A Review of 3D Ink Wash Rendering: Core Techniques, Key Parameters, and Future Directions

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ABSTRACT

3D ink wash painting style rendering is a research direction with distinctive Eastern aesthetic characteristics in the field of Non-Photorealistic Rendering (NPR), aiming to simulate the artistic effects of traditional Chinese ink wash painting through computer graphics techniques. This paper systematically reviews the research progress in 3D ink wash style rendering both domestically and internationally, covering core technologies such as brushstroke simulation, ink diffusion, rice paper texture, and real-time rendering pipelines, and provides in-depth analysis of representative literature. Furthermore, this paper summarizes the key algorithmic parameters and engineering practice points of ink wash rendering from a technical implementation perspective, aiming to provide comprehensive technical references for relevant researchers and developers.

Keywords: ink wash rendering, non-photorealistic rendering, brushstroke simulation, ink diffusion, real-time rendering, GPU acceleration

INTRODUCTION

Ink wash painting, as a treasure of traditional Chinese art, is renowned worldwide for its aesthetic pursuit of "conveying spirit through form" (yi xing xie shen) and "vitality and resonance" (qi yun sheng dong). With the development of computer graphics, integrating ink wash artistic style into three-dimensional digital content creation has become an important research direction in the field of Non-Photorealistic Rendering (NPR). 3D ink wash painting style rendering not only has broad application prospects in digital entertainment industries such as animation, games, and virtual reality, but also holds significant importance for the digital inheritance and innovation of traditional culture.

Starting from the aesthetic characteristics of ink wash style, this paper systematically reviews the core technical aspects of 3D ink wash rendering, including brushstroke modeling, ink diffusion simulation, rice paper texture generation, contour outlining and shading rendering, and provides a comprehensive analysis of representative research achievements both at home and abroad.

AESTHETIC CHARACTERISTICS OF INK WASH STYLE AND DIGITAL CHALLENGES

Core Aesthetic Elements of Ink Wash Painting

The core aesthetic standards of traditional Chinese ink wash painting originate from the "Six Principles" (Liu Fa) proposed by Xie He of the Southern Dynasties in his work "Classified Record of Ancient Paintings" (Gu Hua Pin Lu), namely: "vitality and resonance" (qi yun sheng dong), "bone method in brushwork" (gu fa yong bi), "correspondence to the object" (ying wu xiang xing), "appropriateness of color" (sui lei fu cai), "composition and arrangement" (jing ying wei zhi), and "transmission by copying" (chuan yi mo xie). Among them, "vitality and resonance" ranks first, and "bone method in brushwork" is the second principle. The so-called "qi yun" refers to the vitality and spiritual temperament conveyed by the artist through brush and ink, manifested in the coherence of mountain trends, the direction of water flow, and the sense of direction in branch extension. The "yun" (resonance) is reflected in the rhythm of brushstrokes, the variation of ink density, and the emotional起伏 of the painting.

Another important feature of ink wash painting is the philosophy of "leaving blank" (liu bai). Leaving blank is not emptiness, but an active spatial management strategy---clouds, water bodies, and skies are often expressed without a single brushstroke, yet viewers perceive their presence. This embodies the Eastern philosophy of "creating something from nothing" (wu zhong sheng you). The Qing Dynasty painting theorist Deng Shiru's concept of "treating white as black" (ji bai dang hei) is a precise summary of this idea. For example, in Ma Yuan's "Solitary Fisherman on the Cold River" (Han Jiang Du Diao Tu) of the Song Dynasty, only a small boat and an old fisherman are placed at the bottom of the painting, while the large blank space above symbolizes the vastness of the river, reinforcing the lonely and profound artistic conception.

Furthermore, the concept of "five shades of ink" (mo fen wu se) (scorched, thick, heavy, light, clear) summarizes the rich hierarchical variations of ink tones in ink wash painting, while "bone method in brushwork" emphasizes the importance of line as the foundation of form. Techniques such as flying white (fei bai), wet rendering (yun ran), splashed ink (po mo), and accumulated ink (ji mo) together constitute the unique visual language of ink wash painting. The expression of "five shades of ink" has multiple interpretations; some literature also summarizes it as "dry, wet, thick, light, scorched." This paper adopts the common formulation of "scorched, thick, heavy, light, clear."

