A Proposed XR-based Digital Framework for Nakhwa-nori: Preserving Regional Traditional Festivals and Addressing Safety and Environmental Barrier

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Abstract

Nakhwa-nori, a traditional Korean fireworks display with over 500 years of history, faces preservation challenges due to safety risks from large crowds and limited accessibility. This digital reconstruction aims to preserve cultural identity and ensure that this unique ritual is not lost or misrepresented. This paper proposes a real-time 3D reconstruction system for traditional fireworks using Unreal Engine. The dual-layer particle system simulates large-scale environmental effects and individual ember trajectories with physics-based wind simulation. The prototype was built using key Unreal Engine features such as Nanite virtualized geometry, Lumen global illumination for night lighting, and GPU-accelerated Niagara particle systems. Spline-based rope systems and fire-on-water effects are planned for future implementation. Performance evaluation on consumer hardware demonstrated the potential to reproduce key visual elements such as particle density, lighting conditions, and spatial relationships. This study suggests practical applications of real-time rendering technologies for cultural heritage documentation and indicates that the approach could be extended to other traditions requiring complex particle effects.

1. Introduction

1.1. Physical limitations of the festival itself - the need for preservation

Nakhwa-nori is a unique form of traditional Korean fireworks display in which bamboo sticks filled with oak charcoal powder are ignited, creating a spectacular display of fireworks that rains down on the night sky and water. It is practiced in various parts of the country, including Mujinjeong Nakhwa-nori in Haman, Gyeongnam, Anseong Nakhwa-nori in Anseong, Muju, Jeollabuk-do, and Haechon Nakhwa-nori in Yeoju, Gyeonggi-do. While reflecting the characteristics of each region, fireworks displays have a folkloric and ritualistic character, warding off disease and evil spirits, praying for a good harvest and the well-being of the village, and affirming community cohesion [1] [2]. In this paper, the terms 'Nakhwa-nori', 'Julbul-nori', and 'Nakhwa-yu' are collectively referred to as 'Nakhwa-nori' for simplicity, unless otherwise specified.

Unlike regular fireworks, Nakhwa-nori fireworks continue to burn for about two hours. The harmonious and spectacular sounds have drawn increased public interest in the event [3]. This renewed attention is reflected in BTS RM's solo song "Wild Flower" music video (2022) [4], the TV show "1 Night 2 Days", and the drama "Bloody Heart", and has been widely publicized on social media [5].

In 2023, the Haman Nakhwa Festival attracted approximately 60,000 visitors nationwide in a single day, which is nearly equal to the entire local population. This caused severe traffic congestion and temporary network outages in Haman-gun. In 2024, the event introduced a full online reservation system and accepted only about 7-8,000 visitors, but the second reservation was sold out in less than a minute, and the number of people who could participate in the 2025 event was reduced to 6,500, down from the previous year [6].

Sejong City hosted the "1st Nakhwa Traditional Culture Festival" in October 2016 [7], and since then, it has become a representative local festival with more than 100,000 visitors on the day of the festival [8]. However, because tens of thousands of people gather every year, there have been incidents of visitors being injured by fireworks due to insufficient safety fencing at the festival site [9]. As such, the festival is held only in certain seasons and locations every year, limiting viewing opportunities, consuming considerable time, manpower, and resources for site preparation, and recently, it has become popular through the spread of SNS and media, attracting excessive crowds and raising the risk of safety accidents and environmental damage. In particular, as most of the festival venues are located in small towns, geographical mobility and timing constraints for visitors are a real barrier to the enjoyment of intangible cultural heritage. The lack of alternative means of experience in the event of an event being canceled due to bad weather or acci-

dents is also a major constraint. Therefore, immersive digital experiences can be proposed as an alternative to physical venues, allowing the general public to enjoy traditional play safely and efficiently. This traditional culture, with its spectacular visuals and cultural significance, has the potential to be digitally recorded and preserved through careful archiving and subsequently made accessible not only to the general public but also to the world at large. This research aims to systematically digitize and provide an immersive experience of Nakhwa painting using Unreal Engine.

1.2. The need to protect cultural identity

The preservation of Nakhwa-nori faces critical documentation challenges. According to testimony from Ryu Hancheol, secretary-general of the Andong Hahoe Village Preservation Society, the restoration process was a series of trial and error: "There are no records of how to make the sticks or how to string them... After experimenting for about two years, I found the current recipe by making 50 of them and hanging them."

