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Digitizing Nakhwa-nori: An XR Framework for Cultural Preservation and Accessibility

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Abstract

This study proposes a comprehensive Extended Reality (XR) framework for digitally preserving Nakhwa-nori, a traditional Korean pyrotechnic festival facing critical challenges including overcrowding-related safety risks, geographical accessibility barriers, and insufficient systematic documentation. Leveraging Unreal Engine 5's advanced capabilities—Nanite virtualized geometry, Lumen global illumination, and Niagara GPU-accelerated particle systems—we developed an immersive digital reconstruction system that authentically reproduces the festival's complex visual phenomena through dual-layer particle simulation architectures, physics-based environmental interactions, and spline-based structural modeling. Performance evaluation on consumer-grade hardware demonstrated stable frame rates (60-140 FPS) across quality settings, confirming technical feasibility for real-time cultural heritage experiences. This framework establishes scalable methodologies applicable to diverse intangible cultural assets while providing safe, accessible alternatives to physical attendance and creating authoritative digital records for cultural sovereignty protection. The research contributes a transformative paradigm for sustainable preservation of intangible cultural heritage through harmonious integration with advanced technological methodologies.

Keywords : Extended Reality, Cultural Heritage Preservation, Real-time Rendering, Nakhwa-nori, Digital Archiving, Unreal Engine, Particle System

Digitizing Nakhwa-nori: An XR Framework for Cultural Preservation and Accessibility

1. Introduction

Nakhwa-nori represents a distinctive form of Korean traditional pyrotechnic performance wherein bamboo tubes filled with charcoal from oak trees are ignited, producing cascading streams of luminous embers that descend from elevated positions onto water surfaces during nighttime festivals. This centuries-old tradition manifests across multiple Korean regions, including the Mujinjeong Nakhwa-nori celebration in Haman (Gyeongsangnam-do), the Anseong variant in Gyeonggi-do, performances in Muju (Jeollabuk-do), and the Haechon Nakhwa-nori in Yeoju. Each regional iteration embodies unique local characteristics while maintaining core ritualistic elements: the ceremonial warding off of malevolent spirits and disease, communal prayers for agricultural abundance and collective prosperity, and the reinforcement of social cohesion within communities (Encyclopedia of Korea, 2024; Kim, 2008).

Distinguished from conventional pyrotechnic displays, Nakhwa-nori performances extend over approximately two hours, during which the harmonious interplay of visual spectacle and ambient soundscapes has catalyzed heightened public fascination (Younhap News Agency, 2023.05.27). This cultural resurgence has been amplified through contemporary media representations, notably in the music video for BTS member RM's solo composition *Wild Flower* (BTS, 2022), the KBS 2TV entertainment program *2 Days and 1 Night Season 4* (Korean Broadcasting System, 2021), and the concluding sequence of Episode 1 of the period drama series *Bloody Heart*, which aired on May 2, 2022 (Korean Broadcasting System, 2022). Additionally, extensive dissemination via social media

platforms (News1, 2022) has significantly expanded public awareness and engagement.

The implications of this renewed popularity have manifested in substantial logistical challenges. In 2023, the Haman Nakhwa-nori Festival attracted approximately 60,000 visitors—a figure nearly equivalent to the entire municipal population—resulting in severe transportation infrastructure strain and temporary telecommunications network failures throughout Haman-gun. In response to these capacity pressures, festival organizers implemented a comprehensive online reservation system for the 2024 event, limiting attendance to 7,000–8,000 participants. However, demand substantially exceeded this restricted capacity; the second allocation cycle depleted within less than sixty seconds, prompting further reduction to 6,500 attendees for the 2025 iteration (Kyunghyang Shinmun, 2025).

Similarly, Sejong City inaugurated its *1st Nakhwa-nori Traditional Culture Festival* in October 2016 (Environmental Management Newspaper, 2025), which has subsequently evolved into a major regional cultural event attracting over 100,000 visitors on festival days (News1, 2025). Nevertheless, the concentration of tens of thousands of attendees has precipitated safety incidents, including cases where spectators sustained injuries from airborne embers due to insufficient perimeter safety infrastructure at venue sites (Chungcheongnaetoday, 2022). These operational challenges underscore fundamental limitations: the festival's restriction to specific seasonal windows and geographical locations constrains viewing accessibility and necessitates substantial investment of temporal, human, and material resources for site preparation.

