Image-based Ink Diffusion Simulation and 3D Chinese Wash-ink Paintings Rendering

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Abstract: - An image-based synthesis method of Chinese wash-ink strokes is proposed in the paper. Wash-ink stroke is divided into two regions: primary stroke region and diffused region. Synthesizing process of diffused region begins from the outline of primary stroke region. At first, the outline of primary region is magnified outward in all directions with the same distance. Then the irregular stroke border is created. To simulate pigment granulation in wash-ink strokes, we make the statistics in colour varieties by hand-painted brush strokes, and add the variety errors on the stroke images. We also construct a nonlinear function to compute the colours in the overlap areas of two overlapped strokes. Based on our image-based synthesis method of wash-ink strokes, we present a novel method to render 3D scenes into wash-ink landscape paintings. The rendering results show that our method can synthesize realistic wash-ink brush strokes, and it is efficient as well.

Key-Words: - Simulation of ink diffusion, 3D wash-ink paintings, Non-photorealistic rendering, Image-based rendering, Synthesizing brush strokes, Synthesize algorithm.

1 Introduction

Wash-ink painting has been a Chinese painting art with very long history. Generally painters use certain traditional painting tool including Chinese painting brush, wash-ink and idiosyncratic Chinese art paper ('XUAN' paper). In comparison with traditional Western brush painting, the Chinese brush is made of soft animal hair and has relatively larger water-holding capacity. Chinese ink is a kind of monochromatic pigment, mainly made up of water and black carbon ink particles. Owing to the differences on quantity of carbon ink particles, various dense and brightness of the ink color are revealed. Traditional Chinese art paper is a type of high natural fiber paper with strong water absorption capacity. The permeation behavior of wash-ink on the paper forms unique diffusion effects of Chinese painting art.

Traditional Chinese wash-ink painting includes two predominate styles as "GONGBI" painting and "XIEYI" painting. GONGBI painting is finely painted with meticulous brushwork, which emphasizes realism on daily life objects. However, "XIEYI" painting is generally painted with rugged brushwork on skeleton structure without details, and does not emphasize on replication of appearance of the relevant objects on paper, but more focus on expression of individual painters' inner emotion and personalized styles, Fig.1 is an example of "XIEYI" Chinese wash-ink painting on landscape.

Fig.1 An example of "XIEYI" Chinese wash-ink painting on landscape.

As a fact, the key skill of Chinese wash-ink painting is the dynamic application of Chinese painting brush and wash-ink. In terms of the application of Chinese wash-ink, there goes an old saying that "Chinese black ink possess five elemental colors"[1], which consists of “dry-ink” (implicating the darkest black color), dense-ink (implicating a very dark black color), thick-ink (implicating a dark black color), light-ink (implicating a light black color) and clear-ink (implicating a very light black color). Those five elemental colors are directly associated with the percentage of water content in the respective wash-ink in an escalating order of increase. Apart from the color variation of wash-ink concerned, their diffusion range on Chinese art paper and luminance of the ink are also related to percentage of water content. Normally the higher percentage of water contains, the larger diffusion area will be, and the lighter ink color will appear in paintings. Painters create large variety of images on paintings by dynamic and flexible uses of wash-ink to produce multiple and special art effects based on wash-ink diffusion on Chinese art paper.

Skill of using ink is the soul of drawing technique for ink wash painting. Therefore, simulation of ink diffusion is main topic of the research on ink wash style rendering. In computer graphics, physical based modeling is the most popular method for ink diffusion simulation[2][3][4]. Nevertheless, the movement mechanism of ink particles on paper is quite complicated, and the method of physical based modeling will make calculation much complex.

In this paper, we intend to establish a high-efficient method for generating brush strokes of wash-ink painting based on experience. Subsequently, we will apply our method to rendering 3D scenes and realized automatic rendering from 3D scenes to wash-ink landscape paintings. Rather to develop an interactive painting system, we aim to convert an image to artistic style of ink wash painting. In comparison with previous works, the highlights of this paper are listed below:

- Based on hand-painted samples, we proposed an efficient algorithm to synthesize ink diffusion effects. Such method can produce the expected results while temporal coherence of synthesized images is maintained.
- A simple non-linear computation method to blend color is given, to realize color blending effects on overlapped regions by multi-brush strokes.
- Using the ink diffusion synthesis method of this paper, we give an image-based rendering method for 3D wash-ink painting, which can automatically generate XIEYI ink wash landscape painting from 3D scenes.