This lack of systematic documentation makes it difficult to pass on traditional culture. Dengok-ri Nakhwa-nori was selected as one of the Cultural Heritage Administration's 'Future Intangible Cultural Heritage Discovery and Nurturing Projects' in 2022, and was re-selected in 2024 [10]. However, Nakhwa-nori has not yet been designated as a national intangible cultural property, and systematic preservation policies are still at an early stage [11].

Moreover, the recent popularity of Korean fireworks has led to cultural appropriation concerns. Similar displays, known as 'falling flowers', have emerged in some regions of China [12]. Some Chinese netizens have claimed that Korean fireworks originated from their country's Tacheolhwa (), but Tacheolhwa is a ritualistic act of throwing iron water to create sparks [13], while Korean fireworks uses bamboo firework sticks to drop embers over water, fundamentally different in both ritual context and physical method. This confusion of cultural archetypes is more easily distorted in the absence of digital preservation and documentation. Therefore, XR-based immersive digital documentation can provide objective evidence of cultural identity and origins beyond mere tourism commoditization.

1.3. Research Objectives

Against this background, this research proposes a systematic digital archiving model that aims to (1) address the physical limitations of on-site operations, (2) expand cultural enjoyment without spatial and temporal constraints, and (3) respond to issues of copying and distortion by recreating the shared symbols and landscape elements of the Nakhwa-nori fireworks festivals held in Haman, Yeosu, and Andong, Korea, within a real-time 3D-based XR environment. This study is a novel attempt in digital cultural heritage research that seeks to preserve traditional festivals and extend them into the modern era, contributing to the sustainability of local festivals and the protection of cultural sovereignty in the future.

Utilizing Unreal Engine 5's Nanite mesh processing (ultra-high resolution mesh processing), Lumen global illumination (real-time global illumination), and Niagara GPU particle system (GPU-accelerated large-scale particle processing), this research proposes a methodology to digitally realize the visual and spatial elements of the festival with precision, and provide an immersive experience similar to the actual festival in an XR environment.

The specific objectives of this research are as follows

First, by scientifically analyzing and systematically digitizing and recording the core elements of the fireworks display, such as the process of making firework batons, ignition rituals, firework falling patterns, spatial arrangement, and acoustic environment, a digital cultural heritage preservation model that can experience the essence of the tradition in a three-dimensional space is established.

Second, XR technology fundamentally solves the fire hazards of real fireworks, the possibility of safety accidents due to the concentration of large crowds, the risk of event cancellation due to weather conditions, and geographical accessibility limitations, and presents a new cultural access model that allows anyone in the world to enjoy traditional culture safely and conveniently anytime, anywhere.

Third, by implementing a VR program that allows users to observe festivals from various perspectives and learn the historical background and cultural meanings, we aim to improve the understanding of traditional culture and promote the global spread of Korean culture.

Fourth, we propose a hybrid operation method of real and virtual festivals using digital twin technology to manage the number of visitors at the on-site festival at an appropriate level while providing an expanded festival experience that allows visitors from all over the world to participate simultaneously, contributing to local tourism resource utilization and cultural industry development.

Technically, we develop an integrated technical framework that includes high-resolution processing of complex traditional architecture and terrain using Nanite, gravity, wind, and collision-based naturalistic simulation of thousands of embers using Niagara GPU particles, realistic lighting of the night sky and surrounding landscape using Lumen Global Illumination, and realistic firework reflections on the pond surface using Unreal Engine's native Water Material and Reflection Capture.

Ultimately, this research presents a new paradigm for sustainable preservation and creative succession of intangible cultural heritage through harmonious fusion with modern technology without distorting the essence of tradition, and aims to develop it into a universal methodology that

can be applied not only to the Nakhwa Festival but also to other traditional festivals and digitization of intangible cultural assets, thus contributing to the global spread of Korean cultural heritage and its transmission to the next generation.

2. Related Research

In recent years, attempts to digitally preserve and share traditional cultural heritage have been made both at home and abroad. In particular, XR (extended reality) technology is becoming a new methodology for preservation and education that overcomes physical constraints by making cultural heritage that is only accessible in the real world virtually accessible anytime and anywhere.