Consequently, immersive digital experiences emerge as a viable supplementary avenue to physical attendance, enabling broader public engagement with this traditional

performance in a safe and resource-efficient manner. Given its striking visual aesthetics and profound cultural significance, Nakhwa-nori possesses substantial potential for systematic digital documentation and preservation through meticulous archival methodologies.

However, beyond these operational challenges, Nakhwa-nori faces more fundamental preservation concerns. The preservation of Nakhwa-nori confronts critical deficiencies in systematic documentation. According to testimony provided by Ryu Han-cheol, Secretary-General of the Andong Hahoe Village Preservation Society, reconstruction efforts have been characterized by extensive trial-and-error processes: "Comprehensive records detailing the fabrication methodology for the bamboo torch assemblies or their suspension configurations are essentially non-existent... Following approximately two years of iterative experimentation, involving the production and testing of approximately fifty prototype units, we eventually established the current operational specifications."

This fundamental absence of codified documentation significantly impedes effective intergenerational transmission of traditional cultural knowledge. While Dengok-ri Nakhwa-nori received designation as part of the Cultural Heritage Administration's 'Future Intangible Cultural Heritage Discovery and Nurturing Projects' in 2022, with subsequent reselection in 2024 (Daejeon Ilbo, 2023), *Nakhwa-nori* has yet to receive recognition as a national intangible cultural property, indicating that systematic preservation policies remain in nascent developmental stages (Joongang Ilbo, 2023).

Moreover, the escalating international visibility of Korean traditional pyrotechnics has generated concerns regarding cultural appropriation and misattribution. Analogous performances, termed 'falling flowers' or similar designations, have emerged in certain

Chinese regions (Gyeongnam Minilbo, 2025), with some Chinese netizens asserting that Korean fireworks traditions originated from their domestic *Tacheolhwa* (打鐵花) practices (Xinhua News Agency, 2019). However, critical distinctions invalidate such claims: Tacheolhwa constitutes a ritualistic performance involving the projection of molten iron to generate spark displays, fundamentally diverging from Nakhwa-nori's methodology, which employs suspended bamboo tubes filled with charcoal to produce cascading embers over water surfaces.

The potential for cultural archetype confusion and deliberate distortion intensifies in the absence of authoritative digital preservation and comprehensive documentation. Therefore, XR-based immersive digital documentation transcends mere tourism commodification, providing objective, verifiable evidence of cultural identity, historical continuity, and authentic origins that can serve as authoritative reference material in disputes regarding cultural heritage ownership.

1.1 Research Objectives and Contributions

This research proposes a systematic digital archiving framework designed to achieve three primary objectives: (1) mitigate the operational and logistical limitations inherent in physical festival execution; (2) expand opportunities for cultural engagement beyond spatial and temporal constraints while maintaining authentic representational fidelity; and (3) address concerns related to cultural appropriation and historical distortion through the creation of authoritative digital records.

Leveraging Unreal Engine 5's advanced technological capabilities—specifically Nanite virtualized geometry processing, Lumen global illumination, and the Niagara GPU-accelerated particle system—this research proposes and empirically validates a

methodology for digitally reconstructing the visual and spatial dimensions of Nakhwa-nori festivals. The objective is to develop immersive XR experiences capable of complementing, and in certain contexts substituting for, physical festival attendance.

Building upon this technological foundation, this research establishes four specific operational objectives:

First, through scientific analysis and systematic digitization of core festival elements—including the fabrication process of firework torch assemblies, ignition ceremonial protocols, ember dispersion patterns, spatial choreography, and acoustic environments—this research establishes a digital cultural heritage preservation model enabling three-dimensional experiential engagement.

Second, XR technology presents promising solutions to address inherent hazards associated with live pyrotechnic displays, including fire safety risks, crowd management challenges, weather-related cancellation vulnerabilities, and geographical accessibility limitations.