Technical Challenges in Digital Reproduction

The digitization of ink wash artistic style faces multiple challenges: i. the randomness and unpredictability of brushstrokes---real brush strokes are influenced by various factors such as brush tip angle, writing speed, ink volume, and paper texture, making them difficult to describe precisely with deterministic algorithms; ii. the physical complexity of ink diffusion---the penetration, diffusion, and blending of ink on rice paper involve complex fluid dynamics processes; iii. the difficulty in quantifying abstract aesthetic concepts such as "qi yun" (vitality) and "liu bai" (leaving blank); iv. real-time rendering performance requirements---meeting frame rate demands for interactive applications while maintaining artistic effects.

CORE TECHNICAL METHODS FOR 3D INK WASH RENDERING

Brushstroke Simulation and Extraction Techniques

Brushstrokes are the core elements of ink wash painting, and the quality of their simulation directly determines the artistic level of the rendering effect. Xu et al. [1] proposed a real-time ink wash painting style rendering method based on brushstroke geometric models at SIGGRAPH Asia 2012. This method first creates a particle-based ink footprint model, then extracts classified brushstrokes from ordinary 3D models using existing geometric information, and finally combines brushstrokes with ink to generate immersive painted images. Through GPU parallel processing, real-time rendering can be achieved on consumer-grade PCs.

Chu and Tai [2] designed an efficient deformable virtual Chinese brush model with deployable bristles, capable of real-time operation on consumer-grade hardware. The system renders realistic brushstroke effects based on data captured from six degrees of freedom (6DOF) input devices, providing a technical foundation for digital calligraphy creation. This work has been cited more than 116 times and is a classic reference in the field of virtual brush modeling.

Yao et al. [3] studied the transformation methods of ink wash brushstrokes in three-dimensional space from a design perspective in SIGGRAPH Asia 2024 Art Papers. Based on brushstroke characteristics, they proposed design dimensions and combined brushes with procedural shaders to reproduce the features of surface brushstrokes, edge brushstrokes, and spatial brushstrokes in three-dimensional space, completing three 3D ink wash works: "Bird," "Gourd," and "Cat."

Ink Diffusion and Fluid Simulation

Ink diffusion is one of the most recognizable features of ink wash painting. Yan et al. [4] published a paper in

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Heritage Science, employing an empirical model to simulate ink diffusion effects in rendered image space. The method divides the rendering pipeline into feature line rendering and internal area stylization, performs texture synthesis (cun fa) rendering through texture synthesis and texture mapping, and introduces mesh parameterization to avoid stretching and distortion during texture mapping.

In terms of physical simulation, researchers have adopted various methods: i. the Lattice Boltzmann Method (LBM) simulates fluid flow at the microscopic level, reproducing how ink penetrates fibrous paper; ii. a two-dimensional cellular automaton model simulates brushstrokes with ink wash style, drawing contours along brushstroke paths to achieve effects close to ink wash painting artistic style [5]; iii. a fluid dynamics model based on Perlin noise and Navier-Stokes equations calculates ink penetration direction and intensity [6].

In recent years, AI-driven ink simulation technology has also achieved breakthroughs. Generative diffusion models can predict ink diffusion patterns based on texture, humidity, and brush pressure, and adaptively adjust in real time. Platforms such as Reelmind.ai have integrated these technologies into creative tools, allowing artists to instantly change ink behavior by adjusting parameters such as "paper absorbency" or "ink viscosity" [7].

Rice Paper Texture and Canvas Effects

Yan et al. [4] studied a dynamic canvas texture method based on spatiotemporal consistency, using noise-based algorithms to generate textures that maintain a two-dimensional canvas appearance under camera motion, avoiding the "shower door" effect that occurs with camera movement in traditional methods.