This paper will illustrate the study from the following sections: Section 2 introduces related works about non-photorealistic rendering; Section 3 explains the proposed image-based method of synthesizing ink diffusion effect in detail. Section 4 introduces how to apply our method of synthesizing ink diffusion effect to 3D scenes, and gives the rendering process from 3D scenes into ‘XIEYI’ Chinese landscape paintings. Section 5 discusses advantages and limitations of our rendering method. In Section 6, we give brief summary and possible future directions.

2 Related Works

In the field of non-photorealistic rendering, researchers have proposed various methods for artistic rendering. Among those methods, the most typical one is stroke-based rendering. For example, Way *et al*.[5] used geometrical information of 3D models to control the distribution of strokes, and realized automatically rendering of 3D trees. To mimic an important Chinese drawing technique of “*CUN*” (the method of depicting the texture of rocks and mountains by light ink strokes in traditional Chinese landscape painting), Hsh *et al*. [6] proposed a user controllable method that can generate *CUN* textures, In their study, they successfully simulated two styles of *CUN* textures called "*PIMA CUN*" and "*FUPI CUN*" in Chinese landscape paintings. For rendering based on stroke, Yu *et al.*[7] developed an image-based method to synthesize landscape paintings, and generated mountain texture by texture mapping. In another report, Li[8] proposed a method to rendering Chinese-painting-style lines automatically for 3D scenes. It is necessary to highlight that among those rendering methods, the simulation of stroke textures has been limited due to unavoidable randomness of the stroke textures. It is hard to keep frame-to-frame coherence on stroke textures, so it is impossible to further apply those methods to animation rendering.

In order to maintain temporal coherence of strokes, Xu *et al*. [9] adopted vector strokes to render wash-ink animation. They divided the original wash-ink painting image into multiple stroke regions, and then used vector strokes matching the divided regions to refill these regions. In fact, this method has to be considered as re-draw of the original painting. Although the method was able to realize animation by changing stroke positions or directions, the viewpoint positions to a given painting have been remained unchanged.

For 3D wash-ink animation rendering, Yuan *et al*.[10], and Joo-Hyu *et al*.[11] took different approaches by dividing the rendering process into two separate processes as contour lines drawing and internal shading. These methods can used to render 3D wash-ink animation. Unfortunately, their internal shading methods were too simple to generate realistic effects of ink diffusion.

In non-photorealistic rendering field, research on digital painting system has always been a hot topic. Researchers have established various models of virtual painting brush and pigment for different styles of paintings. Some interesting 3D painting brush models have been reported by Nelson *et al*.[12], Lu *et al*.[13], Wei *et al*.[14] and Xu *et al*.[15] respectively. About pigment models, Cassidy et al [16] gave a three-layer fluid model to simulate watercolor effect. After that, Nelson *et al*.[12] developed a bidirectional, two-layer paint model. Different from the above pigment models mainly to simulate western paintings, simulation of Chinese wash-ink paintings mainly focuses on diffusion and motion behaviors of wash-ink particles on Chinese art paper. Zhang et al [19] studied water and ink particle movements using a simple cellular automaton-based model and applied their method to rendering 3D trees. Huang et al [3] not only studied the movements of water and ink particles but also simulated the "filter effect" occurred when ink particles penetrate in paper fibers. Using a Lattice-Boltzmann equation Nelson et al [2] calculated permeation movement of ink, which realized a real-time rendering of ink diffusion in absorbent paper.

Most available ink diffusion models for the simulation of Chinese wash-ink paintings have computed motion status of water and black carbon particles respectively, resulting rather complex and time consuming processes. Recently, Dong *et a*l.[17] gave a simple non-physical diffusion method and used saliency map to control ink diffusion, but their method cannot maintain temporal coherence. In this paper we give an image-based rendering method. Our method has excluded the fact of ink particle movement (physical behavior) to simplify the modeling calculation and keep the temporal coherence of stroke texture.

In our study, while the proposed method on rendering of 3D wash-ink paintings also takes the advantage of stroke-based rendering principles, our focus is not on rendering of single stroke, but on generating wash-ink effects on the images of whole painting.

3 Synthesizing Brush Strokes

Experimental observation indicated that the types of strokes among the hand-painted wash-ink painting samples can be categorized into two parts - primary stroke area and diffusion area (see Fig.2). Primary stroke area is the region where a painter applied his painting brush onto Chinese art paper. Ink contained in painting brush is transmitted to this region via the direct contact. Penetration of ink from the primary stroke area to the surrounding areas forms diffusion area normally with a ragged boundary. Since the quantity of ink carbon particles decreases gradually during diffusion process, the black ink color tends to attenuate accordingly on paper.