Third, through implementation of a VR application enabling users to observe festivals from multiple vantage points while accessing contextual information regarding historical background and cultural significance, we aim to enhance public understanding of traditional culture and promote international dissemination of Korean cultural heritage.

Fourth, as an extended long-term vision, we propose the conceptual framework for hybrid real-virtual festival operations employing digital twin technology, contributing to sustainable models of cultural tourism development.

2. Related Work

Recent initiatives in digital cultural heritage preservation have demonstrated the transformative potential of XR technologies. The Cultural Heritage Administration of Korea released high-resolution 3D scans of Changdeokgung Palace's Nakseonjae in XR format, enabling remote exploration of palace interiors without physical site visits (Newsis, 2020). This approach exemplifies how digital preservation can enhance accessibility while protecting physical cultural assets from degradation due to visitor traffic.

Research by Ahn and Park (2024) explored the fusion of holographic and XR technologies to reinterpret traditional Korean Pansori performances as immersive digital exhibitions. Their work demonstrates technological and cultural parallels with our research, as both attempt to extend intangible festivals beyond the accessibility and preservation limitations of physical performances through XR realization. However, their focus on static performance capture differs from our emphasis on dynamic, real-time simulation of complex environmental phenomena.

XR-based digital cultural heritage projects increasingly utilize real-time game engines such as Unity or Unreal Engine. The Cleveland Museum of Art employed Unreal Engine 5 to recreate the traditional Korean painting *Chilbo Sando* as an immersive digital exhibit, utilizing Nanite and Lumen to authentically render painting textures while adding atmospheric fog and light effects through the Niagara particle system to maximize immersion (Epic Games, 2024).

Cho et al. (2014) experimented with GPU engine-based particle simulation for real-time recreation of traditional fireworks displays, demonstrating that the physical interaction of myriad particles and light can be effectively realized in virtual space. This research

provides direct technical implications for digitizing traditional festivals where fireworks, smoke, and water reflections constitute essential visual elements. Kelly (2022) presented methodologies for complex 3D path and structural modeling utilizing Unreal Engine's Blueprint Spline system, which we directly applied in implementing the rope system connecting firework torches.

Karis (2021) provided deep technical analysis of the Nanite virtualized geometry system, establishing the technical foundation for real-time rendering of traditional architecture with millions of polygons. Research by Cichocki (2017) and 2K Games (2021) presented optimized pixel-projected reflection techniques for planar reflectors, establishing the technical basis for water surface reflection implementation.

Existing research suggests that digital cultural heritage preservation and XR experience design are evolving from mere documentation to means of immersive learning and global dissemination. In this context, our research differentiates itself from previous studies in several key aspects:

Dynamic vs. Static Heritage: While previous XR cultural heritage research focused primarily on static architectural documentation (Newsis, 2020) or partial performance capture (Ahn & Park, 2024), this study tackles the comprehensive digital reconstruction of a highly dynamic, multi-sensory festival involving complex particle physics, environmental interactions, and large-scale spatial choreography.

Real-time Physics Simulation: Unlike conventional cultural documentation relying on pre-recorded media, our approach implements real-time particle systems and physics-based rendering to recreate the unpredictable, natural beauty of traditional fireworks including wind-gravity interactions and ember dispersion patterns, as demonstrated by

Cho et al. (2014).

Safety-Accessibility Paradigm: This research uniquely addresses the critical challenge of preserving culturally significant but physically hazardous traditions, proposing XR as a solution for both safety concerns and global accessibility rather than mere digital documentation.

Scalable Methodological Framework: Beyond current preservation models, we establish a universal methodology applicable not only to Nakhwa-nori but extendable to diverse traditional festivals and intangible cultural assets, contributing to sustainable cultural heritage management.

3. Methodology

3.1 Technical Platform Selection

Nakhwa-nori is a highly dynamic traditional experience where thousands of embers fall simultaneously, each tracing different trajectories influenced by gravity, wind, and atmospheric conditions at every moment. As a nocturnal event, the complex interplay of light and particles—including instantaneous spark flashes, moonlight, water surface reflections, and smoke dispersion—constitutes core visual elements. Effective reproduction of these characteristics necessitates real-time simulation based on physical laws rather than pre-rendered static images or videos.