In research on real-time 3D ink wash rendering [8], researchers simulated rice paper backgrounds through the combination of fog effects and noise particles. After calculating object dimensions using bounding boxes, multiple noise algorithms were used to simulate ink wash wet rendering effects. The system adopts a four-layer rendering architecture: base texture layer (scanning real rice paper microstructure), ink diffusion layer (real-time calculation of ink particle motion), brushstroke detail layer (adding flying white and brush tip effects), and ambient light effect layer (simulating paper surface light reflection).

Key parameters include: penetration rate 0.2-0.5 px/frame (simulating different paper absorbency), particle density 500-2000 particles/cm^2, edge blur 3-7 px Gaussian blur [6].

Contour Outlining and Shading Rendering

Contour outlining is a key aspect of ink wash style rendering. In research on real-time ink wash style rendering for 3D models [8], outlining is divided into internal and external outlining: external outlining adopts a method combining Fresnel algorithm and normal expansion, using procedural noise to simulate ink wash brushstrokes and solving outline breakage problems through normal processing; internal outlining uses an image processing-based method, utilizing normals and depth of 3D models in the scene for edge detection to draw internal detail lines.

In terms of shading rendering, researchers employ various techniques to simulate ink tonal levels: i. using lighting models to represent depth of field; ii. using texture mapping to represent details; iii. blurring pixels to simulate wet rendering effects; iv. using multi-pass rendering to achieve more realistic ink wash effects [9]; v. using Screen Space Ambient Occlusion (SSAO) to increase scene volume; vi. optimizing shading effects through tone mapping [8].

Huang Qiaozi [10] took "Okami: Zekkei-ban" as an example to study the construction ideas of ink wash animation materials based on Blender Eevee node real-time rendering, improving the performance of ink wash materials in real-time rendering engines from both quality and efficiency perspectives, providing practical references for ink wash material effects in game graphics.

Particle Systems and GPU Acceleration

Particle systems play an important role in ink wash effect simulation. Research on ink wash effects based on

GPU and particle systems [9] points out that the powerful parallel computing capability of GPUs can quickly process large amounts of data, making them particularly suitable for graphics rendering tasks. When implementing ink wash wet rendering effects, GPUs can quickly calculate the diffusion and blending of ink tones on rice paper.

In real-time generative animation design for ink wash landscapes [11], particle systems are used to drive procedural generation of ink wash landscapes. Each particle carries a base color that determines the ink tone level, and the shader superimposes seepage textures and random perturbations on this basis. The rendering pipeline is as follows: first, particles are drawn as point sprites, with each point sprite sampling a brushstroke texture; the Alpha channel of the texture controls ink transparency, and the RGB channel is multiplied with the base color. To simulate seepage effects, the shader applies offsets to texture coordinates based on particle random seeds and lifetime, and samples pre-generated seepage noise maps.

InkBrush [12] is a sketch-based 3D ink wash painting tool developed by Tsinghua University, providing digital calligraphy brushes and various editing tools to generate realistic ink wash brushstrokes with properties such as frayed edges, ink drops, and scattered dots. Users can adjust parameters such as humidity, color, density, dryness/wetness, and brushstroke style. Developed as a Blender plugin, the tool has validated its effectiveness and usability through user studies.

RESEARCH PROGRESS AT HOME AND ABROAD

Domestic Research Progress

Domestic research in ink wash rendering started early and has produced abundant results. Early representative works include: Zhang Haisong et al. [13] proposed a real-time 3D Chinese painting rendering method in 2004; Chen Wei et al. [14] used GPU to render ink wash painting effects in real time in 2005; Fang Jianwen et al. [15] used GPU to render ink wash effects on 3D character models in 2007. These works laid an important foundation for subsequent research.

Yang Lijie et al. [16] proposed a brushstroke stylization method for generating Chinese flower ink wash paintings in 2020, published in the "Journal of Computer-Aided Design and Computer Graphics." This method specifically designed brushstroke stylization algorithms for the characteristics of flower-themed ink wash paintings.