For example, the Cultural Heritage Administration of Korea has released high-resolution 3D scans of the Nakseonjae of Changdeokgung Palace in XR, allowing anyone to explore the palace's interior remotely. This increased accessibility without damaging cultural assets and allowed domestic and international visitors who are unable to visit the actual site to gain a deeper understanding of traditional architecture and spatial organization. This is evaluated as an example of the possibility of sustainable recording and transmission of cultural heritage by expanding viewing that was limited to physical space digitally [14].

There is also active research on preserving and experiencing intangible cultural elements such as traditional performances and intangible culture with XR. Ahn, Hyungki, and Park, Jong-eun (2024) reinterpreted traditional pansori as an immersive digital exhibition by fusing holograms and XR technology to create an immersive digital exhibition of traditional Korean music. This study also has technological and cultural similarities in that it attempts to expand the intangible festival, Nakhwa-nori, into a digital heritage beyond the accessibility and preservation limitations of physical performances by realizing it in XR. [15].

XR-based digital cultural heritage such as this is often created with real-time game engines such as Unity or Unreal. Unreal Engine in particular is increasingly being adopted by traditional art and heritage sectors due to its strengths in high-resolution real-time rendering, physically-based lighting and particle effects, and large-scale data processing. The Cleveland Museum of Art in the US used Unreal Engine 5 to recreate a traditional Korean painting, Chilbo Sando, as an immersive digital exhibit. Nanite and Lumen were used to bring the textures of the real painting to life, and the Niagara particle system was used to add fog and light effects to maximize immersion [16].

Cho, Kim, and Jeong (2014) also experimented with real-time recreation of a traditional fireworks display using GPU engine-based particle simulation, showing that the physical interaction of a myriad of particles and light can be effectively realized in virtual space. This has direct technical implications for the digitization of traditional festivals where fireworks, smoke, and water reflections are important [17].

In conclusion, existing research suggests that digital cultural heritage preservation and XR experience design are evolving from mere documentation to a means of immersive learning and global dissemination. In this context, this study aims to experiment with new possibilities at the intersection of technology and cultural preservation by realizing the unique Korean fireworks tradition of Nakhwanol in Unreal-based XR.

3. Research methodology

3.1. Technical approach

3.1.1. Technical rationale for choosing Unreal Engine

Nakhwa is a highly 'dynamic, natural, and spatial' traditional experience, with thousands of fireworks falling simultaneously, changing their motion in real-time with wind, weather, and gravity, and a complex interplay of light and particles, including spark reflections, waves, and smoke. The nighttime nature of the festival requires the inclusion of light and shadow, sparks, moonlight, and water reflections, all of which are impossible to represent with static modeling and require real-time simulation and VFX.

Unreal Engine is optimized for real-time, high-quality physically-based simulation, with support for real-time ray tracing, Lumen global illumination, Niagara VFX, and more. The GPU-based particle system can handle hundreds of thousands of particles simultaneously with physical rules, with strong representation of natural phenomena such as water, smoke, flames, and fog, and real-time light reflection and refraction are calculated physically. It has the advantage of natively rendering higher quality than Unity to reproduce the unique "light and water interaction" of Nakhwa play with high quality.

Detailed technical features

The Niagara GPU particle system is capable of handling hundreds of thousands of sparks from thousands of fire rods in the Haman fireworks display in real time, managing the physical trajectory and life cycle of each particle individually [18][19]].

Lumen global illumination enables the instantaneous reflection of the fireworks onto the surrounding environment and pond water surface, providing dynamic lighting effects not possible with traditional baked lighting.

Nanite mesh processing technology is a distance-based LOD system that optimizes GPU computation by outputting less detail for distant objects and a denser mesh for closer objects, enabling a high-quality representation of the silent gazebo and surrounding terrain [20].

Combining Planar Reflection and Screen Space Reflection to realistically reproduce real-time flame reflections on

the surface of the water, fully representing the "fire on water" visual appeal that is at the core of fireworks [21][22].

XR optimization and performance

When it comes to balancing performance and detail in immersive XR (especially VR), Unreal Engine offers the latest optimization technologies like Nanite, LOD systems, and level streaming to run at 60-90 FPS real-time even with large particles + dynamic lighting + high-resolution textures.

Built-in VR Templates with Variable Rate Shading to run on major XR devices like Meta Quest 3 and HoloLens 2. Even with complex natural effects, it maintains a stable immersive experience on VR HMDs and MR devices, enabling you to deliver the "sense of space in the night sky" of Falling Flower Play in VR.

