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Interactive Volumetric Fog System in Unreal Engine 5 Using Distance Fields and GPU Particle Simulation

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Abstract. Real-time volumetric fog is a crucial visual effect in modern 3D environments, enhancing depth perception, atmosphere, and immersion. However, conventional fog rendering methods often lack physical accuracy and interactivity, disconnecting players and their environment. To address this issue, this study proposes an interactive volumetric fog system based on Unreal Engine 5, designed to provide realistic static fog rendering and dynamic responses to user interaction. The main objective is to create a system that simulates volumetric fog behaviour in real time while allowing the fog to adapt visually to player movement. The proposed method consists of two core modules: a physically-based volumetric material constructed using distance fields and optical attenuation principles, and a Niagara-based Graphics Processing Unit (GPU) particle system that enables fog displacement and turbulence through programmable repulsion forces. Specifically, the system uses distance-normalized falloff functions, real-time blueprint data communication, and procedural texture modulation to create seamless visual integration between static fog volume and interactive particle behaviour. This study is implemented entirely within Unreal Engine 5 using procedural data and engine-native tools. Results demonstrate that the system effectively simulates soft, immersive fog with natural gradients and dynamically responds to player position visually compellingly. Experimental evaluation confirms the feasibility of deploying this system in real-time applications requiring high atmospheric realism and interaction levels.

Keywords: Volumetric Fog; Unreal Engine 5; Realistic Static Fog Rendering; Dynamic Responses.

1. Introduction

With the rapid development of real-time 3D rendering technologies, creating visually immersive and interactive environments has become a core objective in digital content creation, especially in fields such as video games, virtual reality (VR), simulation, and digital cinematography. Volumetric fog is critical in conveying spatial depth, mood, and realism among various atmospheric effects. Volumetric fog simulates how light interacts with suspended particles in the air, enabling nuanced effects such as soft shadows, scattering, and occlusion. However, most existing volumetric fog systems focus primarily on static visuals, lacking the ability to interact dynamically with players or adapt to real-time environmental changes. This limitation reduces immersion and breaks the continuity between the environment and player behaviour. Therefore, developing a system that combines physically realistic volumetric fog rendering with responsive, player-driven interactions is of significant interest to academic and game development communities.

Volumetric fog rendering has evolved as a key technique in real-time computer graphics, enabling the simulation of atmospheric phenomena such as fog, clouds, and haze with high visual fidelity. Traditional approaches primarily relied on simplistic screen-space overlays or raymarching within static density fields, offering limited realism and interactivity [1]. As hardware capabilities improved, the focus shifted toward physically-inspired models and Graphics Processing Unit (GPU)-accelerated volume rendering pipelines [2, 3]. Recent advancements have aimed to enhance both visual quality and performance. In game development, the volumetric system implemented in The Last of Us Part II employed a voxel-based grid in view space, allowing seamless compositing with transparent objects and supporting dynamic lighting across slices of volumetric fog [4]. This represents a significant departure from earlier systems, which struggled with proper blending and light interaction.

Complementing this, Perez Soler’s real-time simulation of volumetric effects in Unity demonstrates how procedural noise, vector fields, and shader programming can be combined to build responsive fog systems, paving the way for platform-agnostic implementation strategies [3].

Interactivity has also become a central concern. Lam et al. proposed a volumetric fog display using a 2D matrix of fog emitters, allowing users to touch and interact directly with fog visuals in mid-air [5]. Similarly, the RayGraphy system by Yamada et al. renders 3D volumetric graphics by superimposing laser trajectories in fog, producing tangible, spatially anchored effects suitable for augmented reality environments [6]. These works extend fog from a visual impact to a physical interaction medium, showing potential for future spatial interfaces. Regarding light modelling, Jönsson et al. conducted a comprehensive survey on volumetric illumination techniques, distinguishing between local and global lighting models in volume rendering. Their taxonomy underscores the perceptual advantages of advanced effects like half-angle slicing and shadow mapping, which add depth cues and improve interpretability in interactive environments [7]. These insights are vital when integrating fog into dynamic scenes, where lighting must adapt to user motion and environment layout.

Moreover, several recent works have redefined fog as a helpful depth cue, not as visual noise to be removed. Yao et al. proposed the “Foggy Stereo” method, which reverses atmospheric scattering to extract depth hints for stereo matching. This technique constructs a fog volume representation by simulating image dehazing at multiple candidate depths, using structural similarity (SSIM) to select the most probable matches [8]. This research demonstrates how fog can become an information carrier for depth perception and scene understanding. Machine learning also shows promise for volumetric media reconstruction. Lin et al. presented a stereo-based approach for cloud field reconstruction, leveraging 3D Convolutional Neural Network (CNN) and advection modules to recover volumetric shapes and temporal dynamics from sparse stereo pairs [9]. Their model treats clouds—and, by extension, fog—as dynamic volumes, linking simulation with vision and offering inspiration for future real-time fog reconstruction pipelines in virtual environments.