In recent years, domestic research has placed greater emphasis on systematization and technical integration. Research on real-time ink wash style rendering for 3D models [8] achieved an ink wash rendering method without the need to process texture assets and model UVs, capable of adjusting algorithmic parameters according to the attribute characteristics of different objects in the scene. This research also developed a digital ink wash landscape scene application, achieving artistic resources such as mountains, plants, buildings, and rivers/lakes through procedural methods.

In terms of industrial applications, systems such as "Dan Qing Huan Jing" (Cyan Illusion) [6] have implemented physics-based ink wash particle simulation, supporting up to 8 levels of ink wash particle rendering, including base ink layer, middle rendering layer, surface detail layer, and dynamic interaction layer. The system can simulate flying white effects produced by different brush tip types (center tip flying white, side tip flying white, reverse tip flying white, scattered tip flying white), and present frayed edge effects at the ink trace edges and fiber texture of ink penetration into rice paper at the pixel level.

International Research Progress

International researchers have mainly explored ink wash style simulation methods from the perspective of general NPR technical frameworks. Xu et al. [1] published a brushstroke-based real-time ink wash rendering method at SIGGRAPH Asia 2012, which is one of the early representative works, cited 14 times.

Chu and Tai's [2] real-time virtual Chinese brush painting system was published in IEEE Computer Graphics and Applications, cited more than 116 times, and is one of the most influential works in the field of virtual brush modeling. The system designed an efficient deformable brush model with deployable bristles, providing interactive tools for digital ink wash creation.

Wong et al. [17] published "Computational Approaches for Traditional Chinese Painting: From the 'Six Principles of Painting' Perspective" in 2024, systematically analyzing 94 papers from the theoretical perspective of the "Six Principles," classifying and summarizing them according to three dimensions: research focus on artistic elements, four-stage framework of application purposes, and computational techniques, providing a comprehensive literature review for the computational study of ink wash painting.

In terms of tool development, Aluan Wang [18] developed the "Six Bottles of Ink" system, implementing six different ink diffusion modes (ink in water, rough paper charcoal, watercolor wet rendering, rice paper brush, advanced watercolor, slow penetration), simulating the natural flow and diffusion of ink under wind force at 60 fps through feedback shaders.

Summary Of Key Technical Parameters

In NPR, the faithful reproduction of ink wash aesthetics hinges on the precise calibration of a multi-dimensional parameter space that governs physical behavior, textural detail, and computational performance. Unlike photorealistic rendering, where parameters often map to physically measurable quantities (e.g., reflectance, roughness), ink wash parameters straddle both physical simulation and perceptual stylization, requiring careful tuning to achieve the desired artistic expressiveness. Table 1 consolidates the most critical parameters identified across the surveyed literature, grouped into four functional categories: ink diffusion, brushstroke simulation, noise-based texturing, and real-time rendering configuration.

Table 1 Key Technical Parameters for 3D Ink Wash Rendering

Technical Aspect	**Key Parameter**	**Typical Value / Description**
Ink Diffusion	Penetration Rate Particle Density Edge Blur	0.2-0.5 px/frame 500-2000 particles/cm² 3-7 px Gaussian blur
Brushstroke Simulation	Brush Tip Type Humidity Parameter	Center / Side / Reverse / Scattered 0.0-1.0 (controls diffusion range)
Noise Texture	Low-frequency Noise Mid-frequency Noise High-frequency Noise	2-15 cycles/deg (large-area wet rendering) 30-80 cycles/deg (fiber texture) 100-400 cycles/deg (grain detail)
Real-time Rendering	Target Frame Rate Rendering Layers	≥30 FPS (interactive) / ≥60 FPS (smooth) 4-8 layers (base/diffusion/detail/lighting)

