 Analysis of IPQ Responses: To analyze responses to the IPQ, a paired samples t-test is conducted. Across all items, the 3DGS-based system yields higher mean scores than the 360° image-based system, and the mean differences are statistically significant as shown in Table 5. These results suggest that the 3DGS-based virtual museum elicits a significantly greater sense of presence compared to the 360° image-based system in all IPQ dimensions.

Distinction		Descriptive		t(p)
		Mean	SD	
General Presence	360°	-0.53	1.70	-5.825 (0.000)***
	3DGS	1.30	1.12	
Spatial Presence	360°	-0.81	1.44	-7.873 (0.000)***
	3DGS	1.48	0.91	
Involvement	360°	-1.04	1.34	-7.401 (0.000)***
	3DGS	0.73	1.02	
Experienced Realism	360°	-0.83	1.04	-6.180 (0.000)***
	3DGS	0.55	0.79	

Table 5. Results of IPQ metrics.

4.3.2 Analysis of Overall User Perception Responses: Analysis of the overall user perception responses likewise shows that the 3DGS-based system receives higher mean scores than the 360° image-based system across all evaluated items. The paired samples t-test indicates that these differences are statistically significant for each factor, as detailed in Table 6. These findings suggest that the 3DGS-based system leads to more favorable user perceptions overall, particularly in terms of satisfaction, intention to reuse, and preference for widespread use.

Distinction		Descriptive		t(p)
		Mean	SD	
satisfaction	360°	3.20	1.70	-7.870 (0.000)***
	3DGS	4.43	1.12	
intention to reuse	360°	2.70	1.44	-8.394 (0.000)***
	3DGS	4.13	0.91	
preference for widespread use	360°	3.07	1.34	-6.714 (0.000)***
	3DGS	4.63	1.02	
motivation to visit	360°	3.23	1.04	-3.717 (0.001)**
	3DGS	3.97	0.79	

Table 6. Results of overall user perception metrics.

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4.4 Qualitative Analysis

4.4.1 Perceived Strengths: Participants note that the 360° image-based system offers high visual fidelity and clarity, which allow for detailed observation of artifacts and easy readability of descriptive text. This system is widely perceived as suitable for static viewing, with many users emphasizing the intuitive controls and familiar interface, which lower the barrier to entry and enhance accessibility. The predefined linear navigation path is also highlighted as a strength, as it helps convey the curatorial intent behind the exhibition structure.

In contrast, the 3DGS-based system is praised for its strong sense of spatial presence, freedom of movement, immersive experience, and visual resemblance to the real museum environment. Many participants note that the spatial depth and scale of the environment feel authentic, contributing to a heightened sense of presence. The ability to navigate through the environment using an avatar contributes to a realistic museum-walking experience, allowing users to observe artifacts from various angles and distances. Some participants mention that this helps them better estimate the physical scale of the objects, enhancing the sense of realism. The multiplayer functionality, which enables users to share the same virtual space, is also cited as a key contributor to social presence. In addition, environmental effects such as the rendering of reflections and transparency on glass surfaces are perceived as offering a more realistic visual representation compared to traditional methods.

4.4.2 Perceived Weaknesses: For the 360° image-based system, the primary drawbacks include restricted mobility, fixed viewpoints, and a fragmented sense of interaction. Users are limited to navigating between predefined points, which hinders continuous and free exploration. Repetitive clicking and a constrained interaction space are cited as factors that reduce immersion. Some users also report discomfort, including dizziness caused by panoramic view rotation. Overall, the experience is often described as closer to viewing high-resolution 360° images rather than engaging with a fully immersive virtual environment. As a result, several participants perceive the system as better suited for archival viewing rather than interactive museum experiences.

On the other hand, criticisms of the 3DGS-based system focus on lower image resolution, blurred rendering of artifacts and text, and unfamiliarity with the game-like control scheme. Many participants express difficulty in appreciating artifact details due to limited clarity. However, some participants note that the visual quality of the 3DGS-based system is impressively high, to the extent that the difference compared to the 360° image-based system feels negligible. These responses suggest that the visual fidelity of the 3DGS-based system cannot be uniformly regarded as inferior, and may be perceived as sufficient depending on user expectations and context. Other reported issues include visual noise, minor motion sickness, and the lack of avatar shadows, which contribute to a sense of visual dissonance. Several participants point out these aspects as areas in need of improvement.