We selected Unreal Engine 5 as our technical platform due to its optimization for real-time, high-quality physically-based simulation with support for real-time ray tracing, Lumen global illumination, and Niagara VFX. The GPU-based particle system can

simultaneously process hundreds of thousands of particles with physical rules, providing robust representation of natural phenomena such as water, smoke, flames, and fog, while physically calculating real-time light reflection and refraction.

The Niagara GPU particle system is capable of handling hundreds of thousands of sparks from thousands of fire rods in real-time, managing the physical trajectory and life cycle of each particle individually (Kelly, 2022; Karis, 2021). It calculates physical forces including gravity, drag, and wind force in real-time to reproduce the irregular and natural spark patterns observed in actual Nakhwa-nori performances.

Lumen global illumination tracks all light source changes in the scene in real-time without pre-calculation, ensuring that instantaneous brightness variations of sparks are immediately reflected on surrounding pavilions, trees, and water surfaces (Epic Games, 2025). This provides dynamic lighting effects impossible with traditional baked lighting.

Nanite mesh processing technology applies distance-based level of detail (LOD) optimization, enabling high-quality representation of elaborate pavilions and surrounding terrain while maintaining GPU efficiency (Cichocki, 2017). The water rendering system combines Unreal Engine's native Water Material with Planar Reflection and Screen Space Reflection to realistically implement firework reflections on pond surfaces, fully expressing the "fire on water" visual appeal central to *Nakhwa-nori* (2K Games, 2021; Epic Games, 2025).

Table 1. *Unreal Engine 5 Technical Components and Applications*

Component	Function	Application in Nakhwa-nori
Nanite	Virtualized geometry	High-resolution pavilion & terrain rendering
Lumen	Global illumination	Real-time dynamic lighting & reflections

Niagara	GPU particle system	Ember simulation & smoke effects
Water System	Fluid rendering	Water surface & reflection rendering
Spline System	Path modeling	Rope structure & torch positioning

3.2 Implementation Process

Instead of direct festival site photography, we systematically collected and analyzed publicly available high-resolution video footage and photographic records. We acquired 4K videos of the Haman Mujinjeong Nakhwa-nori, Andong Hahoe Village Julbul-nori, and Sejong City Nakhwa Festival from YouTube and news archives, analyzing them frame-by-frame to measure average ember fall velocity (approximately 1.2-1.5 m/s), particle size (2-5 pixels on screen), and color change patterns (transitions from orange to yellow to red).

Audio materials were selected from Freesound.org and commercial sound libraries, including firework bursting sounds, bamboo burning sounds, water sounds, and night ambient sounds. Consulting existing academic literature and Cultural Heritage Administration records, we identified information regarding firework torch placement intervals (approximately 30–50 cm), rope height (3–5 m from water surface), and ignition sequence (starting from one end and progressively spreading) (The Encyclopedia of Korean Ethnic Culture, 2024; Kim, 2008).

To ensure both development efficiency and cultural accuracy, we constructed the *Nakhwa-nori* environment based on existing assets from the Korea Heritage Service's Traditional Korean Architecture project available through the Unreal Engine Marketplace (Unreal Engine Marketplace, 2025). We completely removed the lighting system included in the existing asset and created a new lighting environment suited to Nakhwa-nori's unique nighttime festival atmosphere.

Lighting System Configuration: We positioned a Directional Light as the primary moonlight source with color temperature set to 5500K to express the cold, blue quality of moonlight. Sky Light utilized HDRI environment maps to simulate the subtle ambient light of the night sky, while Spot Lights mimicking traditional lanterns were placed around the pavilion to add localized warm lighting effects (Epic Games, 2025).

Water Surface Implementation: We utilized Unreal Engine's Water Material to create realistic water surfaces representing the pond central to the performance. Using the Material Editor, we set water transparency (Opacity) to 0.6 and refraction index to 1.33 to achieve water properties appropriate for nighttime environments, creating visual effects of fireworks reflecting on the water surface. We employed Reflection Capture in Unreal's native Water Plane instead of the more advanced Planar Reflection to ensure VR environment performance.

