

Non-Photorealistic Rendering for 3D Digitalization of Chinese Painting: Technique–Algorithm Matrix and Case Study of Qian Xuan’s Eight Flowers

Meiru Yin

m.yin0120251@arts.ac.uk

University of the Arts London

Wenzhuo Zhao

Shanghai Bilibili Technology Co., Ltd

Article

Keywords: Chinese painting digitalization, Non-photorealistic rendering, Technique–algorithm matrix, Multidimensional evaluation, Cultural heritage

Posted Date: November 3rd, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-7651404/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on June 24th, 2026. See the published version at <https://doi.org/10.1038/s41598-026-59255-7>.

1
2
3
4
5
6
7
8
9
10
11
12
13

**Non-Photorealistic Rendering for 3D Digitalization of Chinese
Painting: Technique–Algorithm Matrix and Case Study of Qian
Xuan’s *Eight Flowers***

Meiru Yin^{*1}, Wenzhuo Zhao²

¹ Camberwell College of Arts, University of the Arts London, London, UK

² Shanghai Bilibili Technology Co., Ltd., Shanghai, China

Corresponding author: Meiru Yin (m.yin0120251@arts.ac.uk)

Abstract

Traditional Chinese painting is an essential component of cultural heritage, and its 3D digitalization plays a crucial role in cultural dissemination and artistic reproduction. However, existing Non-Photorealistic Rendering (NPR) approaches face limitations in reproducing Chinese paintings, such as loss of artistic spirit, unclear workflows, and high learning costs for creators. To address these issues, this study introduces a “Chinese Painting Technique–NPR Algorithm Matching Matrix,” which quantitatively maps five major categories of traditional techniques to 24 mainstream NPR algorithms, providing systematic guidelines for algorithm selection. Based on this framework, we develop a layered collaborative 3D digitalization pipeline, exemplified through Qian Xuan’s *Eight Flowers*, and incorporate an Artist-in-the-loop mechanism to ensure artistic fidelity. Furthermore, a multidimensional evaluation system was established, combining general metrics (LPIPS, SSIM) with newly designed indicators for color fidelity, brushstroke texture, surface texture, and glossiness, alongside subjective evaluation via blind tests. The results demonstrate that our method achieves a favorable balance between artistic authenticity and computational efficiency, outperforming existing projects in both objective scores and perceptual realism. This research not only provides a new pathway for the digital preservation and dissemination of Chinese paintings but also extends the application potential of NPR techniques in cultural heritage.

Keywords: Chinese painting digitalization; Non-photorealistic rendering; Technique–algorithm matrix; Multidimensional evaluation; Cultural heritage

Introduction

Traditional Chinese painting is an essential component of cultural heritage, and its 3D digitalization plays a vital role in cultural dissemination and innovative applications. In recent years, many artists and practitioners have attempted to transform paintings into three-dimensional forms and apply them in contexts such as museums [1,5], animation

[2], games [3], VR [4–6], and AR [5,6]. These explorations not only integrate traditional culture with modern technologies, breathing new life into cultural heritage and presenting it to the public in new forms, but also advance computer graphics methods such as Non-Photorealistic Rendering (NPR), opening novel paths for artistic expression and offering new visual experiences [7].

As a culturally distinctive art form, Chinese painting has a unique aesthetic system. Unlike Western classical realism, Xie He’s Six Principles emphasized *qi yun sheng dong* (spiritual resonance), which became the highest standard of creation and evaluation [8]. Its techniques are commonly grouped into four types—*xieyi* (freehand), *mogu* (boneless), *gongbi* (meticulous), and *baimiao* (plain line drawing)—with further sub-methods such as color application, texture strokes, and ink breaking. Variations in medium and style across periods create diverse visual effects. Since the 20th century, Chinese painting has modernized through Western integration, expanding expressive power but raising challenges for digital reproduction. Purely physics-based simulation remains limited and costly, so artist-guided 3D workflows have become the mainstream solution.

In this context, NPR technology is particularly valuable. Unlike photorealistic rendering, NPR emphasizes brushstrokes, lines, and textures, making it suitable for simulating artistic styles. It has been applied in cultural heritage preservation [9–11], yet in Chinese painting reproduction faces two key issues: artists rely on plugins without algorithmic understanding, leading to homogenization [12,13]; and communication gaps between developers and artists create unclear workflows and high learning costs [14,15].

To address this, we propose a dual-dimensional framework linking painting techniques with algorithms. A Chinese Painting Technique–NPR Algorithm Matching Matrix quantitatively maps five core techniques to 24 algorithms, offering systematic guidance for algorithm selection. Based on this, we design a 3D digitalization pipeline and apply it to Qian Xuan’s *Eight Flowers*, achieving reproduction that balances artistic

fidelity with engineering efficiency, and providing a new pathway for intelligent cultural heritage preservation.

The main contributions of this study are threefold:

(1) Establishment of a Chinese Painting Technique–NPR Algorithm Matching Matrix: Five core categories of Chinese painting techniques are mapped to 24 mainstream NPR algorithms, providing a systematic basis for algorithm selection in the digitalization process.

(2) Development of a Layered Collaborative 3D Digitalization Workflow: Using Qian Xuan’s *Eight Flowers* as a case study, the stages of “outlining–coloring–texturing–void–solidity” are transformed into operable algorithmic modules. An Artist-in-the-loop mechanism is incorporated to balance artistic fidelity and engineering efficiency.

(3) Construction of a Multidimensional Evaluation System: A comprehensive authenticity validation framework is established by combining general metrics such as LPIPS and SSIM with newly designed objective indicators (color fidelity, brushstroke texture, surface quality, glossiness), alongside subjective scoring experiments.

Related work

Traditional Chinese Painting Techniques

Chinese painting can be divided into two stages: traditional and modern/contemporary, with the first half of the 20th century as the boundary. Technically, it is categorized into four major types—*gongbi* (meticulous), *baimiao* (plain line drawing), *xieyi* (freehand/expressive), and *mogu* (boneless painting)—with *pomo* (splash-ink) later emerging as an independent branch influenced by abstract art [16,17]. Representative works of these categories are shown in **Fig. 1**.

Gongbi painting originated in the pre-Qin and Wei-Jin periods, exemplified by Gu Kaizhi’s *Admonitions of the Instructress to the Court Ladies*. It employed “double-outline with color filling” and reached its peak in the Tang dynasty, where styles such

as *Cao Yi Miao* and *Liuye Miao* flourished. By the Song dynasty, *gongbi* had become the dominant academic style [18].

Baimiao depicts forms solely with lines, conveying contours through variations in thickness and strength [19]. Beyond Tang techniques, Guo Ruoxu in the Song dynasty summarized the “Eighteen Miao,” including *Tie Xian Miao* (iron-wire line) and *Lanye Miao* (orchid-leaf line), which enriched the genre. It could stand alone, as in Li Gonglin’s *Five Horses*, or serve as the preparatory outline for *gongbi*, embodying the principle of “gufa yongbi” (using the brush with structural strength) [20].

The origins of *xieyi* trace back to Wang Wei’s “po mo” (broken-ink), regarded as the beginning of freehand landscape painting [21]. Xu Xi’s “luomo” (falling-ink) fostered ink bird-and-flower painting, while Song masters such as Dong Yuan, Fan Kuan, and Guo Xi advanced texture strokes like *pima cun*, *yudian cun*, and *juanyun cun*, maturing the style [22]. Additional techniques such as “accumulated ink,” “rushed ink,” and “splash ink” further expanded its vocabulary.

Mogu painting, rooted in Zhang Sengyou’s “concave–convex flower,” emphasized shading with color instead of outlines. Xu Xi and Huang Quan anticipated this style, and Xu Chongsi fully established *mogu hua* by shaping forms with washes [23]. Notable works include Liang Kai’s *Immortal in Splashing Ink* and Qian Xuan’s *Eight Flowers*, the latter serving as the case study here.

Overall, under the influence of subject matter, materials, and ideology, traditional Chinese painting developed into a highly integrated and stylistically coherent visual art system. Entering the 20th century, Chinese painting moved toward a fusion of Chinese and Western practices, spurred by new social ideologies and the advocacy of “replacing religion with aesthetic education” [24]. Artists incorporated Western realist techniques, modern art forms, and new media, giving rise to diverse styles such as realist ink figure painting [25], expressionist ink painting [26], and the new *gongbi* style [27], alongside innovations in both technique and material. This period placed greater emphasis on individual expression, with experimental methods such as paper rubbing, print transfer,

ink staining, collage tearing, and glue washing. Consequently, it became difficult to establish a unified framework of techniques, posing greater challenges for digital reproduction.



Fig. 1. Techniques of Chinese Painting

3D Digitalization Projects of Chinese Painting

Explorations into the 3D digitalization of Chinese painting began in the early 21st century, mainly for museum displays. The 2006 Grand Canal Touring System combined 3D modeling with Flash animation to simulate movement, paving the way for the 2010 Shanghai Expo’s animated scroll of *Along the River During the Qingming Festival*. Foreground elements were modeled in high-precision 3D, backgrounds converted to 2D animation, and NPR with special lighting created a day–night cycle. The work gained international attention but still showed “model-like” artifacts at night and lacked interactivity due to offline rendering and frame-by-frame 2D animation.

With advances in computer graphics and DCC tools, projects rapidly evolved. Texture mapping and camera projection allowed stylized 2D-like animation without manual frame drawing, improving both efficiency and quality. In 2018, the British Museum released a 3D film based on the Ming-dynasty *Reading in the Autumn Woods*, using 3D models and layered brushstroke mapping to generate hand-drawn depth, with segmentation techniques creating a “pseudo-3D” effect. This improved fidelity and exhibition flow, but free-viewpoint exploration was still limited. In 2019, the Palace Museum and NetEase launched the mobile game *Yizhen·Miaobi Qianshan*, which

transformed 2D paintings into a navigable 3D virtual environment via Unity and Unreal Engine. It enhanced interactivity and extended displays to mobile and VR platforms, though balancing mobile hardware performance with real-time quality remained a challenge [29].

Application of NPR Techniques in Chinese Painting

Non-Photorealistic Rendering (NPR), a key branch of computer graphics, focuses on generating artistic styles rather than realism. Mainstream methods can be divided into three categories: model-based, image-based, and physics-based simulations. By simulating brushstrokes, lines, colors, and textures, NPR has become central to the digitalization and stylistic reproduction of Chinese painting.

Early studies addressed how to make computer images appear hand-drawn. Winkenbach and Salesin (1994) proposed a pen-and-ink rendering pipeline, replacing grayscale values with strokes [30]. Qing Zhang et al. (1999) modeled ink diffusion and paper fibers with cellular automata, reproducing gradations, smudging, and bleeding effects [31]. Ching (Clara) Chan et al. (2002) realized a 3D-to-2D ink animation workflow using procedural rendering, with their distance-based transparency interpolation still applied today [32]. During this period, frameworks for contour line rendering, interior shading, brushstroke simulation, and texture mapping were gradually established [33,34]. Dietrich A et al. (2007) further proposed an efficient 3D model rendering framework for real-time performance [35].