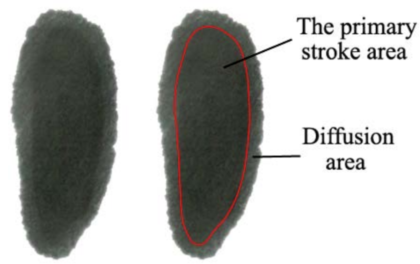


Fig.2 Two wash-ink stroke areas: primary stroke area and diffusion area.

To simulate ink diffusion effect in Chinese paintings, we will consider two key issues in our model: (1) determination of ink color changes on paper, and (2) simulation of ink diffusion area from the primary stroke area. For the first one, we will use an image processing method to mimic pigment granulation. For the second issue, we intend to accomplish ink diffusion process in two steps: formation the main diffusion area, and generation of ragged border area.

3.1 Outline of Rendering Process

The rendering process in this paper has the following three steps: generating main diffusion area of stroke, synthesizing irregular border area around the main diffusion area and adjusting color of strokes according to a selected sample image. Fig.3 shows the flow chart of the proposed rendering process.

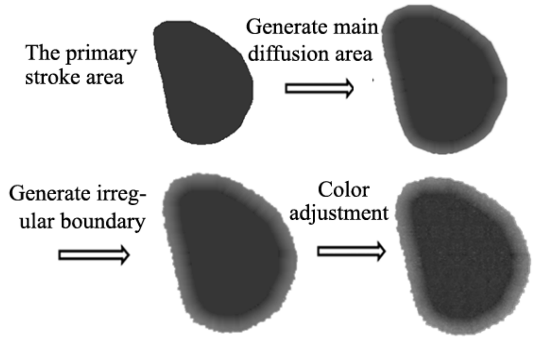


Fig.3 Rendering process of brush strokes of wash-ink on paper.

3.2 Generation of Main Diffusion Area

In the process of forming main diffusion area, we mainly enlarge boundary of the primary stroke area. The enlargement process begins from boundary pixels of the primary stroke area, and then extends gradually outwards to outskirt area with a scheduled changing distance of one pixel every time. During the process, ink quantity of each pixel decreases in consistence with the increase of distance to the primary stroke area (as shown in Fig.4). Ink quantity of current boundary point is calculated as follows:

$$I_p = Average(I_{p_i \in Neighbour}) \times f \quad (1)$$

Where I_p denotes ink quantity of current boundary point p, and *Average( )* is a function of calculating average value; p_i is the boundary point formed in its predecessor enlargement process in the 4-neighboring areas of point p; and f is an attenuation coefficient of ink quantity. For example, in Figure 4, the ink quantity of p is: $I_p = Average(I_{p1}, I_{p2}) \times f$.

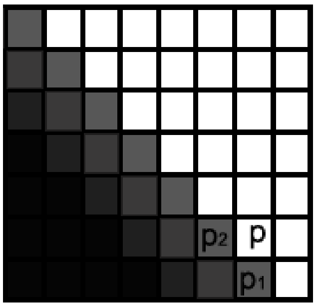


Fig.4 Enlargement process of a primary stroke area to form its main diffusion area.

Assuming integral numbers of 0 to 255 are used to represent different pixel color values, the conversion between the ink quantity I and the color value C of any points can be expressed as:

$$I = 255 - C \tag{2}$$

In our system, d (diffusion distance) and f (attenuation coefficient) are user-adjustable parameters. The value of d can be determined according to paper's absorption capacity and the percentage of water content in the ink used. The value of f can control ink color attenuation speed at diffusion area. By adjusting f, different diffusion effects can be obtained. Fig.5 shows the simulated results under different f values when d = 20.

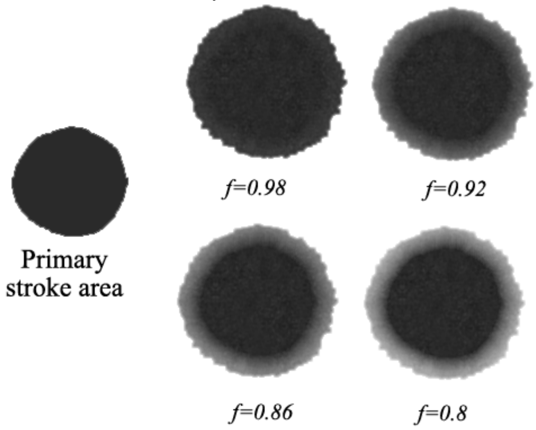


Fig.5 Various diffusion effects obtained under different attenuation coefficients.

