Ink Wash Painting Style Rendering With Physically-based Ink Dispersion Model

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Abstract. This paper presents a real-time rendering method based on the GPU programmable pipeline for rendering the 3D scene in ink wash painting style. The method is divided into main three parts: First, render the ink properties of 3D model by calculating its vertex curvature. Then, cached the ink properties to a paper structure and using an ink dispersion model which is defined by referencing the theory of porous media to simulate the dispersion of ink. Finally, convert the ink properties to the pixel color information and render it to the screen. This method has a better performance than previous methods in visual quality.

1. Introduction
Ink wash painting is a traditional East Asian type of brush painting style originating in China that only uses black ink in various concentrations. By controlling the proportion of water and ink and the strength of the pen, artists can use different shades of black colour to painting different scenes on the rice paper. This artistic form can perform distinctive visual effect and unique aesthetic features of orientalism, meanwhile possess an irreplaceable position and incalculable value in Chinese art history.

The ink wash painting style is a demanding art-form requiring great skill, concentration, and years of training. In the 1960s, Shanghai Animation Film Studio produced a series of Chinese ink wash style animated film such as "Baby Tadpoles Look for Their Mother" and "Mu Di", which were highly praised worldwide and received many awards. However, because of the dispersion of ink on the rice paper is difficult to control, it takes a lot of time to make an ink wash style animated film. A 20 minutes ink wash style animated film usually takes 2 years to be completed. At present, with help of technologies such as 3D rendering and digital effects, the working process can be reduced to a few months. Therefore, this paper endeavor to develop a real-time system in order to improve the efficiency for producing ink wash paintings style animations. For real-time ink wash painting style rendering, the game "Okami" by CAPCOM is a very representative piece of work which realizes the real-time rendering of Japanese ink wash painting style through contour rendering and texture mapping techniques. Yuan et al.[1] and Cao[2] also provided Chinese ink painting real-time rendering systems. However, these techniques have a poor performance on simulating the ink diffusion effect, which is an important defect for these simulate system because of it neglects some significant artistic features.

The method proposed in this paper aims to improve the ink diffusion effect caused by the ink dispersion in the rice paper and the colour sense of ink due to the change of ink and water concentration. The paper will focus on the dispersion model in section 3, including paper structure, ink properties and specific algorithms of dispersion simulation. The ink wash painting style rendering
method is introduced in section 4. The experiment results and conclusion is presented in section 5 and section 6.

2. Related work
For the ink wash painting simulation, Chu and Tai[3] proposed a fluid model based on Lattice Boltzmann Equation (LBE) to simulate the diffusion of ink on rice paper in real time. Way et al.[4] and Sun et al.[5] also proposed and improved the physically-based approach to simulate ink diffusion. These approaches are more suitable for real-time ink wash drawing system but too inefficient for 3D real-time rendering engines. Dong et al.[6] presented an image processing approach to render the picture to the Chinese ink painting style in real-time. Xie et al.[7] achieved an image-based ink wash painting style rendering system by converting the extracted abstract stroke of the photo with predefined ink wash stroke texture. However, the process of stroke extraction requires some user interaction to assist manually, which makes it difficult to realize in real-time rendering. Yang et al.[8][9] proposed a paper-ink simulating model based on porous media and capillary mechanism for simulating ink dispersion in rice paper, which is fast in convergence and suited to take advantage of the GPU's parallel processing features to improve performance for real-time rendering.

For 3D ink wash painting style Rendering, Chan et al.[10] reconstructed the 3D object to generate a 3D geometric model that is specially used for ink wash painting style rendering, use for combined with illumination, viewpoint and other information to simulate the contour, fly white and other techniques of drawing ink wash painting. Tianchen Xu et al.[11] established a particle form of the stroke model, through the stroke model fetch the information from the silhouette of 3D model and then transform into ink brush strokes. Yuan et al.[1] presented a GPU-based real-time ink wash painting rendering system, which proposes a rendering framework for real-time ink wash painting style rendering, and provides a basis for the application of ink wash painting style rendering. Cao[2] summary the techniques of real-time rendering that can be used to Chinese ink painting rendering, and provided an improved rendering system for Chinese ink painting rendering.

This paper mainly refers to the rendering framework of Yuan et al. [1] and combine with the ink dispersion simulation method proposed by Yang et al.[8][9] to propose a real-time ink wash painting style rendering method based on physically-based ink dispersion model.