Recent research has focused on contour line optimization, brushstroke synthesis, and interactive 3D brushes. Meijun Sun et al. (2010) developed an automated system for 2D-to-3D style transfer with multilayer rendering [36]. Yan et al. (2022) improved mountain rendering by solving the “shower door effect” during camera movement [37]. Yao et al. (2024) introduced InkBrush, a sketch-based 3D tool overcoming texture-mapping limitations and enabling fine ink parameter control [38]. Other studies combined Chinese ink aesthetics with cinematic lighting to create 3D animations with 2D qualities, expanding narrative applications [39].

In summary, NPR has evolved from early 2D simulation to 3D real-time rendering, providing the foundation for Chinese painting digitalization. Yet, challenges remain in systematically reproducing techniques and clarifying mappings between artistic styles and algorithms. This study addresses these gaps through a Chinese Painting Technique–Algorithm Matching Matrix and its integration in 3D ink painting digitalization.

Digitalization Methodology

This study integrates literature analysis, expert interviews, and practical experience to categorize Chinese painting techniques and NPR algorithms, each with hierarchical coding. Their visual effects and key features were further distilled to construct a Technique–Algorithm Matching Matrix. This matrix enables evaluation of strengths and weaknesses, selection of suitable combinations, and workflow optimization, which is validated through the case of Qian Xuan’s *Eight Flowers*. The proposed matrix serves as a general framework, offering an operational mapping strategy for different techniques. The feature-matching concept is illustrated in **Fig. 2**.

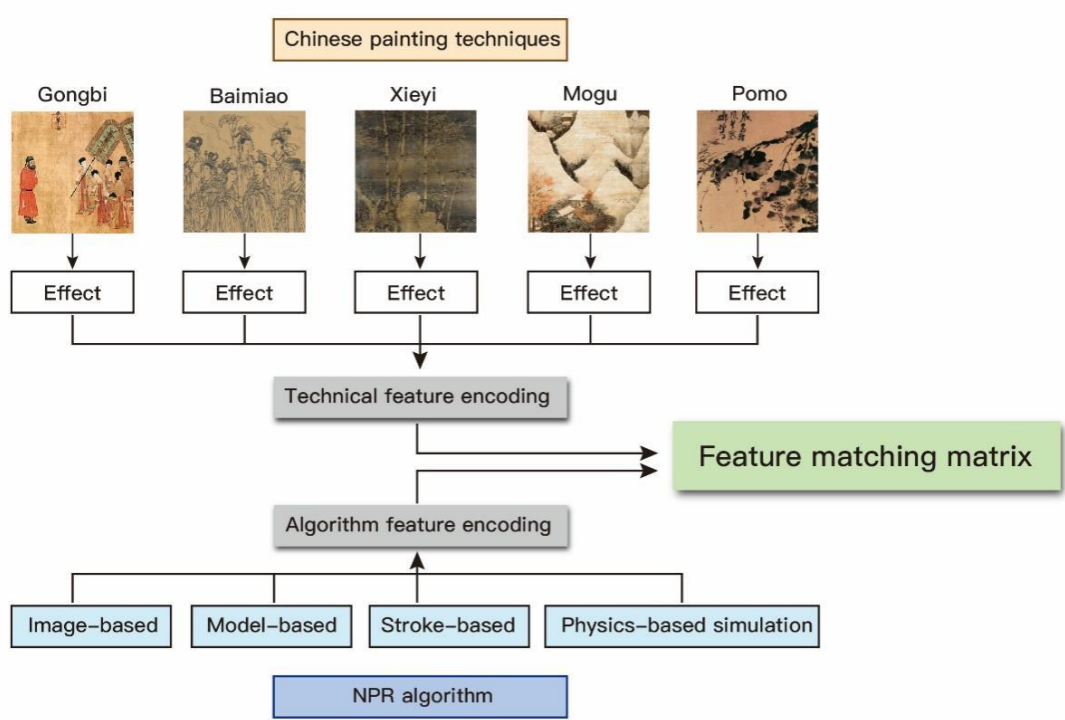


Fig. 2. Mapping framework

Encoding of Chinese Painting Technique Features

Traditional Chinese painting techniques are generally divided into four major categories: *gongbi* (meticulous), *xieyi* (freehand), *moqu* (boneless), and *baimiao* (plain line drawing). However, within *xieyi*, the *pomo* (splash-ink) style has evolved into an independent branch distinct from traditional ink painting under the influence of modern abstract art [16,17]. Therefore, this study treats *pomo* as a separate category, resulting in five primary codes: *xieyi*, *gongbi*, *moqu*, *pomo*, and *baimiao*.

Based on a systematic review of literature describing the characteristics and operational steps of these techniques, key elements were extracted as reference points. Secondary codes were then assigned according to the visual effects of each technique.

Within the *moqu* category, some reference points actually describe *gongbi* methods (e.g., combined use of powder application and layered dyeing). Such cases were counted quantitatively but excluded from secondary classification to avoid confusion in the technical system.

Given the limited research in digital rendering on the optical properties of mineral pigments (e.g., azurite, malachite), algorithm development remains constrained. Therefore, *gongbi* with heavy mineral pigments and *gongbi* with lighter plant-based pigments were consolidated into the single *gongbi* category to maintain logical consistency within technically feasible boundaries.

By quantitatively analyzing the proportion of reference points across different techniques, it is possible to objectively assess their theoretical importance and implementation priority within a given painting system. Taking *xieyi* (freehand) as an example:

(1) “Water–ink blending” (AT_FR_01): 27 reference points (62.8%). Frequent mentions of techniques such as *po mo* (broken ink) and *ji mo* (accumulated ink) confirm its role as the core expressive mechanism in *xieyi*, directly determining ink layering and the generation of *qi yun* (vital artistic resonance).

219 (2) “Calligraphic brushwork” (AT_FR_02): 7 reference points (16.3%). Focused
 220 on brush-angle transitions and rhythmic pressure control, this reflects its function as a
 221 key auxiliary technique enhancing expressive power.

222 (3) “Freehand texture strokes” (AT_FR_03): 5 reference points (11.6%). Mostly
 223 describing methods such as axe-cut and rolling-cloud strokes, these are scene-specific
 224 techniques in landscape representation, indicating that their digital reproduction must
 225 be tailored to object-specific features.

226 This statistical model establishes a mapping between the density of technique
 227 references in literature and their digitalization priority, providing a data-driven basis for
 228 algorithm resource allocation. High-density techniques (e.g., AT_FR_01) should be
 229 prioritized for precise physical simulation, while low-density ones (e.g., AT_FR_03)
 230 may be implemented with simplified parameterization.

231 Based on reference point analysis, the five technique categories were summarized,
 232 with their main sub-techniques, core features, and representative expressions coded at
 233 the secondary level, as shown in **Table. 1**.

234
 235 **Table. 1.** Technique coding and feature analysis.

	Code	Name	Features	Typical Expressions	Reference
Xieyi	AT_FR_01	Ink-and-Wash Fusion	Layered variations produced by water and ink	Broken-ink technique (Pomo): dark over light / light over dark Splash-ink technique (Pomo): large-area ink pouring Accumulated-ink technique (Jimo): multiple ink-layer superimposition	[40]、[41]、[44]、[46]、[47]、[48]、[21]、[50]、[51]、[54]
	AT_FR_02	Calligraphy in Painting	Calligraphic brushwork with rhythm and strength	Brush-angle transitions: center-tip / side-tip switching, pressure variation, speed control (e.g., Xu Wei’s cursive-script-inspired painting)	[41]、[48]、[51]
	AT_FR_03	Xieyi Texture Strokes	Variation of brush tip with a balance of solidity and void	Short hemp-fiber strokes (duan pima cun, Dong Yuan) Raindrop strokes (yudian cun, Fan Kuan) Rolling-cloud strokes (juanyun cun, Guo Xi) Axe-cut strokes (fupi cun, Li Tang)	[40]、[50]、[51]
Gongbi	AT_ME_01	Layered Rendering	Multiple layers of transparent color superimposed	Triple alum–nine dyeings (san fan jiu ran) Layered dyeing (concave dyeing / rotary dyeing) Overlay dyeing with plant pigments (thin washes)	[43]、[44]、[45]、[47]、[54]、[58]
	AT_ME_02	Outline Drawing	Constructing forms through lines with high abstraction	Fine “yousi” outlines (you si miao, Gu Kaizhi) Iron-wire lines (tie xian miao, Li Gonglin)	[40]、[43]、[44]、[45]、[49]、[55]
	AT_ME_03	Mineral and Plant Pigments	Mineral pigments with glue for rich tones; plant pigments diluted with water for subtle hues	“Hollow filling” (taotian): color not covering outlines Reverse underlay (fanchen): backing color from sides Powder accumulation (jifen): leaving white along petal edges	[40]、[54]、[57]、[58]
	AT_ME_04	Meticulous Texture Strokes	Contour and texture first, then coloring;	Hemp-fiber texture with shading contrasts Dense strokes in shadowed areas, sparse in highlights Combined outlining, texturing, and shading	[44]、[55]、

			integration of ink and pigment		
Mogu	AT_BO_01	Collision Dyeing Technique	Collision of water, powder, and color in a wet state	Water collision (zhuang shui): injecting water into lit surfaces Powder collision (zhuang fen): mineral pigments sinking Mixed collision washes: multiple pigments merging	[46]、[47]、[52]、[53]、[54]
	AT_BO_02	Hidden-line Modeling	Volumetric representation without contour lines	Shaping with tonal variations: e.g., Zhang Sengyou's "concave-convex flowers" Watercolor-like edge diffusion	[46]、[47]、[53]、[54]
Pomo	AT_BR_01	Fluid Control	Natural flow and guided movement of ink	Pouring (qingpo): direct container pouring Dragging (tuoyi): pulling with cloth strips Post-process brush refinement	[40]、[48]、[21]、[51]、[52]
	AT_BR_02	Abstract Textural Effects	Uncontrollable ink blot forms	Random ink blot diffusion: e.g., Liang Kai's Immortal in Splashing Ink Cloud-and-mist blurring effect: e.g., Mi family cloud landscapes	[21]、[54]
Baimiao	AT_LI_01	Bone-brush Technique	Expressive rhythm of lines	Willow-leaf outlines (liuye miao, Wu Daozi) "Nail-head, mouse-tail" lines (ding tou shu wei miao, Li Gonglin)	[40]、[21]、[49]、[55]

236

237 **Feature Encoding of 3D Digitalization Methods**

238 Based on a review of previous studies on NPR algorithms, 24 mainstream approaches

239 were categorized into four types for coding: image-based, model-based, physics-based

240 simulation, and brush-based methods [59,60]. Strictly speaking, image-based

241 algorithms are not NPR methods, but in artistic workflows they often contribute to post-

242 production during the compositing stage and thus form an essential part of the

243 digitalization process. Therefore, they are also included in the statistics of this study.

244 The features and limitations of each algorithm were summarized from the literature and

245 coded at the secondary level, as shown in **Table. 2**.