4.4.3 Additional Feedback: Several participants propose integrating the strengths of both systems to create a more comprehensive virtual museum experience. It is commonly suggested that combining the high-resolution visuals of the 360° image-based system with the interactive and immersive features of the 3DGS-based system would result in a more complete solution. Users often distinguish between the strengths of each system: the 360° image-based system being preferable for close inspection of details, and the 3DGS system offering a more engaging and immersive experience. When asked to choose, many participants express a preference for the 3DGS-based system and support its broader adoption in virtual museum development. In addition, the 3DGS system is recognized as a realistic alternative to physical museum visits, especially for individuals unable to travel due to physical constraints. Lastly, participants recommend implementing user-adjustable sensitivity and control customization features to accommodate differences in age and digital familiarity.

5. Discussion

This study compares two virtual museum systems—one based on 360° images and the other on 3DGS. Both quantitative and qualitative analyses show that the 3DGS-based system received more favorable user feedback. While the 360° image-based system provides high-resolution visuals, its limited interactivity and continuity reduce immersion, reflecting a traditional exhibition approach focused on visual documentation. In contrast, despite some issues with text readability and resolution, the 3DGS-based system enables greater spatial immersion and realism through free navigation, avatar-based movement, and multi-user features. Some participants regard it as a viable alternative to physical museum visits, indicating its potential value for users facing temporal or spatial limitations.

These findings suggest that while visual fidelity is an important component of virtual museum experiences, it is not sufficient on its own. Immersion and presence must be supported through the structural integration of meaningful user interaction and engagement. Notably, the 3DGS-based system demonstrates the potential to deliver both relatively high visual quality and interactive immersion within a single platform, offering a more holistic approach to virtual museum design.

However, The 3DGS-based system faces technical challenges in image acquisition, post-processing, and implementation. The acquisition stage requires careful control of variables like camera path, image overlap, and settings, demanding more time and resources than 360° images. Reconstructing the indoor environment demands substantial resources, requiring 1,419 high-resolution images totaling 14.0 GB. The optimization of Gaussian splat parameters over 300,000 iterations is also time-intensive, taking approximately 3.5 hours and generating a large output file of 709 MB. Sunlight reflections introduce noise on floors, limiting shooting to times when only indoor lighting is present and natural sunlight is absent, while blank surfaces like white walls cause noise due to lack of features. In implementation, the lack of avatar shadows reduces visual realism and immersion. These issues underscore the need for further technical refinement to improve 3DGS applicability in indoor virtual environments.

To improve the quality of 3DGS-based virtual museum systems, targeted strategies are required across key stages. In the acquisition phase, using stabilized video capture with gimbals and slow motion, followed by frame extraction, offers a practical alternative to time-intensive photo shooting. Ensuring consistent lighting conditions also helps reduce post-processing errors. In the processing stage, advances in fast rendering algorithms (Diels et al., 2025; Hanson et al., 2025), efficient computation (Liu et al., 2023), and enhanced Gaussian modeling (Chao et al., 2025) provide promising solutions. Hybrid approaches that combine 3DGS with laser scanning or photogrammetry may serve as viable alternatives to address current limitations. At the implementation level, real-time lighting and shadow rendering techniques (Bi et al., 2024; Guo et al., 2024) can enhance immersion and help maintain consistent realism under varying viewing and lighting conditions.

Ultimately, combining high-resolution visual fidelity with immersive, interaction-oriented design is key to creating virtual museums that are both visually and experientially engaging. These findings highlight the importance of a holistic design approach that incorporates interactivity, user agency, and spatial and social presence from the outset. Achieving this requires a clear exhibition philosophy and close collaboration among curators, developers, and users. Curators provide interpretive context, developers build immersive systems, and users offer feedback to refine the experience. Especially for advanced systems like 3DGS, aligning stakeholder workflows is essential for ensuring high-quality outcomes.

6. Conclusion

This study compares two virtual museum systems—one based on 360° images and the other on 3DGS—constructed using identical exhibition content. Through quantitative and qualitative evaluation, it examines how differences in system design and interaction structure affect user experience, providing practical insights for the future development of virtual museum environments.

Quantitative analysis of IPQ responses and overall user perception metrics shows that the 3DGS-based system scores significantly higher than the 360° image-based system across all evaluation categories. While the 360° image-based system is appreciated for its visual clarity and ease of use, the 3DGS-based system delivers a comparably satisfactory visual experience, along with stronger spatial and social presence, greater freedom of navigation, and a more immersive and interactive environment. Several participants note that its spatial configuration, viewing flexibility, and multi-user functionality contribute to a realistic and emotionally engaging museum experience. The system's ability to integrate spatial realism with experiential depth suggests a new direction beyond the conventional trade-off between visual fidelity and interactivity.

Overall, this study underscores the need for virtual museum systems that not only engage users through immersion, interactivity, and social presence, but also convey a convincing sense of realism. 3DGS provides a promising foundation for the next generation of virtual museum environments.

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