Development Efficiency

With a vast asset marketplace and Blueprint visual scripting, traditional Korean architectural elements and complex particle logic can be implemented without coding, significantly increasing development productivity. This comprehensive combination of features simultaneously fulfills both 'rendering quality' and 'development efficiency' compared to other engines such as Unity, proving to be the optimal platform to most effectively realize the dynamic, natural, and spatial characteristics of Nakhwa-nori.

3.2. Research Methodology and Implementation Process

3.2.1. Reference data collection and environmental analysis

Instead of directly photographing the festival site, we utilized recently released high-resolution video and photographic footage of the festival to analyze ember size, burn rate, and pond and pavilion placement. Instead of field sounds, we selected fireworks, water sounds, and night sounds from free and commercial sound libraries to use as background sounds. We also consulted existing academic literature and local festival archives to understand the placement of the fireworks, the order of ignition, and incorporate them into the simulation design.

3.2.2. Building a 3D environment based on existing assets

To ensure both development efficiency and cultural accuracy, we built the Nakhwa play environment based on existing assets from the Traditional Korean Architecture Map project. The lighting system included in the existing asset was completely removed, and a new lighting environment was created to match the unique nighttime festival atmosphere of Nakhwa-nori. We utilized the Sky Light system provided in the asset, but adjusted the placement and intensity values of the lights to suit the scene to simulate moonlight and soft ambient light. In addition, Directional Light was placed to represent the main source of moonlight, and Spot Light was installed at the pavilion and key viewing points to create localized lighting effects and atmosphere [23].

To represent the pond, which is the centerpiece of the play, we utilized Unreal Engine's Water Material to create a realistic water surface. The Material Editor was used to adjust the water's transparency, reflectivity, and refraction to achieve the right water properties for a nighttime environment, and to create the visual effect of the fireworks reflecting off the water's surface. Real-time reflections were minimized and handled with Reflection Capture in Unreal's native Water Plane instead of the more advanced Planar Reflection.

3.2.3. Modeling the baton and implementing a spline-based string system

The core element of the event, the bamboo stick, was modeled separately and imported into Unreal Engine. The sticks were designed to realistically recreate the traditional bamboo structure and hanji packaging of charcoal powder, with individual Material Instances for each stick to represent visual changes as the stick burns. The strings connecting the firecrackers were implemented using Unreal Engine's Spline system to physically simulate the natural sagging of the strings and the slight swaying in the wind that can be found in real firecrackers. The Spline Mesh Component was used to dynamically adjust the length and shape of the ropes, allowing for precise control of the position of the baton in each section [24][25].

3.2.4. Designing a Dual-Structure Niagara Particle System

Two different Niagara particle systems were designed to accurately reproduce the visual characteristics of fireworks. The first is a whole-environment diffuse particle system (HangingParticulates), which is responsible for the fine fire particles and smoke effects that spread throughout the festival site. The system uses an Emitter State set to "Self Infinite" to ensure continuous particle generation, and the Wind Force and Aerodynamic Drag modules to create a natural diffusion effect under the influence of the wind. The Shape Location was set to Box or Plane to ensure that the particles are evenly distributed over a large space, and the Scale Sprite Size and Scale Color modules were used to represent the size change with distance and the color change with the degree of burning.

The second is a particle system attached to the individual fireworks, which is responsible for the sparks and falling embers directly from each firework. This system was individually attached to the position of each firework and set up to generate particles only at that point. The Particle State module was utilized to precisely control the life cycle of the flame, and the Solve Forces and Velocity modules were used to physically calculate the gravity and initial

eruption velocity to achieve realistic ember trajectories. In the Initialize Particles step, the initial velocity and direction of each particle was randomized to replicate the irregular and natural flame patterns found in real-world fireworks displays. Light color changes, afterglow effects, etc. were handled simply using Unreal's default material parameters.

3.2.5. Implementing XR integration and user interaction

We used the Unreal VR Template to enable only the default VR perspective and teleportation movement. We used the VR Template's default movement system to allow users to teleport between two or three viewing points, such as around the gazebo or by the pond, and minimally utilized Level Blueprints to control key logic. We also implemented a simple explanatory overlay (on/off button) with UMG widgets to display the cultural meaning of the fireworks or pop-up local information. Instead of complex spatial sounds, we utilized Unreal Engine's native Attenuation feature to naturally attenuate fire and water sounds based on location.