246

247 **Table. 2.** Algorithm coding and feature analysis.

248

	Code	Name	Features	Limitations	Reference
Model-based (AL_MD)	AL_MD_01	Outline Rendering	Surface differential geometry Visibility detection	Mechanized line quality	[30]
	AL_MD_02	Fresnel-based Stroke Rendering	View-normal angle edge enhancement	Inaccurate reproduction; surface discontinuities	[35]
	AL_MD_03	Markov Fractal Perturbation	Fractal noise perturbation of normals/curvature	Excessive distortion	[61]
	AL_MD_04	Multi-level Shading	Normal layering + tonal partitioning	Rigid tonal transitions	[33]、 [34]
	AL_MD_05	Geometric Deformation Shading	Vertex displacement for brushstroke simulation	Topology disruption	[38]
	AL_MD_06	Material Boundary Detection	Material ID boundary extraction	Neglect of gradient transitions	[62]
	AL_PH_01	Cellular Automata-based Ink Diffusion	Water molecule grid motion simulation	Lack of 3D penetration	[31]
	AL_PH_02	Particle System Fluid Dynamics	SPH(Smoothed Particle Hydrodynamics)	High computational cost	[63]

Physics-based (AL_PH)	AL_PH_03	Xuan Paper Fiber Permeation	Capillary effect + porous media modeling	Parameter sensitivity	[31]
	AL_PH_04	Brush–Paper Contact	Hair cluster physics + friction computation	Dependence on high-precision input devices	[64]
	AL_PH_05	Wet–Dry Ink Layer Mixing	Fick’s diffusion law + evaporation equation	Poor real-time performance	[32]
	AL_PH_06	Silk Weave Rendering	Fabric structural illumination model	Unsuitable for <i>xuan</i> paper	[65]
Image-based (AL_IM)	AL_IM_01	CNN-based Style Transfer	CNN feature extraction + Gram matrix matching	Relatively high computational cost	[66]
	AL_IM_02	Edge-preserving Filtering	Joint bilateral / guided filtering	Blurred details	[67]
	AL_IM_03	Ink Tone Layer Extraction	Hue separation + alpha-channel reconstruction	Requires preset color palettes	[68]
	AL_IM_04	Brushstroke Texture Synthesis	MRF (Markov Random Field) generation	Detached from physical basis	[30]
	AL_IM_05	GAN-based Ink Painting Generation	Conditional generative adversarial networks	Strong randomness, uncontrollable	[69]
	AL_IM_06	Multi-scale Image Fusion	Laplacian pyramid blending	Loss of high-frequency information	[70]
Brush-based (AL_BR)	AL_BR_01	Pressure-sensitive Brush Strokes	Pressure-sensitivity mapping → brush-tip morphology	Reliance on artistic expertise	[38]
	AL_BR_02	Ink Particle Brush	Trajectory-based ink particle system	Over-diffusion of particles	[31]
	AL_BR_03	3D Spatial Ink Rendering	Spatial stroke triangulation + fluid shading	Heavy computational load	[38]
	AL_BR_04	Brush Hair Splitting Simulation	Brush-hair elasticity mechanics model	Complex parameterization	[71]
	AL_BR_05	Dynamic Brushstroke Mapping	Stroke UV projection + animated textures	Lack of physical interactivity	[68]
	AL_BR_06	Gesture-controlled Cun Simulation	Gesture recognition noise generation	High learning curve	[38]

249 Preliminary Matching of the Framework Matrix

250 As shown in Tables 1 and 2, representative technique–algorithm pairs illustrate the
251 logic of the matching process. For example, *pomo* (splash ink), “mineral and plant
252 pigments” in *gongbi*, “water–ink blending” in *xieyi*, and “collision dyeing” in *moqu*
253 rely primarily on physical interactions between media—such as capillary action, fluid
254 dynamics, and molecular diffusion—as their core generative mechanisms. These
255 techniques are characterized by strong randomness, uncontrollable processes, and
256 emergent visual outcomes, making them more suitable for physics-based simulation
257 algorithms rather than rule-based procedural generation.

258 In addition, techniques such as “layered rendering” and “outlining” in *gongbi* or
259 “implicit contour modeling” in *moqu* are rooted in craftsmanship, emphasizing form,
260 inherent color, and shading. These methods pursue visual integrity through highly

controllable workflows with strong regularity and parameterization, and are therefore better aligned with model-based algorithms.

Techniques like “calligraphic brushwork” in *xieyi* and “ancient brush methods” in *baimiao* fundamentally rely on the artist’s brush experience and aesthetic sensibility. Such expressive qualities are difficult to reproduce through algorithmic means and instead require brush-based algorithms with artist-in-the-loop intervention. Meanwhile, image-based algorithms can serve as post-compositing tools after model rendering, further enhancing stylistic effects by combining features of different approaches.

It should be noted that Algorithm AL_PH_06, designed for silk texture rendering, is not applicable to paintings on *xuan* paper and was therefore excluded from the matching matrix. The preliminary “Chinese Painting Technique–NPR Algorithm Matching Matrix” is presented in **Table. 3**.

273

Table. 3. Preliminary matrix of Chinese painting techniques–NPR algorithms.

275

Technique	Primary Algorithm	Features	Limitations	Alternative Algorithm	Features	Limitations
AT_FR_01	AL_BR_02	Fluid dynamics, strong artistic effect, controllable wet–dry parameters	Particles prone to over-diffusion; high computational cost	AL_PH_05, AL_IM_05	Realistic reproduction of <i>po mo</i> (broken-ink) effects	Strong randomness, uncontrollable
AT_FR_02	AL_BR_01, AL_MD_03	Precise brush movement, natural brushstrokes	Possible distortion in AL MD 03	AL_BR_04	Suitable for dry-brush strokes	Limited applicability
AT_FR_03	AL_MD_03, AL_BR_04	Fractal noise for stroke diversity + brush-splitting dynamics	Complex parameter tuning; requires artistic guidance	AL_MD_04, AL_IM_04, AL_BR_06	Procedural generation; texture aligned with model structure	Low fidelity
AT_ME_01	AL_MD_04, AL_IM_03	Layered shading + ink extraction	Requires preset color palettes	AL_BR_05, AL_IM_06	Realistic texture quality	AL_IM_06 prone to high-frequency detail loss
AT_ME_02	AL_MD_01	Structural precision, dynamic brushstrokes	Dependence on artistic expertise	AL_MD_02, AL_MD_03	Procedural generation; high structural accuracy	Easily distorted, lacking detail
AT_ME_03	AL_MD_06, AL_IM_02	Clear boundaries + edge enhancement	Neglect of gradient transitions	AL_IM_04	Generation of complex textures	Detached from physical basis
AT_ME_04	AL MD_01, AL_IM_03, AL_BR_06	Accurate contouring + layered ink extraction	Manual annotation of tonal regions required	AL_MD_04, AL_IM_04	Procedural generation; texture aligned with model structure	Low fidelity
AT_BO_01	AL_PH_03, AL_BR_03	Physical fidelity, three-dimensional strokes	High computational cost	AL_PH_05, AL_BR_02	Simple workflow	Particle diffusion hard to control; insufficient accuracy for collision dyeing
AT_BO_02	AL MD 04,	Structural accuracy,	Detail loss	AL PH 01,	Basic ink-	Lack of 3D

	AL_IM_02	softened edges	caused by AL_IM_02	AL_IM_05	diffusion simulation; rich texture generation	penetration; strong randomness and uncontrollability
AT_BR_01	AL_PH_02, AL_IM_05	Fluid simulation + GAN-based enhancement	Heavy computational load	AL_BR_03, AL_IM_01	Strong sense of three-dimensionality	Style transfer lacks spatial consistency
AT_BR_02	AL_IM_05	Random generation	Strong uncontrollability	AL_BR_02, + AL_IM_04	High creative flexibility	Particles prone to over-diffusion; detached from physical basis
AT_LI_02	AL_MD_01, AL_IM_05	Precise lines, style adaptability	Lines lack pressure sensitivity	AL_BR_01,	Realistic reproduction of pressure and brush-tip variation	Requires artistic expertise; labor-intensive

276 Validation of the Framework

277 To validate the rationality and practicality of the proposed “Chinese Painting
278 Technique–NPR Algorithm Matching Matrix,” we conducted semi-structured
279 interviews with Chinese painting experts (N = 3), NPR researchers (N = 3), and digital
280 art practitioners (N = 2). The average interview length was 43.5 minutes.

281 The interviews were organized into three modules. The first module focused on
282 participants’ understanding of the current state of integration between technology and
283 art, as well as the challenges they perceived. The second module introduced NPR
284 algorithms to Chinese painting experts and, conversely, explained Chinese painting
285 techniques to NPR researchers, asking for their evaluation of the matrix. The emphasis
286 varied across groups: for painting experts, one guiding question was, “*What do you*
287 *consider the most difficult aspect of digitalizing the mogu (boneless) technique?*”; for
288 NPR researchers, an example question was, “*What are the limitations of the current*
289 *matching algorithms (e.g., AL_PH_03 + AL_BR_03)?*” The third module invited open-
290 ended suggestions, allowing participants to share perspectives beyond the specific
291 domain of Chinese painting digitalization.

292 We applied content analysis to the interview data and coded key insights from
293 experts. A summary of expert opinions and corresponding response strategies is
294 provided in **Table. 4**.

295
296 **Table. 4.** Interview results for framework validation.
297

Expert Type	Key Insights (Representative Statements)	Implications and Response Strategies
Chinese Painting Technique Experts	<i>“The matching of Water–Ink Blending (AT_FR_01) with the Particle System (AL_PH_02) is very intuitive; the randomness and dynamics of particles are well-suited to simulating ink diffusion.”</i>	Validates the matching logic between physics-based algorithms and <i>xieyi</i> (freehand) techniques.
	<i>“Using only contour rendering (AL_MD_01) for Gongbi Outlining (AT_ME_02) appears mechanical; it should be combined with algorithms that simulate brush-tip variation.”</i>	For <i>gongbi</i> techniques, precise rendering should be complemented with brush-dynamics algorithms, forming combined strategies.
	<i>“The ‘collision dyeing’ effect in Mogu painting matches well with the Xuan Paper Fiber Model (AL_PH_03), but requires additional wet–dry brush transition control to enhance realism.”</i>	More refined control parameters are needed in physics-based simulations to capture complex artistic effects.
NPR Researchers	<i>“The current Gongbi Outlining (AL_MD_01) relies too heavily on geometric edge detection; integrating a brush dynamics model (AL_BR_01) could enhance the vitality of the lines.”</i>	Algorithm combinations should balance structural accuracy and artistic expressiveness; AL_MD_01 + AL_BR_01 can serve as an optimized pairing.
	<i>“The Xuan Paper Fiber Penetration Model (AL_PH_03) is theoretically strong, but real-time computation is a challenge; precomputed texture maps could approximate the effect.”</i>	While pursuing physical fidelity, computational efficiency must be considered, with engineering strategies such as precomputation and LOD (Level of Detail).
Digital Art Practitioners	<i>“Algorithms should not overshadow artistry. Artists must be able to easily control final effects, such as ink density and brush wetness.”</i>	Emphasizes the importance of Artist-in-the-Loop (AITL) . Tools should provide high-level, intuitive sliders aligned with artistic perception rather than exposing low-level technical parameters.
	<i>“A more intuitive interface is needed to adjust the strength of the ‘Martens Fractal Perturbation’ (AL_MD_03), instead of directly modifying code parameters.”</i>	System design should prioritize user experience, translating algorithmic parameters into visually meaningful adjustments for artists.
Consensus Recommendations	<i>“Algorithms should serve artistic intent rather than dictate creation.”</i>	The digitalization workflow should remain centered on artistic intent, with algorithms serving as enabling tools.
	<i>“This matrix framework is valuable, but attention should be paid to subtle stylistic differences across dynasties and individual painters. In the future, it could be extended into a configurable ‘Technique–Algorithm’ knowledge base.”</i>	The proposed matrix offers a foundational framework with strong scalability, allowing future integration of additional stylization parameters.