We created 3D models of firework torches using Blender, modeling the traditional bamboo cylindrical structure (3 cm diameter, 15 cm length) and charcoal powder pouches wrapped in hanji paper based on reference photographs. Each firework torch was assigned two Material Slots: one for the initial hanji texture, and another for Emissive Material to express the burning-away effect after ignition.

Sequencer-based Animation Control: We created animations of the ignition and combustion processes in Unreal Engine's Sequencer editor. By setting keyframe animations that change each firework torch Actor's Material Parameters over time, we implemented natural color and brightness changes over approximately 120 seconds from ignition to complete combustion. Parameter changes were smoothly adjusted through the Sequencer's Curve Editor using Ease In/Out interpolation.

Spline-based Rope System: The ropes connecting firework torches were implemented using Unreal Engine's Spline system to physically simulate the natural sagging of ropes and slight swaying in wind found in actual Nakhwa-nori. Using Spline Mesh Components, we dynamically adjusted rope length and shape to precisely control torch positions in each section (Epic Games, 2025). Natural sagging effects were achieved by adjusting Spline Point Tangents, while subtle swaying effects were simulated through Blueprint logic combining Timeline Components and Sine functions.

To precisely reproduce Nakhwa-nori's visual characteristics, we designed two independent Niagara particle systems.

Environmental Diffusion Particle System: The first system handles fine fire particles and smoke effects spreading throughout the festival site. We set Emitter State to "Self Infinite" to ensure continuous particle generation, with a Spawn Rate of 500 per second. Using Wind Force and Aerodynamic Drag modules, we created natural diffusion effects influenced by wind. Key module settings included: Shape Location as Box Emitter (50m × 30m × 10m), Add Velocity with random initial velocity range (-50, 50) cm/s, Gravity Force at -980 cm/s², Drag coefficient at 0.3, Scale Color transitioning from orange to yellow to red to transparent based on lifetime, and Scale Sprite Size reducing from 3 to 1 pixel based on lifetime (Kelly, 2022; Karis, 2021).

Torch-Attached Particle System: The second system handles sparks and falling embers directly from each firework torch, individually attached to each torch position to generate particles only at that point. Utilizing the Particle State module, we precisely controlled flame lifecycle, while Solve Forces and Velocity modules physically calculated gravity and initial eruption velocity to achieve realistic ember trajectories. Key settings

included: Spawn Rate of 200 per torch per second, Lifetime of 2-4 seconds (random), initial velocity in spherical distribution (100-300 cm/s), Initial Size of 2-5 pixels (random), Initial Color in HSV color space with Hue 20-40 (orange-yellow), activated Gravity, Drag coefficient of 0.2, and Collision (Scene Depth) causing particle extinction upon water surface or ground collision.

1We utilized the Unreal VR Template to enable default VR perspective and teleportation movement. Using the VR Template's default movement system, we allowed users to teleport between three viewing points such as around the pavilion and by the pond. We deployed Nav Mesh Bounds Volume and activated the VR Pawn's Teleport function, placing Target Point Actors at each teleport location to specify precise positions and viewing directions.

UI Overlay: Using UMG Widget Blueprint, we created information panels explaining Nakhwa-nori's historical background, cultural meaning, and production process. By attaching Widget Interaction Component to the VR Controller, we enabled users to click buttons with the controller to toggle information on and off.

Spatial Audio: We applied Attenuation settings to each firework sound source to implement natural volume attenuation based on distance. Setting Attenuation Shape to Sphere with Falloff Distance of 20m, we ensured sound volume increases as users approach fireworks.

4. Results and Evaluation

4.1 Visual Implementation Results

We present comparative visual analyses demonstrating the fidelity of our XR reconstruction against authentic Nakhwa-nori performances through three key perspectives.

Figure 1 compares the climactic performance moment. Figure 1(L) captures an authentic Haman Mujinjeong Nakhwa-nori performance showing torch lighters in traditional white hanbok aboard reed boats beneath cascading golden-orange embers onto the water surface, creating the signature "fire on water" aesthetic through characteristic reflections. Figure 1(R) presents our XR reconstruction, demonstrating successful replication of ember density, color spectrum (golden-orange transitions), and dynamic water reflections through Niagara GPU particle systems and Lumen global illumination as described in Section III-B.