3. Physically-based ink dispersion model
According to the paper-ink simulating model proposed by Yang et al.[9], rice paper is abstracted into a two-dimensional finite element group consisting of anisotropic capillary tubes, as same as dividing a piece of rice paper into numerous square grids. Each grid corresponds to an element that contains many capillary tubes called paper cells. As shown in figure 1(a), grid i is called a paper cell, and in, ie, is, iw is the adjacent paper cells of i. The main procedure of ink dispersion simulation includes ink adding on the surface of the paper, the ink penetrating into the paper from the paper surface, and the ink dispersing between adjacent paper cells.

Figure 1. (a) Paper cell i and its surrounding paper cells (b) Paper structure and ink properties
3.1. Paper structure and ink properties
For simulating the dispersion of ink in rice paper, this paper defines a double layer rice paper structure which is used to store the ink properties. The paper structure consists of a surface layer and a paper layer. The surface layer is used for recording the ink properties on the rice paper surface. The paper layer is used for recording ink properties in the rice paper. The ink properties stored in the surface layer include the ink volume on the surface and the quality of carbon in the ink on the surface. The ink properties stored in the paper layer include the ink saturation in the paper cell and the quality of carbon in the ink in the paper cell. The paper structure is represented by a render target texture, with a pixel represents a paper cell, and the ink properties are stored as RGBA value, as shown in figure 1(b). Furthermore, the properties of rice paper are also defined, including the diffuse color of paper and porosity of the rice paper. The porosity is a fraction of the volume of voids over the total volume of the paper cell, between 0 and 1. The diffuse color and porosity of rice paper are represented by two texture map respectively, as shown in figure 2.

![Image](3.1. Paper structure and ink properties)

**Figure 2.** (a) Diffuse color texture of rice paper (b) Porosity texture of rice paper

3.2. Paper penetration
Paper penetration describes the process of ink flowing into the interior of paper from the surface of rice paper. When a drop of ink drops on the surface of the paper cell $i$, it gradually flows into the inside of paper from the surface, the flow rate is influenced by ink density, gravity, the porosity of paper cell $i$, and the kinetic viscosity of ink:

$$\Delta V_i = \frac{\rho g \phi(i)^2}{3\mu}$$

(1)

Where $\mu$, $g$, $\phi(i)$, $\mu$ denote the ink density, the acceleration of gravity, the porosity of paper cell $i$ and the kinetic viscosity of ink respectively. In order to reduce the calculation error, the kinetic viscosity of the ink is an approximate value influenced by the concentration of ink:

$$\mu = \mu_{water} + \frac{\omega_i}{\omega_{max}}(\mu_{ink} - \mu_{water})$$

(2)

Where $\mu_{water}$ and $\mu_{ink}$ denote the kinetic viscosity of pure water and pure ink respectively, which are defined by the real measurement. $\omega_i$ is the concentration of ink on the surface of paper cell $i$. $\omega_{max}$ is maximum dilution concentration of ink defined by the user. If the concentration of ink is greater or equal to the $\omega_{max}$, it means that the kinetic viscosity of the ink can be equivalent to water.

3.3. Dispersion in the paper
Dispersion in the paper is the process of transferring the ink in the paper cell to the adjacent paper cell. When a paper cell $i$ containing ink and has no ink in its adjacent paper cell $j$, like the boundary area of an ink stroke, the paper cell $i$ in the ink will be transferred to the paper cell $j$. With the ink transferring, the boundaries of the ink will expand and form a diffusion effect. The rate of ink transferring from paper cell $i$ to paper cell $j$ is calculated by the equation as follow:
\[ Q_{ij} = \begin{cases} 0 & S_i < S_j, \\ -\frac{\Phi(i)^2}{\mu} (S_i - S_j) & S_i \geq S_j, \end{cases} \]  

(3)

Where \( S_i \) and \( S_j \) are the ink saturation in the paper cell \( i \) and paper cell \( j \) respectively, \( S_t \) is a constraint threshold value. When the ink saturation in paper cell \( i \) is lower than \( S_t \), the ink in the paper cell \( j \) no longer transfers to the adjacent paper cell. As a threshold, the size of \( S_t \) determines the ink's ability of diffuse. According to the actual observation, it can be found that different concentrations of ink have different diffusion on rice paper. Depending on the concentration of ink in each paper cell, the threshold will also be different. the \( S_t \) is calculated by the equations as follow:

\[ S_t = S_{water} + e^{-\omega_{mean}} (S_{ink} - S_{water}) \]  