298

299 The results show that most experts acknowledged the overall framework of the
300 matrix. In particular, the matching of *water–ink blending* with particle fluid simulation
301 (AL_PH_02) was described as “highly compatible” (Expert A). The integration of the
302 *collision dyeing* effect in *mogu* painting with the Xuan paper fiber model (AL_PH_03)
303 was also affirmed, though experts recommended adding wet–dry brush transition
304 control to enhance realism.

305 Furthermore, experts widely emphasized that “algorithms should serve artistic
306 intent rather than dominate creation,” highlighting the importance of the artist-in-the-
307 loop. One NPR researcher noted: *“The current matrix relies too heavily on geometric*
308 *edge detection in the gongbi outlining part (AL_MD_01); introducing a brush*
309 *dynamics model (AL_BR_01) would enhance the vitality of lines.”*

Based on these insights, minor adjustments were made to the matrix. The revised version is shown in **Fig. 3**.

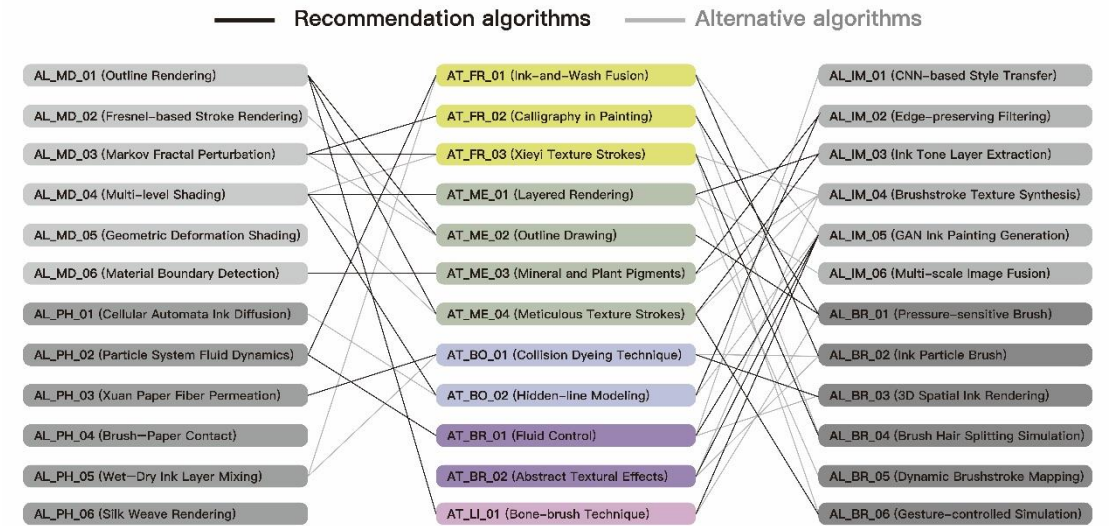


Fig. 3. Visualization of optimized matching matrix.

Ethical approval

All methods were carried out in accordance with relevant guidelines and regulations. All experimental protocols, including interviews and questionnaires, were approved by the Academic Committee of Camberwell College of Arts, University of the Arts London. Informed consent was obtained from all participants prior to their involvement in the study.

3D Digitalization Workflow of Qian Xuan’s *Eight Flowers*

Within the scope and length of this study, *Eight Flowers* by Qian Xuan was selected as a representative case, focusing on the applicability of the framework to *mogu* painting and related techniques. The mapping of other techniques will be gradually explored in future research. Based on the technique–algorithm matching matrix established above, a layered collaborative 3D digitalization workflow was designed for *Eight Flowers* (**Fig. 4**).

The choice of this work was guided by two considerations: first, it combines gongbi outlining with *mogu* rendering, offering representativeness across multiple

techniques; second, it provides a feasible verification model at a manageable scale for a single researcher.

The workflow centers on the technique–algorithm matching rules, integrating both artistic guidance and procedural processing, and consists of three stages:

(1) Image analysis and modeling: analyze the techniques and aesthetic characteristics of the painting, assign algorithm combinations according to the matrix, and construct the symbolic 3D model.

(2) Core rendering: process layers of the model, canvas, and subjects, applying optimized algorithms to balance efficiency and accuracy.

(3) Post-correction: artists digitally retouch specific artistic effects, followed by comparison with the original painting and post-processing to enhance the restoration of shen yun (artistic spirit).

This pipeline translates algorithm combinations from the matrix (e.g., AL_MD_03 fractal perturbation, AL_IM_04 brushstroke texturing) into an operable process. The following sections elaborate on its implementation in the *Eight Flowers* case.

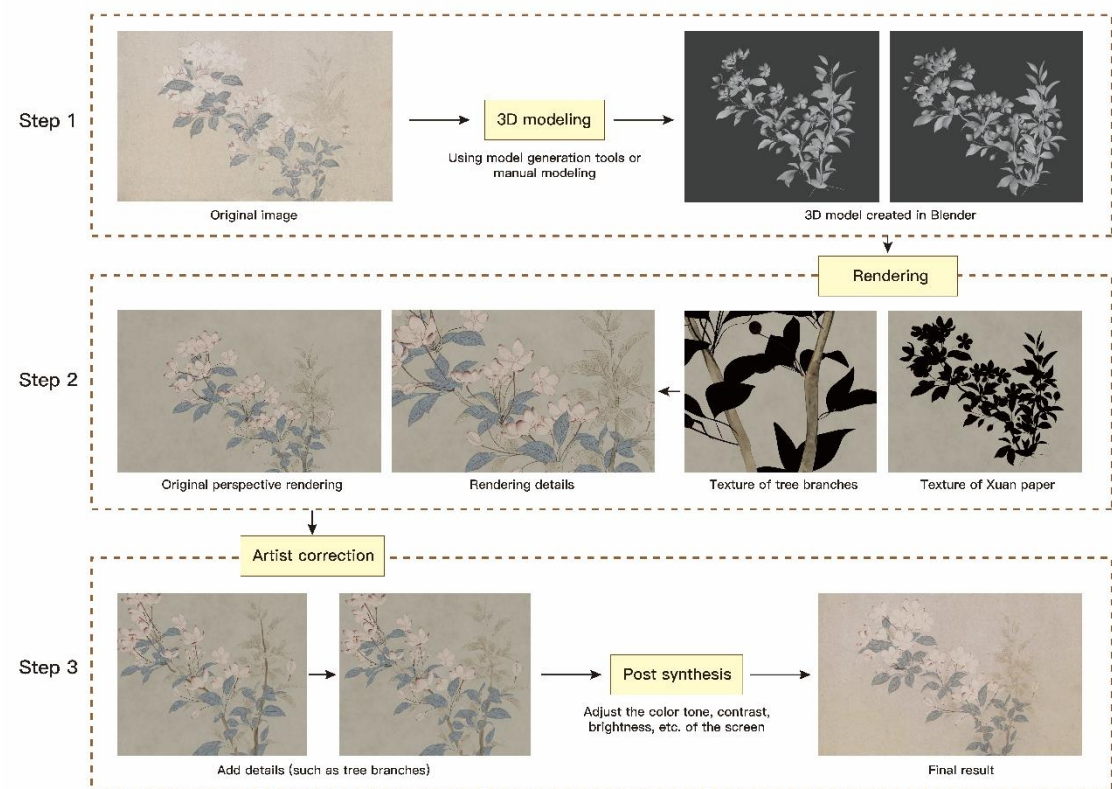


Fig. 4. Digitalization process using *Eight Flowers* as an example.

Preliminary Image Analysis of *Eight Flowers*

The author of *Eight Flowers*, Qian Xuan, was a Yuan-dynasty painter whose work inherited the refined style of Song-dynasty court bird-and-flower painting, characterized by realism, technical precision, and elegant coloration. The flowers are depicted with meticulous form observation and expressive line variation, while repeated light washes—especially of white pigment—create translucency and subtle literati aesthetics. The linework blends *mogu* and *gongbi*, alternating between faint ink outlines and integrated brush-color effects, producing “color within line, line within color.”

From this analysis, *Eight Flowers* can be identified as a paper-based colored painting. The canvas, influenced by traditional papermaking techniques and aging, appears rough and yellowed. The branches (secondary subjects) are divided into contour lines and interior coloring, corresponding to techniques AT_ME_02 and AT_ME_01. Since the branches occupy a minor portion of the composition and are not the visual focus, rendering performance was prioritized, and both were implemented using alternative algorithm combinations. The primary subjects (flowers and leaves) mainly employ techniques AT_BO_02 and AT_LI_02. Given the limited workload manageable by a single researcher, the main algorithm combinations were applied in conjunction with artistic guidance, ensuring efficiency while reducing the risk of overly mechanical results.

Algorithm Application and Core Rendering

Based on the above analysis, the original painting was reconstructed in 3D using Blender, a free and open-source software with strong community support, well-suited for independent stylized creation. The *Eight Flowers* model contains 488,326 vertices, 465,175 faces, and 930,422 triangles.

For the canvas, the texture of *xuan* paper was simulated using noise-based rendering. Parameters such as noise scale, lacunarity, and persistence were defined, and noise values for each point in 3D space were normalized to the [0,1] range. These coefficients were interpolated as grayscale values and mapped through color gradients, with the final color output projected into world coordinates. For the branches, internal coloring was simulated by painting directly on the UV map with digital brushes. The contour lines were rendered using Fresnel-based edge detection, with the algorithm defined as:

$$Fresnel\ Fac = \max\left(0, \min(1, bias + scale \times (1 - |N \cdot V|)^{power})\right) \quad (1)$$

Fresnel Fac (Fresnel factor) denotes the reflection coefficient varying with view angle, enhancing contour visibility as the angle approaches tangency. Here, N is the surface normal, V the view direction, while *power*, *bias*, and *scale* are artist-controlled parameters for edge sharpness, base offset, and scaling.