Ink Diffusion Parameters. The penetration rate, typically set between 0.2 and 0.5 pixels per frame, directly governs the apparent speed at which ink permeates the virtual paper substrate. This rate is not uniform but should ideally vary dynamically in response to local paper porosity, ink viscosity, and brush pressure to simulate the characteristic "halo" effect observed in genuine rice-paper paintings. Lower values produce crisp, controlled strokes reminiscent of mature gongbi (meticulous) styles, whereas higher values yield the diffuse, bleeding boundaries typical of freehand xieyi (sketchy) styles. The particle density---ranging from 500 to 2,000 particles per square centimeter---determines the granularity of the diffusion simulation. Sparse particle populations reduce computational overhead but risk producing discontinuous or aliased wetting fronts; denser populations, by contrast, afford smoother and more organic ink boundaries, yet demand substantially greater GPU memory bandwidth and parallel processing throughput. The edge blur parameter (3--7 pixels in Gaussian kernel radius) functions as a perceptual smoothing operator that emulates the optical softening caused by light scattering within the fibrous paper matrix, effectively modulating the transition sharpness between inked and blank regions.

Brushstroke Simulation Parameters. The brush tip type serves as a high-level stylistic control that emulates distinct calligraphic and painting traditions. The four principal categories---center, side, reverse, and scattered tips---correspond to different brush orientations and handling techniques, each producing characteristic track widths, pressure distributions, and flying-white (feibai) effects. Center tips generate even, symmetrical strokes; side tips produce graduated width variations; reverse tips yield rough, textured edges; and scattered tips simulate the split-hair effects typical of dry-brush techniques. The humidity parameter, normalized from 0.0 (completely dry) to 1.0 (fully saturated), exerts a nonlinear influence on both diffusion range and pigment deposition. At low humidity, strokes appear fragmented and highly textured with pronounced flying-white; at high humidity, they exhibit extensive lateral spreading and tonal uniformity, akin to wet-on-wet application. This parameter often interacts multiplicatively with penetration rate, meaning its effective impact is conditionally dependent on the underlying paper absorption model.

Noise Texture Parameters. Procedural noise constitutes the backbone of surface stylization in ink wash rendering, serving as a compact yet powerful generative primitive for simulating paper microstructure and ink granulation. The parameter space is stratified into three distinct frequency bands, each targeting a different visual scale. Low-frequency noise (2--15 cycles per degree, or cycles/deg) governs large-area wet-blending patterns and gentle luminance gradients that evoke the atmospheric diffusion of ink across open paper expanses. Mid-frequency noise (30--80 cycles/deg) corresponds to the visible fibrous texture of Xuan paper---the irregular, thread-like structures that become apparent upon close inspection and lend the surface its characteristic matte, absorbent quality. High-frequency noise (100--400 cycles/deg) introduces microscopic grain and particulate irregularities, which manifest visually as the subtle rough edges around ink borders and the stochastic distribution of pigment agglomerates. In practice, these three bands are linearly or exponentially combined with artist-adjustable weights, enabling continuous interpolation between smooth, refined finishes and coarse, heavily textured surfaces.

Real-time Rendering Parameters. Target frame rate serves as the primary performance constraint that cascades downward to influence all other parameter selections. For interactive applications---such as virtual painting systems and 3D sculpting interfaces---a minimum of 30 FPS is generally deemed acceptable, provided that input latency remains below perceptual thresholds. For immersive VR/AR experiences and cinematic-quality animations, however, 60 FPS or higher is mandated to prevent visual judder and preserve the illusion of fluid brushwork. The rendering layer count, typically ranging from 4 to 8 distinct layers, delineates the composition pipeline into functional strata: base texture layer (pre-computed paper background), ink diffusion layer (real-time particle or fluid simulation), stroke detail layer (brush trajectory and flying-white rendering), lighting and shading layer (ambient occlusion and specular modulation), and optional additional layers for post-process effects such as color toning and vignetting. Increasing layer count enhances visual depth and material authenticity but imposes a near-linear scaling of per-pixel computational cost; thus, layer selection embodies the fundamental trade-off between aesthetic richness and runtime efficiency, and should be adapted dynamically based on scene complexity and target hardware specifications.