(4)

\[ \omega_{mean} = \frac{\omega_i S_i + \omega_j S_j}{S_i + S_j} \]  

(5)

\[ \omega_i = \frac{\rho_{ink} V_i}{m_i} - 1 \]  

(6)

\[ V_i = \Phi(i) V_{cell} S_i \]  

(7)

Where \( S_{water} \) and \( S_{ink} \) denote the constraint threshold value of pure water and pure ink respectively, which are defined by the user. \( V_i \) and \( V_{cell} \) are the volume of voids in paper cell \( i \) and the total volume of paper cell respectively.

4. Ink wash painting style rendering

This section mainly introduces the ink wash painting style rendering system. The detailed rendering framework is described in section 4.1 and illustrated in figure 3.

4.1. Rendering framework

The framework of the rendering method in this paper extends on the basis of the method of Yuan et.al[1] that adds an image processing shader as an additional step by utilizing programmable GPU vertex and fragment shaders. The rendering method mainly consists of three parts, including interior shading, dispersion simulation and final output.

**Figure 3. Rendering process**

In the part of interior shading, at the first utilizing a vertex and fragment shader to render the curvature of 3D objects and then convert the curvature into the ink properties. The ink properties will be cached into a render target texture which is delivered to next stage.
In the part of dispersion simulation, the procedure of dispersion will be simulated in fragment shader that is used for image processing. There are four passes to process the steps of dispersion simulation as shown in figure 3. First, read the ink properties from the render target texture which is delivered from the last stage, and add them to a render target texture for the paper structure which is defined in section 3.1. Second, input the paper structure to the ‘Penetration Simulate’ pass which is used to simulate the penetration and described in section 3.2. Then, output the results to the paper structure and input the paper structure to the ‘Dispersion Simulate’ pass which is used to simulate the dispersion and described in section 3.3. The result of dispersion simulation which is the volume of ink that stream between the paper cell and its adjacent paper cells is cached in a render target texture for an ink flow buffer. Finally, input the buffer and paper structure to the ‘Update Ink Properties’ pass to update the value of ink properties in the paper structure. In order to present the color sense of ink and the different diffusion effects due to the different ink concentrations, we add ink properties in five times according to the five levels of the quantized curvature. The lightest ink properties are added to the surface layer in first, after a certain number of iterations, the next level of ink properties are added. When all level of ink is finish simulated, the final result of ink properties will be cached into the render target texture for paper structure and delivered to next stage.

In the last part, the ink properties of paper structure are transformed to the pixel color information and rendered to screen.

4.2. Interior shading and color transform
In a general rendering method, the object was usually rendered base on diffuse lighting, such as Lambertian shading. But in our method, the curvature of the model vertices are calculated and mapped to the pixels as color values directly. According to the method proposed by Penner et al.[12], we calculate the vertex curvature value of pixel i by solving the Eqn.(8), the example of calculation result is shown in figure 4.

\[
k_i = \frac{\Delta N}{\Delta P} = \frac{|fwidth(\text{normal})|}{|fwidth(\text{position})|}
\]  

\[
V_{surface} = \begin{cases} 
0 & k_i \leq 0.1 \\
V & k_i > 0.1 
\end{cases}
\]  

\[
m_{surface} = \rho_v V_{surface} \left(1 + \frac{\omega}{k}\right)^{-1}
\]  

\[
k = \begin{cases} 
0.1 & 0.1 < k_i \leq 0.3 \\
0.3 & 0.3 < k_i \leq 0.45 \\
0.45 & 0.45 < k_i \leq 0.6 \\
0.6 & 0.6 < k_i \leq 0.8 \\
0.8 & 0.8 < k_i
\end{cases}
\]
Where \( k_i \) represents the curvature value in pixel \( i \). \( \rho_{\text{ink}} \) is the density of pure ink, \( V \) and \( \omega \) are the volume of ink and the concentration of ink respectively defined by the user. In order to simulate the gradation of ink color, we quantify the curvature to correspond to the five levels of ink color in the ink painting, the part of \( k_i \leq 0.1 \) is blank, which means that no ink is added to this part.