From a broader perspective, Roettger and Ertl’s view-dependent Level of Detail (LOD)-based volume rendering algorithm showcases efficient rendering of fog and cloud scenes through octree tetrahedral mesh simplification, significantly reducing computational overhead while preserving perceptual fidelity [2]. This optimization is echoed in the Visualization Handbook, consolidating strategies across scalar field volume rendering, transfer functions, and GPU acceleration for fog-like phenomena in large-scale data visualization contexts [10]. The literature demonstrates a clear trajectory from static, opaque fog to highly interactive, information-rich, and physically grounded systems. The system aligns with this trend by integrating Niagara GPU particles, distance field sampling, blueprint-driven force interaction, and dynamic falloff effects, contributing a practical and extensible architecture for real-time, immersive fog rendering within Unreal Engine 5.

The main objective of this study is to design and implement an interactive volumetric fog system that enhances immersion through real-time responsiveness and visual realism. Specifically, first, a physically-based volumetric material is constructed using Unreal Engine's Volume Domain and distance field features to simulate fog density, soft edges, and optical attenuation. This module provides a static, realistic fog backdrop that reacts to scene lighting. Second, a Niagara GPU-driven particle system is created to introduce interactive fog behaviour, where player movement dynamically affects particle displacement, scale, and turbulence. Third, the player position is transferred in real-time via blueprints to the Niagara system, enabling the fog to respond through programmable force fields and distance-normalized falloff effects. The system also incorporates multi-layered texture noise, time-driven unique visitor (UV) animation, and curvature-based particle scaling to improve realism further. The experimental results demonstrate that the proposed system produces highly immersive fog environments with static and dynamic properties. Using normalized distance and repulsion-based force fields effectively creates intuitive, visually compelling responses as players move through the fog. In particular, particle turbulence and scaling contribute to the perception of environmental liveliness and depth. This work offers practical value for real-time applications where immersive atmosphere and environmental feedback are essential and lays the groundwork for future exploration into multi-agent fog interaction, temporal coherence, and scalable scene deployment in next-generation 3D environments.

2. Methodology

2.1. Proposed Approach

This study presents a novel interactive volumetric fog system implemented within Unreal Engine 5, designed to simulate dynamic fog behaviour with immersive visual and physical interaction. The system integrates two primary modules: (1) a physically based volumetric material system for static fog rendering and (2) a GPU-driven particle system using Niagara for real-time fog interaction based on player movement. Together, these components enable the realistic simulation of environmental fog that visually responds to the presence and movement of characters within the game world. The workflow begins with constructing a volumetric material using Unreal Engine's Volume Domain shader features. This material simulates fog density, colour gradients, and optical absorption based on spatial coordinates and distance fields. Subsequently, the Niagara system introduces dynamic particles rendered with the fog material, driven by real-time positional data from the player's blueprint. A repulsion field is created using hostile attraction forces and distance-based fall-off, allowing the fog to disperse naturally as players move through it. The overall technical pipeline is illustrated in Fig. 1. First, volumetric fog is generated through material parameters and distance field attenuation. Second, a Niagara particle system is initialized and customized for GPU simulation. Finally, blueprint scripting is used to pass the player location to the particle system, which dynamically calculates forces and size transitions using normalized distance metrics.

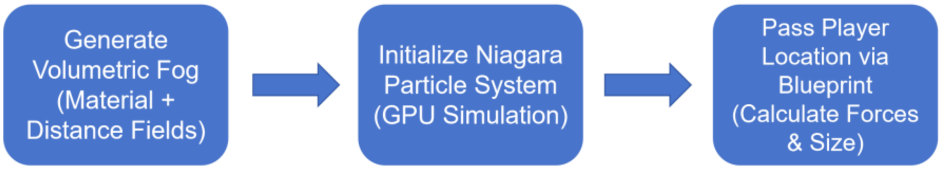

Figure 1. The overall technical pipeline (Photo credit: Original)

2.1.1. Volumetric Material System Based on Distance Fields.

The first module involves designing a 3D volumetric material leveraging Unreal Engine's Volume Domain and Additive blend mode. This material simulates static volumetric fog with physically-inspired visual features such as gradient transitions, multi-layered texture overlays, and light attenuation. The material is created by sampling the Absolute World Position and dividing it by a configurable tiling parameter to acquire a UV coordinate system in 3D space. This space is used to fetch volumetric texture samples. The output value from the texture is then modified through Multiply and Power functions to control the brightness and transparency gradient. A bias parameter is introduced to globally shift the fog density. To simulate realistic scattering and soft boundary fading, distance fields are incorporated. By using the “Distance to Nearest Surface” node, each sample point calculates its proximity to the closest mesh surface. This value is normalized by a reference scalar (typically 395) and then inverted (1-x) to yield an opacity mask where regions near geometry are opaquer. A Power function modulates the falloff, allowing control over the fog's spatial fading behaviour.