Collectively, these parameters do not operate in isolation but form an interdependent system, where adjustments to one often necessitate compensatory changes in others to maintain visual coherence. For instance, increasing the penetration rate may require a concomitant reduction in edge blur to avoid over-softening, while deploying high-frequency noise at elevated amplitudes demands higher rendering layers to prevent aliasing artifacts. In practice, researchers and practitioners typically establish a baseline parameter set for a given style (e.g., xieyi versus gongbi) and subsequently perform iterative fine-tuning based on visual inspection, as objective quality metrics for stylized rendering remain an open research problem (see Section 5).

DEVELOPMENT TRENDS AND CHALLENGES

The evolution of 3D ink wash rendering is shaped by several converging technological trajectories, alongside persistent theoretical and engineering obstacles that warrant further investigation.

i. AI-Driven Generative Ink Wash Synthesis

The advent of generative artificial intelligence, particularly denoising diffusion probabilistic models, is fundamentally reshaping the production pipeline for ink wash aesthetics. Future rendering systems are expected to autonomously synthesize stylistically coherent artworks from high-level semantic inputs---such as natural language descriptions or rudimentary sketches---thereby substantially lowering the creative threshold for non-expert users while expanding the expressive repertoire for professional artists.

ii. Real-Time Interaction and Immersive Environments

The proliferation of virtual and augmented reality (VR/AR) platforms is progressively shifting 3D ink wash art from passive, static presentation toward dynamic, immersive interactivity. These emerging media enable users to engage in simulated brushwork within virtual spaces, facilitating real-time observation of ink diffusion, color gradation, and fluid blending behaviors as they unfold across three-dimensional surfaces, thus enhancing both perceptual engagement and artistic agency.

iii. Cross-Platform Lightweight Deployment

Achieving ubiquitous, high-fidelity ink wash rendering on resource-constrained platforms---including mobile devices and web browsers---constitutes a critical engineering frontier. Promising solutions encompass model compression techniques, adaptive level-of-detail (LOD) management, and progressive asset streaming, all of which aim to reconcile visual richness with stringent memory, bandwidth, and computational constraints inherent to heterogeneous client environments.

iv. Digital Preservation and Cultural Innovation

Beyond entertainment and visualization, 3D ink wash rendering offers a powerful instrumentality for the digital safeguarding and creative revitalization of intangible cultural heritage. Procedural generation methodologies enable the scalable production of stylized assets, facilitating the integration of traditional ink wash motifs into contemporary media ecologies, such as animated features, interactive games, and virtual museum exhibitions, thereby fostering broader public accessibility and cross-cultural dialogue.

v. Persistent Technical and Theoretical Challenges

Despite considerable progress, several fundamental challenges remain unresolved. First, the formal quantification of inherently subjective aesthetic principles---exemplified by the classical notion of qi yun (spiritual vitality or rhythmic energy)---into computable metrics continues to elude a satisfactory solution. Second, achieving a robust equilibrium between real-time performance and high-fidelity artistic expression in geometrically and optically complex scenes remains technically demanding. Third, existing models often exhibit limited cross-domain generalization, struggling to adapt to diverse brushwork styles or unconventional scene compositions. Finally, the field lacks standardized, objective evaluation benchmarks specifically tailored for non-photorealistic ink wash renderings, which significantly impedes systematic comparison, reproducibility, and progress assessment across different research groups. Addressing these multi-faceted challenges will be essential for the continued maturation and broader adoption of the technology.

CONCLUSION

3D ink wash painting style rendering is a typical interdisciplinary field at the intersection of computer graphics and traditional art, possessing important academic research value and broad application prospects. This paper systematically reviews the core technical methods in this field, including brushstroke simulation, ink diffusion, rice paper texture, contour outlining, and shading rendering, along with other key aspects. It also reviews representative research achievements from both domestic and international sources and summarizes the critical technical parameters.

In the future, with the continuous development of AI, real-time rendering, and XR technologies, 3D ink wash rendering will maintain the essence of traditional culture while presenting richer forms of digital expression, thereby providing strong technical support for the contemporary dissemination and innovation of Eastern aesthetics.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts Of Interest

The authors declare that they have no conflicts of interest.

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