Since direct rendering appeared too uniform, Martens fractal noise was introduced to perturb normals and mimic brushstroke effects. The algorithm computes a disturbance scalar (*offset*) from world coordinates and generates a perturbation direction $\vec{D}$. The perturbed normal $\vec{N}_{pert}$ is then given by:

$$\vec{N}_{pert} = \frac{\vec{N}_{orig} + a \cdot offset \cdot (\vec{D}_x \vec{T} + \vec{D}_y \vec{B})}{\|\vec{N}_{orig} + a \cdot offset \cdot (\vec{D}_x \vec{T} + \vec{D}_y \vec{B})\|} \quad (2)$$

Here, a is a constant in [0,1]; smaller values yield finer brushstroke variation. $\vec{T}$ and $\vec{B}$ are orthogonal tangents to $\vec{N}_{orig}$, with the perturbation vector lying in their tangent plane.

For the coloring and outlining of the crabapple flowers and leaves, shading follows the same method as the branches. Since the outlines are drawn in a *gongbi* style, the edge rendering adopts a contour algorithm with noise perturbation (*Shading Normal Contour Edges*). Contours typically arise from silhouette edges, contour edges, and material edges (see *Real-Time Rendering, Fourth Edition*).

This study focuses on the first two. A silhouette edge separates the object from the background, while a contour edge connects two adjacent faces where one is front-facing and the other back-facing relative to the view. Silhouette edges are a subset of contour edges and can be defined mathematically as follows.

Let an edge $e = (v_i, v_j)$ in the mesh connect two adjacent faces f_a and f_b , with face normals $\vec{n}_a$, $\vec{n}_b$. Define the view direction vector $\vec{v}$ (from the camera toward the object). An edge is classified as a contour edge if it satisfies: $(\vec{n}_a \cdot \vec{v})(\vec{n}_b \cdot \vec{v}) < 0$

In practice, brush pressure produces edges of varying thickness and intensity. Accordingly, baseline line width and opacity can be adjusted by curvature and depth, while random perturbations and noise textures are applied to simulate real brushstrokes. The rendering results are shown in **Fig. 5**.



Fig. 5. Rendering results and detail display.

Post-Correction Stage

Building on the preliminary images from the core rendering stage, artists intervene with subjective adjustments informed by their understanding of the original work, aesthetic judgment, and creative experience. This process goes beyond parameter tuning and represents a re-creation through digital instructions.

Details were refined by adding two material maps to the leaves, distinguishing their front and back surfaces to reproduce the color differences in the original painting. For the branches, colors were adjusted to show a gradient from dark at the base to light at the tip, producing the intended variation in solidity. In terms of spatial composition, the flowers and foreground leaves serve as the visual focus with brighter colors, while

the background leaves on the right act as supporting elements with lighter tones, enhancing spatial hierarchy. Depth and height values were used to vary transparency, simulating the original's near–far and solid–void contrast.

Finally, the rendered images were processed in the Blender compositor rather than on the 3D model itself. Brushstroke textures were overlaid, and adjustments to hue, contrast, and brightness were applied. The final results are shown in **Fig. 6**, alongside a comparison with the original painting.



Fig. 6. Final rendered image vs. original painting.

Evaluation and Validation

We established a comprehensive evaluation framework combining objective and subjective measures. Objectively, LPIPS and SSIM were used as baseline image similarity metrics, supplemented by four custom dimensions tailored to Chinese painting—color fidelity, brushstroke texture, surface texture, and glossiness. Subjectively, a questionnaire targeting students and practitioners in Chinese painting and computer graphics was conducted. All scores were normalized to the [0,1] range, with higher values indicating greater similarity to the original.

The rationale rests on two aspects: (1) vision science and perception theory—color fidelity reflects sensitivity to color difference (CIE Lab), while brushstroke and texture capture material perception and gloss responds to highlights; (2) the aesthetic particularity of Chinese painting, where authenticity depends on the combined effect of color, line, texture, and light, beyond what general metrics like LPIPS and SSIM can

capture. Overlapping dimensions, such as color fidelity, were included in both objective and subjective evaluations to test consistency.

For comparison, four representative 3D digital projects were selected: *Qiushan Wendao Tu* (Project B), *Qiulin Dushu Tu* (Project C), *Shiyong Tu* (Project D), and *Qingming Shanghe Tu* (Project E). These cover both scholarly heritage projects (B, D) and high-profile cultural showcases (C, E), spanning gongbi and xieyi styles. Some comparison images were sourced from published screenshots with limited resolution, which may introduce minor evaluation bias, but consistency was maintained to ensure valid results.

Objective Evaluation Metrics

LPIPS (Learned Perceptual Image Patch Similarity) is a deep-learning-based metric for perceptual image similarity [72]. It extracts multi-level features using a pretrained CNN and computes cosine distances in the feature space. In this study, the VGG network was adopted, as prior research shows it performs well in quantitative comparisons and aligns closely with human perceptual judgments.

SSIM (Structural Similarity Index) evaluates image similarity by jointly considering luminance, contrast, and structural information [73]. Using a fixed sliding window (11×11 pixels in this study), it aggregates statistics such as mean, variance, and covariance to compute similarity scores. Compared to pixel-based error metrics, SSIM better reflects perceptual structural consistency and has been widely used in image reconstruction, compression, and cultural heritage preservation.

In addition, four custom objective metrics were developed to capture Chinese painting-specific characteristics:

1. Color fidelity: based on mean color difference.
2. Brushstroke texture: computed using LBP features, scored by Bhattacharyya distance of LBP histograms (radius = 3, n_points = 24).
3. Surface texture: based on variance of Laplacian responses.
4. Glossiness: combining Bhattacharyya distance of brightness histograms with the

proportion of highlight pixels ($V > 220$).

Evaluation results based on these metrics are summarized in **Table. 5**.

Table. 5. Objective indicator evaluation results.

	Project A	Project B	Project C	Project D	Project E
LPIPS	0.55	0.29	0.57	0.45	0.31
SSIM	0.74	0.33	0.49	0.67	0.61
Color Fidelity	0.96	0.81	0.92	0.88	0.82
Brushstroke Texture	0.98	0.81	0.96	0.77	0.71
Surface Texture	0.78	0.16	0.53	0.05	0.46
Glossiness	0.99	0.94	0.98	0.99	0.94

Except for SSIM and color fidelity, which require strict pixel alignment, the other analyses can theoretically assess overall image characteristics. As shown in **Fig. 7–11**, our method achieves higher fidelity across multiple dimensions.

Art Restoration Evaluation Report

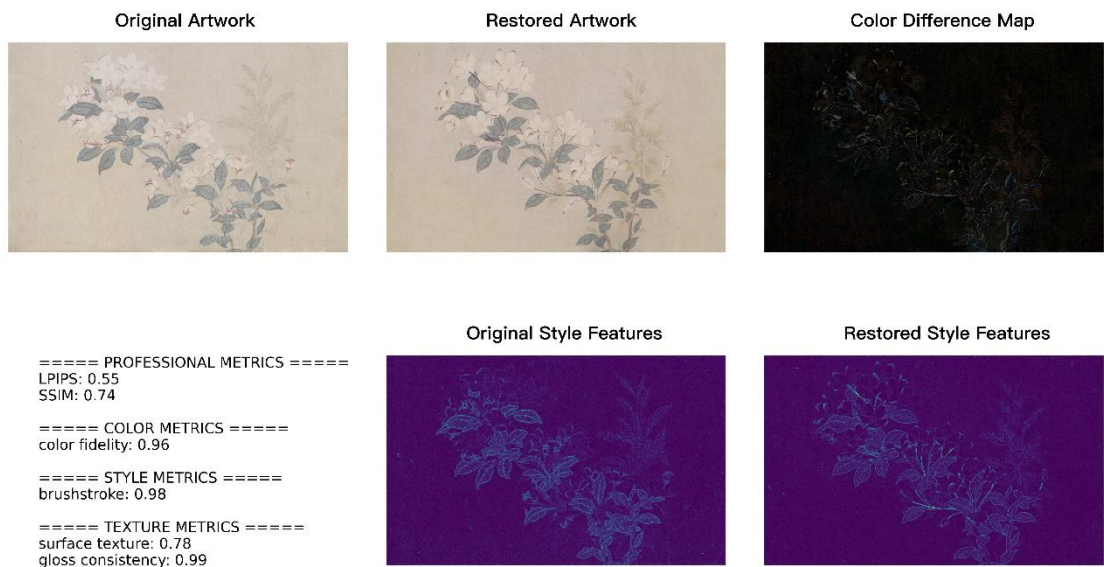


Fig. 7. Algorithm evaluation results of *Eight Flowers* (project A).

Art Restoration Evaluation Report

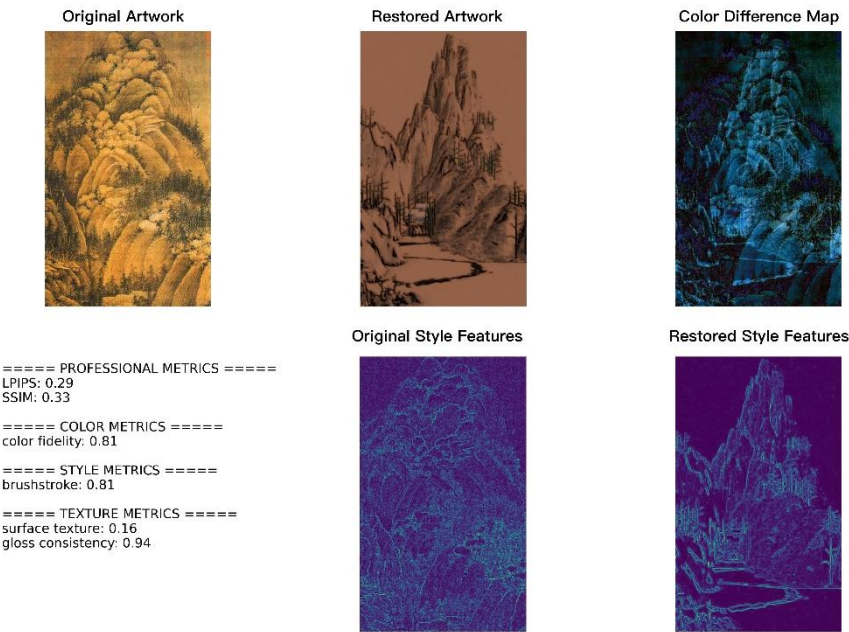


Fig. 8. Algorithm evaluation results of *Autumn Mountains: Seeking the Way* (project B).