Furthermore, the system adds multiple texture layers with optional bump offsets to enhance fog dynamism—conditional switches control whether additional noise-based textures are combined. Sprite layer brightness is corrected using Multiply functions to compensate for grayscale blending. Light absorption is simulated using the Beer-Lambert Law. The fog's final extinction coefficient is passed to the `Beer's Law` node, using the previously saturate-clamped value for thickness and an adjustable depth scale to control shadow depth. The output is multiplied by fog colour and an intensity parameter before connecting to the material's emissive colour or reflectance channel.

This module effectively constructs a visually realistic volumetric fog field that can be integrated with lighting and post-processing systems in Unreal Engine.

2.1.2. Niagara-based Interactive Particle System.

The second module focuses on implementing an interactive fog response system using Unreal Engine's Niagara GPU particle system. This component allows volumetric fog to respond visually to character presence through real-time force fields and particle transformations.

A Niagara system is created from the "Hanging Particulates" template and configured for GPU Compute Simulation to ensure high-performance processing of up to 20,000 fog particles. The particles are rendered using the same volumetric fog material to maintain visual consistency. A vector parameter named “Person Position” is exposed in the Niagara system to enable interaction. In the player blueprint, an `Event Tick` node captures the character's capsule component location and updates this vector parameter every frame using ‘Set Niagara Variable (Vector3)’. This linkage allows the particle system to track player movement continuously.

A repulsion field is implemented using the `Point Attraction Force` module with a negative strength (e.g., -2000), reversing the conventional pull into a push. The `Falloff` parameter is introduced as a clamped float normalized based on the distance between each particle and the player position. The normalized range ensures spatial consistency across large scenes. To control particle behaviour adaptively, “Curl Noise Force” is applied with strength modulated by a Lerp (float) function. This interpolation sets stronger noise for distant particles (800) and lower values for nearby particles (100), controlled via the falloff value. This ensures a natural, turbulent behaviour around the player without abrupt movement.

Particle size is dynamically scaled using the `Scale Sprite Size` module. A Lerp node defines particle size transition from 0 near the player to a larger value further away. The transition curve is refined using a `Float from Curve` node, with a sigmoid-like function for smooth in-out scaling. This creates a visual effect where particles near the character are small or invisible, while distant particles remain visible, enhancing the illusion of movement through fog.

2.2. Implementation Details

The system is developed within Unreal Engine 5.3 on a standard Windows platform. The volumetric material uses 3D noise and grayscale textures with manually tuned Power and Multiply parameters. Niagara systems are GPU-accelerated with a spawn rate of 20,000 particles and random non-uniform sprite sizing. No external datasets are used; procedural animation and positional data are dynamically generated in real time. Default values include: Attraction Force = -2000, Distance Normalisation Threshold = 230, and Particle Curl Noise Frequency = 500.

3. Results and Discussion

This chapter evaluates the outcomes and practical visual effects of the proposed interactive volumetric fog system. The results are analyzed in two parts corresponding to the two main modules discussed in the methodology section: (A) the static volumetric material system and (B) the dynamic Niagara-based particle system. Each section includes visual demonstrations and analysis of the influencing parameters, behaviours, and their visual impact on realism and immersion.

3.1. Volumetric Material Effects

Fig. 2 demonstrates the rendering results of the distance-field-based volumetric fog material. In the image, the fog density is spatially distributed with a smooth vertical gradient and soft fading near geometric surfaces. The Beer's Law-based attenuation model effectively creates a light-absorbing volume that becomes denser in areas close to the geometry, fading out smoothly into the background. The observed result is primarily driven by the normalized distance field and the Power function controlling the falloff. The closer a point is to a surface, the higher the opacity due to the inverted normalized value. The Power function sharpens or softens the gradient based on the falloff parameter. Using multi-texture overlays with animated UVs enhances the visual turbulence and motion illusion. The significance of this effect lies in its ability to simulate real-world volumetric behaviours such as atmospheric scattering, while remaining efficient and tunable within a real-time engine. The material-driven fog creates a convincing illusion of depth and volume without heavy simulation.