4. Results

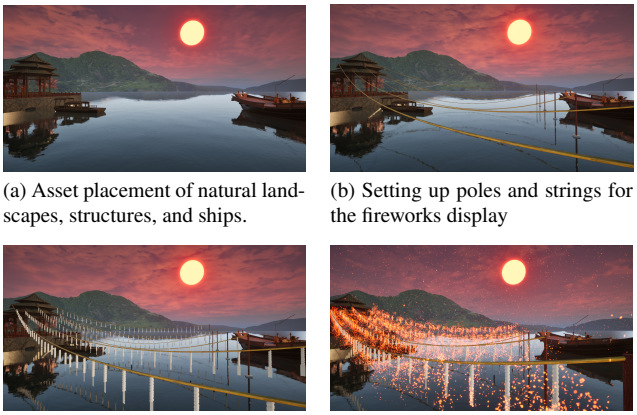
This research utilized Unreal Engine 5's Nanite mesh processing, Lumen global illumination, and Niagara GPU particle system to create a demonstration-quality digital model of the visuals and spatiality of a typical fireworks display. Nanite is processed with a distance-based level of detail (LOD) that allows viewers to see the detailed textures of the gazebo and fireworks as they get closer, while Lumen and the Reflection system provide a more realistic representation of flame reflections on the water and night sky glow. Niagara particles were used to recreate key effects such as the falling of embers and wind-gravity reactions with simple particle simulations.

4.1. Visual Results

The Unreal default Water Material and Reflection Capture were used to create reflections of the flames on the surface of the pond, and the two Niagara particle systems were used to realistically reproduce the effects of fine particles diffusing through the environment and individual flames from the falling embers. Public 3D assets from the National Heritage Agency's National Heritage Digital Service and Good SKY assets were utilized to compose the background (gazebo, trees, night sky) to create a harmonious sense of space between the fireworks and the water and night sky [26].

4.2. Limitations and Future Research Plans

The significance of this prototype is that, based on high-resolution publicly available video and photo data and previous research, we confirmed that it is possible to create basic digital records and visual reconstructions of actual festivals without actually photographing or measuring them. "However, at this stage the experience is limited to basic viewing on a PC screen or desktop VR, and full-scale XR interaction, user navigation, and detailed audio adjustments remain as tasks for future implementation."



(a) Asset placement of natural landscapes, structures, and ships.

(b) Setting up poles and strings for the fireworks display

(c) Setting up fireworks rods

(d) Fireworks display after ignition

Figure 1. Overall caption for all four images

The prototype of this research utilizes Unreal Engine's particle simulation, physics-based rendering, and spatial acoustics features to create an initial virtual representation of the Nakhwa playground, and plans to expand the VR experience beyond simple visualization to include educational elements. We will also distribute the VR build for free so that anyone can safely experience traditional fireworks without time and space constraints, and verify the immersion, satisfaction, and learning effects through user evaluations.Through this, we propose the possibility of safely and sustainably enjoying traditional festivals that are difficult to view on-site due to physical and environmental constraints, and plan to expand the scope of research to other Korean intangible cultural heritage, starting with the Nakhwa-nori.

References

[1] The Encyclopedia of Korean Ethnic Culture. Nakhwayu, 2024. [Online]. Available: https://encykorea.aks.ac.kr/Article/E0011671. 1

[2] I. Kim. An ethnographic study on the regional distribution and types of 'nakhwa-nori'. *Korean Folklore*, 48:111–140, 2008. 1

[3] Financial Review. Economic review in history: Nakhwa-nori, 2022. [Online]. Available: http://www.financialreview.co.kr/news/articleView.html?idxno=31223. 1

[4] BTS. Bts rm - wild flower mv, 2022. [Online]. Available: https://www.youtube.com/watch?v=u18be_kRmC0. 1

[5] News1. Bts rm's falling flower play popular in music video, 2023. [Online]. Available: https://www.news1.kr/industry/hotel-tourism/4897399. 1

[6] Kyunghyang Shinmun. Haman's 'nakhwa-nori' to be a hit this year?, 2025. [Online]. Available: https://www.khan.co.kr/article/202503042038035. 1

[7] Environmental Management Newspaper. Traditional festival sejong intangible culture festival buddhist nakhwa - yanghwa in winter, yinhwa in summer, harmonizing yin and yang, 2025. [Online]. Available: http://ionestop.kr/bbs/board.php?bo_table=B07&wr_id=464. 1