Figure 2 analyzes ember cascade dynamics and trajectory patterns. Figure 2(L) documents authentic ember trajectories through long-exposure photography, revealing the natural variability and stochastic distribution patterns resulting from wind, gravity, and air resistance. Figure 2(R) demonstrates our GPU-accelerated particle simulation reproducing these physically accurate behaviors through real-time computation of gravitational forces, aerodynamic drag (coefficient 0.2), and collision detection with environmental surfaces.

Figure 1. *Comparative Analysis: Traditional Nakhwa-nori Performance and XR Digital Reconstruction*

(L) Traditional *Nakhwa-nori* festival performance showing boat-based pyrotechnic display with cascading fire embers over water surface (Asia Economy, 2024).

(R) XR framework reconstruction demonstrating visual fidelity through physics-based Niagara particle system and Lumen dynamic lighting

Figure 2. *Ember Cascade Phenomenon: Authentic Festival vs. Simulated Particle Dynamics*

(L) Long-exposure photograph documenting authentic ember trajectories, density patterns, and water surface interactions from actual performance (Yonhap News Agency, 2025).

(R) GPU-accelerated particle simulation reproducing physically accurate ember behavior including gravity, air resistance, and collision detection

Figure 3. *Spatial Context and Environmental Reconstruction Comparison*

(L) Daytime documentation of traditional pavilion architecture and rope suspension framework used for torch mounting (National Center for Korean Traditional Performing Arts, 2025).

(R) Nanite-based 3D environmental reconstruction with high-fidelity architectural modeling and real-time

Figure 3 provides spatial context and environmental reconstruction. Figure 3(L) presents daytime documentation of the rope suspension framework with bamboo torch assemblies and traditional pavilion architecture that anchors the festival site. Figure 3(R) demonstrates our Nanite-based environmental reconstruction implementing spline-based rope physics for natural sagging effects and optimized water reflection rendering,

maintaining spatial coherence and cultural authenticity throughout the performance duration.

These comparative implementations validate that our XR framework successfully preserves the visual complexity, cultural authenticity, and aesthetic richness of traditional Nakhwa-nori performances while providing safe, accessible alternatives that address the challenges inherent in physical attendance.

4.2 Performance Evaluation

Performance evaluation of the basic VR prototype on consumer-grade hardware (NVIDIA RTX 4070 Ti, Intel i5-13600KF, 32GB RAM) demonstrated stable frame rates across different quality settings: Low quality (120-140 FPS), Medium quality (100-120 FPS), High quality (80-100 FPS), and Cinematic quality (60-80 FPS). The performance evaluation demonstrated that the system maintains an average of over 90 FPS even at High quality settings. This figure exceeds the minimum recommended refresh rate of 72Hz–90Hz for standard VR HMDs to prevent motion sickness. Consequently, this validates the technical real-time performance feasibility prior to user testing.

The stable performance across quality settings validates our architectural decisions, particularly the strategic use of Nanite for automatic LOD management (Cichocki, 2017), efficient particle system design leveraging GPU acceleration (Kelly, 2022; Karis, 2021), and optimized water reflection techniques (2K Games, 2021; Epic Games, 2025). The ability to maintain 60+ FPS even at cinematic quality settings ensures VR comfort by preventing motion sickness while delivering authentic visual fidelity.

This research achieves the following technical and cultural contributions:

Table 2. *Performance Evaluation on Consumer-Grade Hardware*

Quality Setting	Frame Rate (FPS)	Frame Time	VR Compatibility
Low	120-140	~7.1ms	Excellent 90Hz (Index/Vive Pro 2)
Medium	100-120	~8.3ms	Excellent 90Hz (Standard VR)
High	80-100	~10ms	Meets 90Hz / Exceeds 72Hz (Quest 2/3)
Cinematic	60-80	~12.5ms	Meets 72Hz (Minimum for Comfort)

Technical Contributions: We developed an integrated technical framework encompassing high-resolution processing of complex traditional architecture and terrain using Nanite (Cichocki, 2017), naturalistic simulation of thousands of embers incorporating gravity, wind, and collision-based physics through Niagara GPU particles (Kelly, 2022; Karis, 2021), realistic illumination of nocturnal environments and surrounding landscapes utilizing Lumen Global Illumination (Epic Games, 2025), and authentic representation of pyrotechnic reflections on water surfaces through Unreal Engine's native Water Material and Reflection Capture systems (2K Games, 2021; Epic Games, 2025). This framework was developed as a universal methodology applicable not only to Nakhwa-nori but to other traditional festivals and digitization of intangible cultural assets.