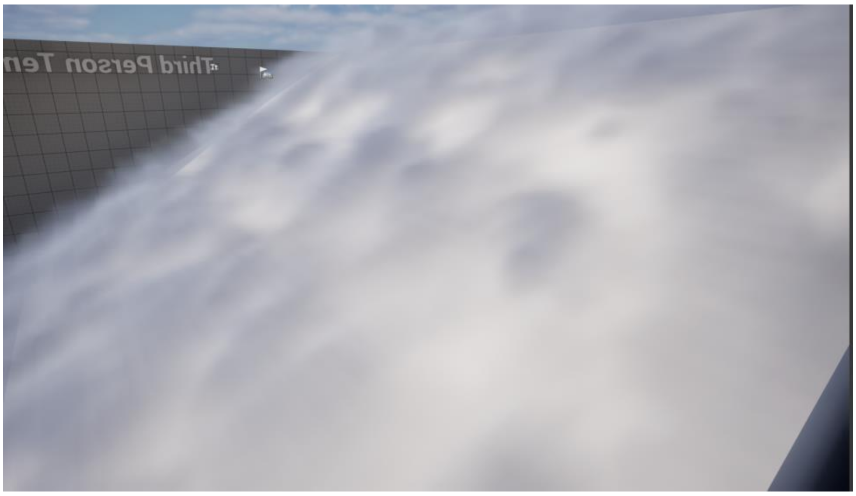

Figure 2. Volumetric fog material with distance-field gradient and soft boundary attenuation (Photo credit: Original)

3.2. Particle Interaction Effects

Fig. 3 presents the effect of the Niagara-driven interactive fog system. As shown, particles surrounding the character dynamically reduce in size or are displaced outward when the character approaches. This effect is controlled via the Point Attraction Force with negative strength, and the normalized falloff value modulates both the displacement force and the visual scale of particles. The result illustrates a compelling interaction between character and environment, making the fog appear alive and responsive. The strength and scale of the repulsion vary with distance, producing a smooth transition zone that avoids harsh visual artefacts. Furthermore, curl noise force adds randomized turbulence, enhancing realism. The modular separation of particle dynamics and material rendering allows for independent control and scalability. Minor changes to the falloff range or force magnitude significantly alter the interaction effect, demonstrating the system's flexibility and real-time responsiveness.

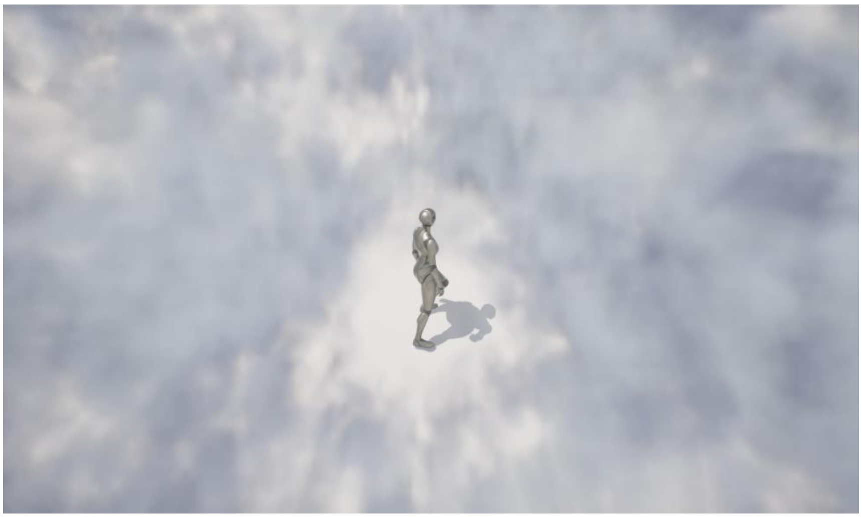

Figure 3. Dynamic fog particle system showing player-induced repulsion and turbulence-based displacement (Photo credit: Original)

In summary, the results validate the design's effectiveness in generating both static atmospheric effects and responsive visual feedback. The combination of material simulation and GPU-driven interactivity provides a balanced, immersive fog system suitable for real-time applications such as games or simulations.

4. Conclusion

This study introduces an interactive volumetric fog system to enhance realism and immersion in 3D virtual environments. The objective was to develop a framework that enables real-time volumetric fog rendering and dynamic interaction using Unreal Engine 5's rendering pipeline. A two-stage approach is proposed to analyse the spatial fog behaviour and its response to player movement. First, a volumetric material module was constructed using distance fields and gradient functions to simulate fog density and light absorption. Second, a Niagara GPU particle system was implemented, receiving player location data through blueprints and applying hostile attraction forces and normalized falloff parameters to simulate repulsion and turbulence. Experimental results show the system successfully reproduces soft, immersive fog fields and enables realistic, responsive interactions between fog and characters. The results confirm the method's visual plausibility and performance feasibility in real-time environments. In the future, temporal consistency and multi-agent interaction will be considered research objectives for the next stage. The research will analyse fog memory effects, overlapping force fields, and optimization techniques to support larger-scale deployment and multi-character interactions in expansive game scenes.

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