Art Restoration Evaluation Report

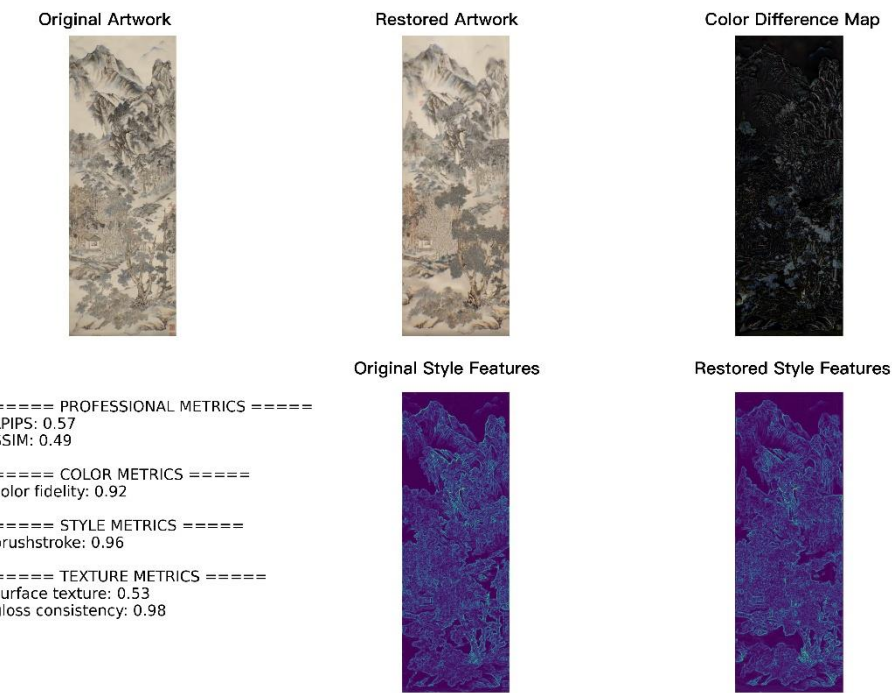


Fig. 9. Algorithm evaluation results of *Reading in the Autumn Woods* (project C).

Art Restoration Evaluation Report

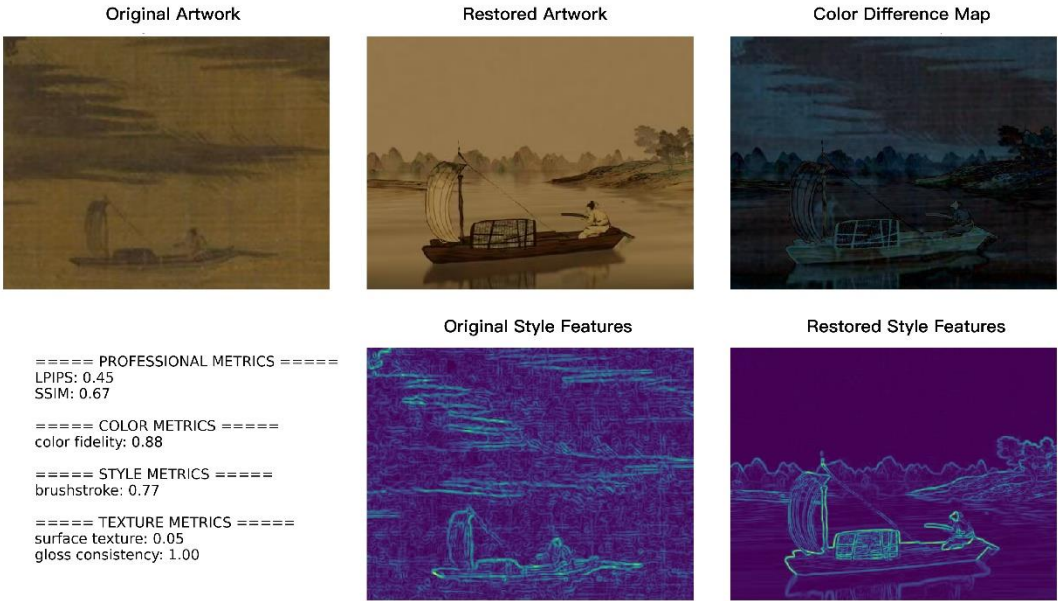


Fig. 10. Algorithm evaluation results of *Ten Ode Paintings* (project D).

Art Restoration Evaluation Report

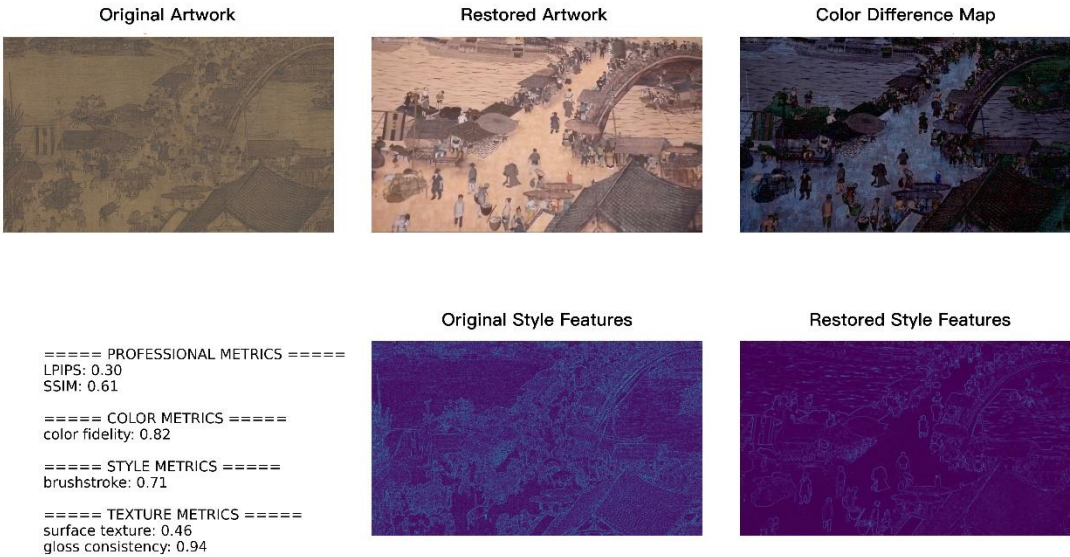


Fig. 11. Algorithm evaluation results of *Along the River During the Qingming Festival* (project E).

Subjective Evaluation

We conducted a questionnaire survey involving 50 participants—28% from Chinese painting (n=14), 22% from computer science (n=11), 8% from art theory (n=4), 22% from digital media/art technology (n=11), and 20% from other fields (n=10)—to blind-

test and rate five Chinese painting 3D digitalization projects.

Blind test results showed that our *Eight Flowers* reproduction achieved the highest misidentification rate (38%), indicating strong “fooling” ability. The average confidence for these judgments was 62.5% (M=2.5/4.0), lower than for other projects (B: 69%, M=2.76; C: 61%, M=2.44; D: 73%, M=2.92; E: 81.5%, M=3.26), suggesting closer visual resemblance to the original.

Multidimensional scores (Fig. 12) provided further evidence. Using a 5-point Likert scale and paired-sample t-tests, our project (A) outperformed all others across six evaluation dimensions ($p < 0.001$). Compared to the next best (C), it showed significant advantages in color fidelity ($t(49) = 3.92, p < 0.001$), brushstroke naturalness ($t(49) = 2.87, p = 0.006$), and overall satisfaction ($t(49) = 4.35, p < 0.001$).

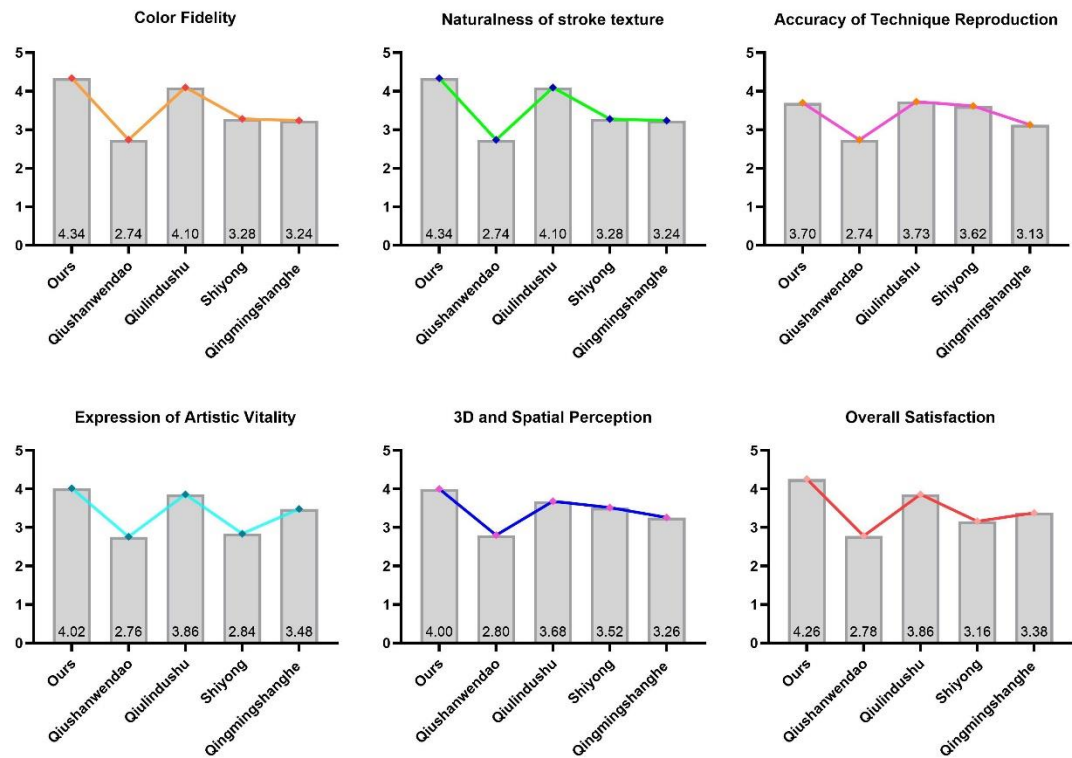


Fig. 12. Multi-dimensional questionnaire evaluation results.

We also collected qualitative feedback from professional audiences, including students and practitioners in Chinese painting and computer science. In the blind test for “best-performing work,” 34% (n=17) of respondents selected our *Eight Flowers*

reproduction as the most faithful (Project B: n=2; C: n=5; D: n=6; E: n=4; 16 gave no clear choice). Supporters highlighted its strengths in “color and form fidelity,” noting that the “brushstrokes are close, the colors soft, and the spirit matches the qualities of Song paintings.” Others praised its “comfortable color and modeling with a strong Chinese painting aura, almost without mechanical feeling,” and emphasized its effectiveness in reproducing core *gongbi* techniques such as “texture rendering” and “layered washes,” which contributed to a convincing artistic atmosphere.

Despite this recognition, some respondents pointed to areas for improvement, particularly in brushstroke naturalness and detail richness: comments included “brushstrokes lack expressiveness,” “leaves and petals appear too uniform,” and “leaf veins lack liveliness, lines are overly rigid.” These critiques align with the quantitative evaluation, where brushstroke naturalness scored $M=3.94$, indicating room for improvement. Respondents suggested enhancing brush-based dynamic simulation (AL_BR algorithms) to improve artistic expressiveness.