When the calculated ink properties are stored in the surface layer, the dispersion model simulates the diffusion of ink by iterating the process of paper penetration and dispersion. Finally, we convert the ink properties of paper layer to screen pixel color value by solving the equation as follow:

\[
C(i) = 1 - \left(1 + (0.01C_j)^2 \right)^{\frac{1}{2}}
\]  

(12)

5. Experimental results

Our render method is implemented in Unity, and our test machine is equipped with the Graphic Card Nvidia R Geforce GTX1060 and Intel (R) Core (TM2) i5-6300HQ CPUs.

In the experiment, we use vertex and fragment shader to render the model in curvature and simulate ink dispersion in the fragment shader. The render texture is used for the buffer to store and deliver the ink properties during the simulating. The rendering method in this paper is tested with the terrain model generated by terrain editor in Unity.

Figure 5. Mountain rendered in ink wash painting style: the method of Yuan et.al (top); our method(bottom)

Compare the visual quality of our method with the previous method. As shown in the figure 5, the top of the figure is rendered with the method of Yuan et.al[1]. Our result showed on the bottom of the figure comes from this paper. In the simulation of ink diffusion, the effect of ink diffusion generated by our method is more natural, and the color variation of the image is softer. By shading model with the curvature of vertex, our method can show the aesthetic of irregularity in shapes and forms commonly seen in ink wash painting.

Table 1. The performance of rendering method

| Resolution of paper structure | FPS   |
|------------------------------|-------|
| 800×600                      | 120 - 140 |
| 1024×768                     | 75-90  |
| 1280×720                     | 65-80  |
Table 1 present the rendering speed of our method statistics for various resolutions. Because the simulation requires traversing all the pixels of the paper structure, the performance of our method is obviously influenced by the resolution of paper structures.

6. Conclusion and Future works
This paper proposes a physically-based ink dispersion model is proposed. By defining the paper structure model and ink properties, the theory of the porous media and capillary mechanism are used to abstract the flowing of ink in rice paper. Then, explore the method of ink wash painting style rendering by using dispersion model. Finally, utilizing Unity to build a rendering system and test the terrain model to generate some images in ink wash painting style. Comparing with previous method, this method has a better performance on visual quality.

The future work could be focused on the interior shading of 3D models and improves the performance of dispersion models further more expected to combine the method with fluid simulation to improve temporal coherence and generate more artistic effects.

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References
[1] Yuan, M., Yang, X., Xiao, S., & Ren, Z. 2007. GPU-based rendering and animation for Chinese painting cartoon. graphics interface.
[2] Cao, M. 2016. A study of how Chinese ink painting features can be applied to 3D scenes and models in real-time rendering.
[3] Chu, N. S., & Tai, C. 2005. MoXi: real-time ink dispersion in absorbent paper. international conference on computer graphics and interactive techniques, 24(3), 504-511.
[4] Way, D. L., Huang, S. W., & Shih, Z. C. 2003. Physical-based model of ink diffusion in Chinese paintings. Journal of Wscg.
[5] Sun, M., Sun, J., & Yun, B. 2005. Physical Modeling of "Xuan" Paper in the Simulation of Chinese Ink-Wash Drawing. International Conference on Computer Graphics, Imaging and Vision: New Trends (pp.317-322). IEEE.
[6] Dong, L., Lu, S., & Jin, X. 2014. Real-time image-based Chinese ink painting rendering. Multimedia tools and applications, 69(3), 605-620.
[7] Xie, N., Laga, H., Saito, S., & Nakajima, M. 2010. IR2s: interactive real photo to Sumi-e. non-photorealistic animation and rendering.
[8] Yang, Y., Zhu, Q., & Liu, Y. 2015. Simulating water dispersion in Chinese absorbent paper with capillary tubes model. international conference on computer graphics and interactive techniques.
[9] Yang, Y. C. 2016. Research on Temporal coherent oriental ink style 3D rendering. (Doctoral dissertation, Beijing University of Technology).
[10] Chan, C. C., Akleman, E., & Chen, J. 2002. Two methods for creating Chinese painting. pacific conference on computer graphics and applications.
[11] Xu, T., Yang, L., & Wu, E. 2012. Stroke-based real-time ink wash painting style rendering for geometric models. international conference on computer graphics and interactive techniques.
[12] Penner, E., & Borshukov, G. (2011). Pre-Integrated Skin Shading. GPU Pro 2.