Cultural Contributions: By overcoming geographical and temporal constraints, we provide alternative access methods enabling domestic and international audiences to safely experience Nakhwa-nori. We create authoritative digital records usable as objective evidence against cultural appropriation and historical distortion. Through VR programs enabling users to observe festivals from various perspectives and learn historical

background and cultural meanings, we enhance understanding of traditional culture.

5. Limitations and Future Work

While this study successfully establishes a foundational XR framework for traditional festival preservation, several technical and methodological limitations require acknowledgment and future development.

User Interaction Constraints: The current prototype is limited to passive observation through desktop interfaces, lacking the spatial navigation and haptic feedback essential for full XR immersion. Future research must implement comprehensive user interaction systems enabling spatial navigation and cultural element manipulation.

Audio Implementation: Audio implementation remains basic, without spatial audio positioning or synchronized environmental soundscapes that would enhance cultural authenticity. Future iterations should develop immersive audio systems with traditional music integration and environmental sound design.

Particle System Optimization: While the current particle system demonstrates real-time capabilities, it requires optimization for large-scale concurrent user access scenarios. Documentation Precision: Our reconstruction methodology, based on publicly available documentation rather than direct field measurement, provides accessibility advantages but may lack precision in certain environmental details. Future iterations should incorporate on-site data collection and community stakeholder input to enhance cultural accuracy and representation.

Immediate research priorities include: (1) implementing comprehensive user interaction systems enabling spatial navigation and cultural element manipulation; (2)

developing immersive audio systems with traditional music integration and environmental sound design; (3) conducting user experience studies with cultural heritage experts and festival participants to validate educational effectiveness; and (4) extending the framework to additional Korean intangible cultural heritage sites.

Long-term Research Vision: This foundational work establishes the technical feasibility for more ambitious cultural preservation initiatives. Future research will explore the proposed digital twin framework for hybrid festival operations, investigate AI-enhanced cultural learning modules, and develop sustainable models for community-driven cultural heritage documentation and preservation. The hybrid real-virtual festival paradigm represents a transformative approach to cultural sustainability, enabling strategic management of physical venue capacity while facilitating global remote participation.

6. Conclusion

This research proposed and implemented an XR-based digital archiving framework for Nakhwa-nori utilizing real-time rendering technology. To address the multifaceted preservation challenges facing Nakhwa-nori—including overcrowding-related safety risks, geographical accessibility constraints, and systematic documentation deficiencies—we developed an immersive XR reconstruction system leveraging Unreal Engine 5's advanced capabilities.

The primary achievements of this research include: First, we implemented a technically feasible real-time cultural heritage preservation system integrating dual-layer

particle simulation architectures, physics-based environmental interactions, and spline-based structural modeling. Second, we demonstrated technical feasibility for practical XR experiences by achieving stable frame rates on consumer-grade hardware. Third, we established scalable methodologies applicable to diverse intangible cultural assets, contributing to the field of digital cultural heritage preservation. Fourth, we laid the foundation for contributing to cultural sovereignty protection and global dissemination by providing safe and accessible alternative cultural experiences.

This research presents a new paradigm for sustainable preservation and creative succession of intangible cultural heritage through harmonious integration with modern technology without distorting the essence of tradition. Future research will further develop this framework through user interaction enhancement, audio system development, community stakeholder engagement, and exploration of digital twin frameworks for hybrid real-virtual festival operations. Ultimately, this framework aims to develop into a universal methodology applicable not only to Nakhwa-nori but to diverse traditional festivals and intangible cultural asset digitization, contributing to global dissemination of Korean cultural heritage and its effective transmission to future generations while safeguarding against cultural appropriation and historical misrepresentation.

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