When asked about the standards for an “ideal Chinese painting 3D digitalization,” participants frequently stressed balancing *qi yun* (spirit resonance), naturalness of color and brushwork, and fidelity to the original aesthetic qualities. They agreed that digitalization should not pursue an “excessively technological or three-dimensional appearance,” but instead aim to “faithfully preserve artistic characteristics of the original,” while avoiding results perceived as “oily,” “rigid,” or “mechanical.” Notably, multiple respondents explicitly stated that “digital technology should serve artistic intention rather than dominate creation,” a view consistent with our study’s core principle of Artist-in-the-Loop.

Based on the above multidimensional evaluation, the comprehensive results are summarized in **Table. 6**. (All scores are normalized to the 0–1 range, with higher values indicating better performance.)

Table. 6. Comprehensive evaluation results.

Indicators	Objective Indicators			Subjective Indicators
	LPIPS	SSIM	Multidimensional Evaluation System	
A: <i>Eight Flowers</i>	0.55	0.74	0.93	0.77
B: <i>Inquiring of the Dao in Autumn Mountains</i>	0.29	0.33	0.68	0.44
C: <i>Reading in an Autumn Grove</i>	0.57	0.49	0.85	0.71
D: <i>Ten Ode Scroll</i>	0.45	0.67	0.67	0.51
E: <i>Along the River During the Qingming Festival</i>	0.31	0.61	0.73	0.57

Discussion

Significance of the Technique–Algorithm Mapping Framework

The proposed technique–algorithm mapping framework proved both rational and applicable. *Gongbi*’s feature of “color within lines, lines within color” was reproduced through contour rendering with fractal-disturbance coloring, while *xieyi*’s brushstroke randomness and ink diffusion were captured via physics-based simulation and brush models. *Mogu*’s “line-free, color-focused” style benefited from color stratification and texture mapping for natural transitions.

By translating artistic techniques into algorithmic modules, the framework overcomes the difficulty of digitally formalizing painting methods and establishes a clear link between algorithms and artistic semantics. Although validated mainly on *Eight Flowers*, its structured design is extensible to other genres such as landscapes and figure painting, making it a reusable foundation for broader digitalization research.

Layered Digitalization Process

The proposed “outlining–coloring–texture–spatial depth” layered process effectively reproduced the stylistic features of Chinese painting in the *Eight Flowers* case. Outlining used contour extraction based on normal–view relationships with fractal disturbance to simulate the liveliness of *gongbi* lines. Coloring applied layered shading and texture mapping, producing natural transitions aligned with *mogu*’s “color-forming” principle. Texture was enhanced through simulated xuan paper fibers and pigment

diffusion, while spatial depth was reinforced with Fresnel-based edge enhancement, highlighting the layered space typical of Chinese painting.

Compared with 2D style transfer, this workflow offers finer control and avoids stylistic rigidity; compared with conventional 3D rendering, it balances local detail and overall style through layered parameters. Crucially, the artist-in-the-loop mechanism allows intervention during outlining and coloring, ensuring outcomes that align with both technical fidelity and artistic authenticity.

Validation through a Multi-Dimensional Evaluation System

The multi-dimensional evaluation system effectively verified both the authenticity and artistic consistency of the proposed method. Objectively, LPIPS and SSIM indicated high similarity between generated images and the original. LPIPS (with VGG features) aligned well with human perceptual differences, while SSIM performed strongly on structural consistency but was less sensitive to color and brushstroke detail. Subjective evaluations confirmed this gap: participants rated color layering and brushstroke subtlety higher than objective metrics suggested. Blind tests further showed that about one-third of generated results were misidentified as originals, underscoring the method's strong visual authenticity.

In sum, the alignment between objective and subjective trends, combined with “original-level” misidentifications, demonstrates the system's reliability in validating digital reproduction. These results highlight that cultural heritage digitalization requires both objective and subjective measures to fully capture artistic realism and aesthetic value.

Application Value and Future Potential

The proposed technique—algorithm mapping framework and layered workflow extend beyond the *Eight Flowers* case and can be applied to other genres and materials. For landscape painting, adjusting the void–solid layer and ink diffusion algorithms can better capture spatial depth and natural gradation; for figure painting, emphasizing

588 outlining and coloring highlights fabric textures and facial details. While this study
589 focused on paper and silk, the framework can also adapt to murals and other substrates
590 by incorporating corresponding texture and optical modeling.

591 In practice, the method provides a new technical pathway for cultural heritage
592 preservation and high-fidelity digital archiving. Integrated into virtual display
593 environments, it can enhance interactive exhibitions in digital museums, offering
594 viewers more immersive experiences. In art education, it serves as a teaching aid to
595 illustrate stylistic differences and allow learners to simulate traditional painting
596 processes in digital settings.

597 **Limitations and Future Directions**

598 Despite its promising results, this study has several limitations. First, the experiment
599 focused solely on *Eight Flowers*, limiting the scope and making it difficult to fully
600 assess applicability across diverse subjects and styles. Future work will extend the
601 framework to landscapes, figure paintings, and murals for broader validation. Second,
602 the rendering process insufficiently modeled the physical–optical properties of
603 pigments and paper/silk, such as the gloss of mineral pigments and the scattering of
604 xuan paper fibers. Incorporating physically based rendering models could improve
605 material realism. Third, the subjective evaluation involved a relatively small and
606 homogeneous participant group, which may affect robustness. Expanding sample size,
607 engaging participants from varied disciplines, and integrating multimodal data (e.g.,
608 eye-tracking, perceptual experiments) will enhance reliability and generalizability.
609 Addressing these limitations will refine the method and strengthen its role in the digital
610 preservation and dissemination of Chinese painting.

611 **Conclusion**

612 This study addresses the challenge of digitally reproducing Chinese painting techniques
613 by proposing a technique–algorithm correspondence framework for 3D digitalization.
614 Using Qian Xuan’s *Eight Flowers* as a case study, we mapped traditional methods such

as *gongbi*, *xieyi*, and *mogu* to NPR algorithms and implemented a layered workflow of “outlining–coloring–texture–spatial depth.” The results effectively reproduced brushstroke characteristics and spatial hierarchy. Evaluation with objective metrics (LPIPS, SSIM) and subjective tests confirmed high fidelity in color, stroke detail, and overall visual consistency. The method provides a reusable technical path for 3D digitalization of Chinese painting and offers new perspectives for heritage conservation, virtual exhibition, and art education. Future work will extend to diverse genres and materials, incorporating real-time rendering and knowledge-base integration for broader application.

Data availability

The data supporting the present study are available from the authors, but the availability of these data is restricted and so are not publicly available. Data are, however, available from the corresponding authors upon reasonable request.

Reference

- [1] Raimo, N., De Turi, I., Ricciardelli, A. & Vitolla, F. Digitalization in the cultural industry: evidence from Italian museums. *Int. J. Entrep. Behav. Res.* 28, 1962–1974 (2022).
- [2] Yang, X. Application of digital media technology in animation design. *Int. Conf. on Multi-modal Information Analytics*, 947–951 (Springer, Cham, 2022).
- [3] Xie, J., Zheng, H., Lin, J. & Tang, X. Digital gamification design of Chinese landscape painting based on gesture interaction. *Int. Conf. on Human-Computer Interaction*, 127–142 (Springer, Cham, 2024).
- [4] Jin, S., Fan, M., Wang, Y. & Liu, Q. Reconstructing traditional Chinese paintings with immersive virtual reality. *Extended Abstracts of the CHI Conf. on Human Factors in Computing Systems*, 1–8 (2020).
- [5] Shih, N. J. AI- and AR-assisted 3D reactivation of characters in paintings. *Heritage* 8, 207 (2025).
- [6] He, Q. & Kosenko, D. Application and innovation of digital exhibition design in the dissemination of Chinese intangible cultural heritage. *Art Des.* 4, 11–21 (2024).
- [7] Winkenbach, G. & Salesin, D. H. Computer-generated pen-and-ink illustration. *Proc. 21st Annu. Conf. Comput. Graph. Interact. Tech.*, 91–100 (1994).
- [8] Zong, B. *Meixue Sanbu* [A Walk in Aesthetics], 82–99 (Shanghai People's Publishing House, 1981).
- [9] Ackerman, A., Auwaerter, J., Foulds, E., Page, R. & Robinson, E. Cultural landscape visualization: the use of non-photorealistic 3D rendering as an analytical tool to convey change at Statue of Liberty National Monument. *J. Cult. Herit.* 62, 396–403 (2023).
- [10] Yan, M., Wang, J., Shen, Y. & Lv, C. A non-photorealistic rendering method based on Chinese ink and wash painting style for 3D mountain models. *Herit. Sci.* 10, 1 (2022).

- 654 [11] Qin, Y. S. Research on non-photorealistic rendering based on texture mapping.
655 Master's thesis, Sichuan Fine Arts Institute (2023).
656 <https://doi.org/10.27344/d.cnki.gscmc.2023.000171>
- 657 [12] Gatys, L. A., Ecker, A. S., Bethge, M., Hertzmann, A. & Shechtman, E.
658 Controlling perceptual factors in neural style transfer. *Proc. IEEE Conf. Comput. Vis.*
659 *Pattern Recognit.*, 3985–3993 (2017).
- 660 [13] Yao, Z., Sun, Q., Liu, B., Lu, Y., Liu, G., Yang, X. D. & Mi, H. InkBrush: A
661 sketching tool for 3D ink painting. *Proc. CHI Conf. Hum. Factors Comput. Syst.*, 1–15
662 (2024).
- 663 [14] Li, M., Hsiao, T. C. & Chen, C. C. Exploring the factors of cooperation between
664 artists and technologists in creating new media artworks: based on AHP. *Sustainability*
665 12, 8049 (2020).
- 666 [15] Zhang, Y. & Candy, L. Investigating interdisciplinary collaboration: case studies
667 in art and technology. *Proc. 3rd Int. Conf. on Qualitative Research in IT and IT in*
668 *Qualitative Research (QualIT 2006)* (2006).
- 669 [16] Luo, X. On the intrinsic connection between Zhang Daqian's splash-ink and
670 splash-color painting and Western abstract expressionism. *Zhonghua Wenhua Luntan*
671 9, 92–95 (2014).
- 672 [17] Zhou, F. & Wang, Y. Re-exploration of the relationship between Zhang Daqian's
673 splash-ink/splash-color painting and Western abstract art. *J. Neijiang Normal Univ.*
674 33(7), 34–37 (2018). <https://doi.org/10.13603/j.cnki.51-1621/z.2018.07.007>
- 675 [18] Xu, S. *Song Dynasty Painting History* (Renmin Meishu Chubanshe, 2008).
- 676 [19] Ye, H. On the form and connotation of Chinese baimiao painting. *Beauty and*
677 *Times (Middle Edition)* 1, 4–8, 154 (2025).
678 <https://doi.org/10.16129/j.cnki.mysdz.2025.01.043>
- 679 [20] Cui, X. Chinese traditional painting baimiao and its application. *Beauty and Times*
680 *(Middle Edition)* 3, 8–9 (2019). <https://doi.org/10.16129/j.cnki.mysdz.2019.03.003>