[8] News1. Picturesque fireworks: 100,000 people attend sejong nakhwa festival, 2025. [Online]. Available: https://www.news1.kr/local/sejong-chungbuk/5765966. 1

[9] Chungcheongnaetoday. Three emergency attendees at sejong city's 'nakhwa-nori' event, 2022. [Online]. Available: https://www.cctoday.co.kr/news/articleView.html?idxno=2169207. 1

[10] Daejeon Ilbo. Selected for the 2024 future intangible heritage discovery and fostering project of the sejong city eungok-ri nakhwa cultural heritage administration.... support up to 200 million won per year, 2023. [Online]. Available: https://daejeonpress.co.kr/news/view.php?idx=55966. 2

[11] Joongang Ilbo. Subtle but colorful...'beauty of contradiction' zulbulnori, 2023. [Online]. Available: https://www.joongang.co.kr/article/25196129. 2

[12] Gyeongnam Minilbo. Controversy over china's imitation of korean nakhwa-nori, 2024. [Online]. Available: https://www.idomin.com/news/articleView.html?idxno=940957. 2

[13] Xinhua News Agency. Throwing molten iron – a dangerous and dazzling firework art, Feb 2019. [Online]. Available: https://www.xinhuanet.com/english/2019-02/19/c_137834095.htm. 2

[14] Newsis. Cultural heritage administration changdeokgung nakseonjae xr experience service, 2020. [Online]. Available: https://mobile.newsis.com/view/NISX20200727_0001108851. 3

[15] H. Ahn and J. Park. Development of intangible heritage xr convergence contents using hologram: A case study of namwon national gugak center suguangmaru exhibition. *Journal of Museum Studies*, 47:87–116, 2024. 3

[16] Epic Games. Cultural heritage digital experience powered by unreal engine, 2023. [Online]. Available: https://www.unrealengine.com/en-US/developer-interviews/a-cultural-heritage-digital-experience-powered-by-unreal-engine-and-the-epic-ecosystem. 3

[17] C. W. Cho, K. H. Kim, and C. S. Jeong. Fireworks modeling technique based on particle tracking. *J. Inst. Electron. Inf. Eng.*, 51(6):102–109, Jun 2014. 3

[18] Epic Games. *Niagara Overview*. Unreal Engine 4.27 Documentation, 2025. [Online]. Available: https://docs.unrealengine.com/4.27/RenderingAndGraphics/Niagara/Overview/. 3

[19] Epic Games. *How to Create a GPU Sprite Effect in Niagara*. dev.epicgames.com, 2025. [Online]. Available: https://dev.epicgames.com/documentation/en-us/unreal-engine/how-to-create-a-gpu-sprite-effect-in-niagara-for-unreal-engine. 3

[20] Epic Games. *Unreal Engine 5.0 Release Notes: Lumen Global Illumination and Reflections*. Unreal Engine 5.0 Documentation, 2025. [Online]. Available: https://docs.unrealengine.com/5.0/en-US/unreal-engine-5.0-release-notes. 3

[21] Epic Games. *Planar Reflections in Unreal Engine*. Unreal Engine 4.27 Documentation, 2025. [Online]. Available: https://docs.unrealengine.com/4.27/en-US/BuildingWorlds/LightingAndShadows/PlanarReflections. 4

[22] Epic Games. *Screen Space Reflections*. Unreal Engine 4.26 Documentation, 2025. [Online]. Available: https://docs.unrealengine.com/4.26/en-US/RenderingAndGraphics/PostProcessEffects/ScreenSpaceReflection/. 4

[23] Epic Games. *Lighting the Environment*. Unreal Engine 4.27 Documentation, 2025. [Online]. Available: https://docs.unrealengine.com/4.27/en-US/BuildingWorlds/LightingAndShadows/. 4

[24] Epic Games. *Blueprint Splines*. Unreal Engine 5.0 Documentation, 2025. [Online]. Available: https://dev.epicgames.com/documentation/en-us/unreal-engine/blueprint-splines?application_version=5.0. 4

[25] Epic Games. *USplineMeshComponent*. Unreal Engine 5.1 C++ API Documentation, 2025. [Online]. Available: https://docs.unrealengine.com/5.1/en-US/API/Runtime/Engine/Components/USplineMeshComponent/index.html. 4

[26] Unreal Engine Marketplace. Korea heritage service, 2025. [Online]. Available: https://www.fab.com/ko/sellers/KOREA%20HERITAGE%20SERVICE. 5