- 681 [21] Sun, E. *Research on Splash-Ink Painting*. Master's thesis, China National
682 Academy of Arts (2010).
- 683 [22] Yang, X. *Study on the use of brush and ink techniques in Song dynasty landscape*
684 *painting*. Master's thesis, Shenyang Normal University (2020).
685 <https://doi.org/10.27328/d.cnki.gshsc.2020.000733>
- 686 [23] Zhang, Q. *The origin of mogu method and contemporary characteristics of mogu*
687 *flower-and-bird painting*. Master's thesis, Jiangsu Normal University.
- 688 [24] Wu, Z. Reconstruction of the modernity of ink painting: the path of Sino–Western
689 aesthetic fusion in Wu Guanzhong's art. *Meishu Wenxian* 8, 86–88 (2025).
690 <https://doi.org/10.16585/j.cnki.mswx.2025.08.024>
- 691 [25] Yang, J. On the artistic authenticity of contemporary realist ink figure painting.
692 *Meishu* 9, 146–147 (2021). <https://doi.org/10.13864/j.cnki.cn11-1311/j.006511>
- 693 [26] Lin, J. Returning to nature: Tian Liming's new expressionist ink practice.
694 *Zhongguo Meishu Yanjiu* 1, 138–144 (2023).
- 695 [27] The contemporaneity of “New Gongbi” painting: a discussion on my bird-and-
696 flower creations. *Meishu Guancha* 10, 132–133 (2019).
- 697 [28] Pan, Z., Yuan, Q., Chen, S. & Zhang, M. Research and progress on digital display
698 and interactive technologies for cultural heritage. *J. Zhejiang Univ. (Sci. Ed.)* 47(3),
699 261–273 (2020).
- 700 [29] Liu, K. The crossover of museum traditional cultural art resources and games: a
701 case study of the mobile game *Painting the True—Miao Bi Qian Shan*. *Bowuyuan* 5,
702 123–130 (2020).
- 703 [30] Winkenbach, G. & Salesin, D. H. Computer-generated pen-and-ink illustration.
704 *Proc. 21st Annu. Conf. Comput. Graph. Interact. Tech.*, 91–100 (1994).
- 705 [31] Zhang, Q., Sato, Y., Takahashi, J. Y., Muraoka, K. & Chiba, N. Simple cellular
706 automaton-based simulation of ink behaviour and its application to Suibokuga-like 3D
707 rendering of trees. *J. Vis. Comput. Animat.* 10(1), 27–37 (1999).

- 708 [32] Chan, C., Akleman, E. & Chen, J. Two methods for creating Chinese painting.
709 *Proc. 10th Pacific Conf. Comput. Graph. Appl.*, 403–412 (IEEE, 2002).
- 710 [33] Yeh, J. W. & Ouhyoung, M. Non-photorealistic rendering in Chinese painting of
711 animals. *J. Syst. Simul.* 14(6), 1220–1224 (2002).
- 712 [34] Way, D. L., Lin, Y. R. & Shih, Z. C. The synthesis of trees in Chinese landscape
713 painting using silhouette and texture strokes. *Proc. WSCG* 10(3), 499–507 (2002).
- 714 [35] Dietrich, A., Gobbetti, E. & Yoon, S. E. Massive-model rendering techniques: a
715 tutorial. *IEEE Comput. Graph. Appl.* 27(6), 20–34 (2007).
- 716 [36] Sun, M. et al. Multi-layer rendering based Chinese Ink-Wash Painting styled 3D
717 generation. *Proc. 2nd Int. Conf. Inf. Sci. Eng.*, IEEE (2010).
- 718 [37] Yan, M., Wang, J., Shen, Y. & Lv, C. A non-photorealistic rendering method based
719 on Chinese ink and wash painting style for 3D mountain models. *Herit. Sci.* 10, 186
720 (2022).
- 721 [38] Yao, Z., Sun, Q., Liu, B., Lu, Y., Liu, G., Yang, X. D. & Mi, H. InkBrush: A
722 sketching tool for 3D ink painting. *Proc. 2024 CHI Conf. Hum. Factors Comput. Syst.*,
723 1–15 (2024).
- 724 [39] Liu, S. Chinese Ink-and-Brush Painting with Film Lighting Aesthetics in 3D
725 Computer Graphics. *Doctoral dissertation* (2015).
- 726 [40] Yu, J. Notes on Chinese painting techniques: “All phenomena under the brush,
727 myriad images in the mind.” *Meishu Zhi You (Friends of Fine Arts)* 1, 25–28 (2007).
- 728 [41] Wang, X. *From Material to Concept*. Master’s thesis, Northeast Normal
729 University (2016).
- 730 [42] Yang, Y. *Research and creative practice on color composition in contemporary
731 mogu flower-and-bird painting*. Master’s thesis, Sichuan Normal University (2024).
732 <https://doi.org/10.27347/d.cnki.gssdu.2024.000298>
- 733 [43] Song, X. *Research on the tradition and modern development of gongbi painting*.
734 Master’s thesis, Central Academy of Fine Arts (2008).

735 [44] Chang, X. *Study on the evolution of coloring techniques in ancient blue-and-green*
736 *landscape painting*. PhD thesis, China National Academy of Arts (2017).

737 [45] Ren, J. Innovation and integration of gongbi and mineral-pigment rock painting
738 materials and techniques. *Meishu Jiaoyu Yanjiu (Art Education Research)* 18, 16–18
739 (2023).

740 [46] Cai, J. *On the water-and-powder collision method of Ju Chao and Ju Lian*. PhD
741 thesis, China National Academy of Arts (2012).

742 [47] Lin, R. The modern significance of mogu. *Meishu Guancha (Fine Arts*
743 *Observation)* 4, 38–44 (2004).

744 [48] Yin, S. *A study on the origins of bird-and-flower freehand painting in the Ming*
745 *dynasty*. PhD thesis, Central Academy of Fine Arts (2011).

746 [49] Liu, A. *Research and creative application of gongbi flower-and-bird painting*
747 *techniques in the Song dynasty*. Master's thesis, Shandong University of Arts (2023).
748 <https://doi.org/10.27281/d.cnki.gsdyc.2023.000236>

749 [50] Bian, J. Aesthetic implications of brush-and-ink techniques in Song dynasty
750 freehand landscape painting. *Yishu Pingjian (Art Evaluation)* 23, 63–68 (2023).

751 [51] Fu, J. & Liu, C. Analysis of the technical language of freehand brush-and-ink.
752 *Taoci Kexue Yu Yishu (Ceramic Science and Art)* 58(3), 68–69 (2024).
753 <https://doi.org/10.13212/j.cnki.csa.2024.03.056>

754 [52] Li, K. Modern mogu and splash painting: my artistic exploration and practice.
755 *Meishu Guancha (Fine Arts Observation)* 8, 25–26 (1996).

756 [53] Li, Q. The relationship between traditional mogu painting techniques and
757 calligraphic brush use. *Tiangong* 14, 57–59 (2024).

758 [54] Hui, S. *Performance and techniques of traditional Chinese pigments*. Master's
759 thesis, Shanxi Normal University (2010).

760 [55] Zhao, Q. *A historical outline of painting techniques, materials, and tools in ancient*
761 *Chinese art*. PhD thesis, China National Academy of Arts (2001).

762 [56] Liu, J. The connotation and application of Chinese painting techniques. *Meishu*
763 *(Fine Arts)* 5, 72–78 (2013). <https://doi.org/10.13864/j.cnki.cn11-1311/j.2013.05.015>

764 [57] Liu, L. The evolution of techniques in Chinese heavy-colored figure painting.
765 *Meishu Yanjiu (Art Research)* 1, 71–76 (1979).

766 [58] Yue, X. *The application of water-and-powder collision method in contemporary*
767 *gongbi figure painting*. Master's thesis, Yan'an University (2024).
768 <https://doi.org/10.27438/d.cnki.gyadu.2024.000382>

769 [59] Kumar, M. P., Poornima, B., Nagendraswamy, H. S. & Manjunath, C. A
770 comprehensive survey on non-photorealistic rendering and benchmark developments
771 for image abstraction and stylization. *Iran J. Comput. Sci.* 2, 131–165 (2019).

772 [60] Strothotte, T. & Schlechtweg, S. *Non-photorealistic computer graphics: modeling,*
773 *rendering, and animation*. Morgan Kaufmann (2002).

774 [61] Wang, J., Shen, Y. & Ding, W. A method for ink-wash painting rendering for 3D
775 scenes. *Proc. Int. Joint Conf. Inf. Media Eng. (ICIME)*, 205–210 (2018).

776 [62] Sander, P. V., Wood, Z. J., Gortler, S., Snyder, J. & Hoppe, H. Multi-chart
777 geometry images. (2003).

778 [63] Müller, M., Charypar, D. & Gross, M. Particle-based fluid simulation for
779 interactive applications. *Proc. SIGGRAPH/Eurographics Symp. Comput. Anim.*, 154–
780 159 (2003).

781 [64] Xu, S., Lau, C. F., Xu, C. & Pan, Y. Virtual hairy brush for digital painting and
782 calligraphy. *Sci. China Ser. F Inf. Sci.* 48, 285–303 (2005).

783 [65] Mochizuki, K. et al. Multispectral reflection measuring and rendering method for
784 silk textiles. *J. Silk Sci. Soc. Jpn.* 23, 17–26 (2015).

785 [66] Gatys, L., Ecker, A. S. & Bethge, M. Texture synthesis using convolutional neural
786 networks. *Adv. Neural Inf. Process. Syst.* 28 (2015).

787 [67] Tomasi, C. & Manduchi, R. Bilateral filtering for gray and color images. *Proc. 6th*
788 *Int. Conf. Comput. Vis.* 839–846 (1998).

- 789 [68] Way, D. L. & Shih, Z. C. The synthesis of rock textures in Chinese landscape
790 painting. *Comput. Graph. Forum* 20(3), 123–131 (2001).
- 791 [69] Tomasi, C. & Manduchi, R. Bilateral filtering for gray and color images. *Proc. 6th*
792 *Int. Conf. Comput. Vis.* 839–846 (1998).
- 793 [70] Burt, P. J. & Adelson, E. H. The Laplacian pyramid as a compact image code. In
794 *Readings in Computer Vision* 671–679 (Morgan Kaufmann, 1987).
- 795 [71] Lee, J. Physically-based modeling of brush painting. *Comput. Netw. ISDN Syst.*
796 29(14), 1571–1576 (1997).
- 797 [72] Zhang, R., Isola, P., Efros, A. A., Shechtman, E. & Wang, O. The unreasonable
798 effectiveness of deep features as a perceptual metric. *Proc. IEEE Conf. Comput. Vis.*
799 *Pattern Recognit.* 586–595 (2018).
- 800 [73] Wang, Z., Bovik, A. C., Sheikh, H. R. & Simoncelli, E. P. Image quality
801 assessment: from error visibility to structural similarity. *IEEE Trans. Image Process.*
802 13(4), 600–612 (2004).

Author contributions

M.Y. contributed to the conception and design of the study, conducted the literature review, user interviews, data analysis, and manuscript writing. W.Z. contributed to the algorithm development, data analysis, and manuscript writing.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Competing interests

The authors declare no competing interests.