3.3 Generation of Irregular Diffusion Boundary Area

At the second stage of ink diffusion, irregular boundary forms around the main diffusion area. Zhang *et al* [18] have adopted a fractal method to generate irregular boundary. However, such method has limitation in maintaining temporal coherence of strokes. Our method shared some principles of the cellular automaton [19]. In order to simplify the computation in this study, we will omit the calculation of movement behavior of water and ink carbon particles. Also water evaporation factor is not counted.

Given that the irregular border of diffusion is commonly simulated based on motion of ink particles in paper, ink diffusion begins from boundary pixel in the main diffusion area, with each pixel regarded as the smallest element of paper structure and the basic unit of absorbing ink[20]. In this paper we assume that every pixel point absorbs ink to some certain proportion from all the boundary points located in its 8-connected neighboring areas (see fig.6). Suppose the maximum absorbable ink quantity of the current pixel point is I_p, the initial ink quantity of the i-th boundary point in its 8-connected neighboring areas is I_i, and the corresponding current remaining ink quantity is I_i' and the whole absorption process is completed after n times of iteration, the ink quantity absorbed from the i-th boundary point at each time is calculated as:

$$\Delta I_i = I_p / n \times proportion \quad (i) \tag{3}$$

$$if\,(I_i' \le I_r) \qquad \Delta I = 0$$
$$if\,(\Delta I_i > I_i' - I_r) \qquad \Delta I = I_i' - I_r$$

Here, I_r represents the residual ink quantity of each boundary point, and it is a constant in our system. When ink quantity of a boundary point is low than I_r, its neighboring point will not absorb ink from it. *Proportion(i)* is absorption ratio of the i-th boundary point. Suppose there are m boundary points in 8-connected neighborhood of the current pixel, the absorption ratio of i-th boundary point is calculated as:

$$proportion(i) = (I_i - I_r) / \sum_{k=1}^{m} (I_k - I_r) \tag{4}$$

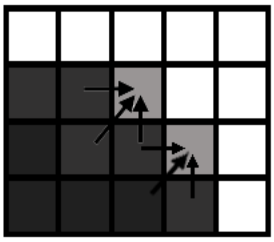


Fig.6 Enlargement process of a point with absorbed ink from all the boundary points in its 8-connected neighborhood.

Since ink diffusion range on paper is directly linked to the percentage of water in ink. The larger percentage of water is, the stronger its diffusion capacity associated with the lighter ink color will be. So the initial ink quantity Ii of each point on the boundary of its primary stroke area can be considered with corresponding value to its color. After each time of diffusion, color values and ink quantity of the new boundary points are calculated via Formula (1) of this paper.

We use an image template of grayscale to represent the density and distribution pattern of natural fibers in Chinese art paper. In the template, each pixel value stands for the maximum ink amount that the pixel point can absorb. Usually, natural fiber distribution pattern in paper is random or irregular with no fixed pattern. Fig.7 is the image template of grey scale used in this article.

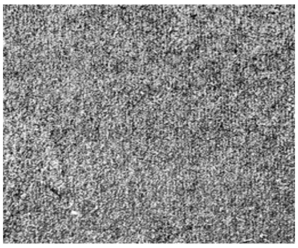


Fig.7 An image template that represents absorption capacity of ink in Chinese art paper.

3.4 Color Modulation

As shown in Fig.2, due to the asymmetrical absorption for ink particles and its uneven or rough surface of Chinese art paper, significant irregular undulation effect occurs in ink colors for the application of each stroke on paper. In order to reproduce such artistic effect, we use a hand-painted sample image to calculate local undulation errors of its colors, and then modulate colors of synthesizing strokes via these error values.

For color modulation purpose, a two-dimensional array was used to store the color variation. Firstly, Gaussian low-pass filtering is applied on the sample images. The color errors are obtained by subtracting the filtered image colors from the sample image colors (as shown in Fig.8). Then add these errors in the array to the corresponding pixels of the strokes. The results may be negative or larger than 255, all negative numbers are defined as 0 and all the numbers over 255 are set to 255.

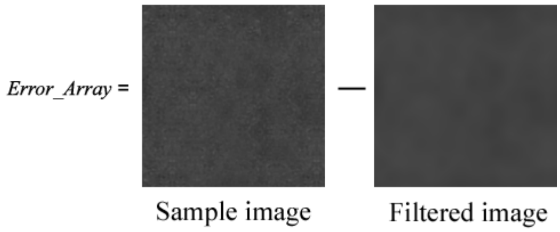


Fig.8 Calculation of color undulation errors.

3.5 Blending Overlapped Strokes

When two strokes are overlapped, ink colors in the overlapped regions may change. If water of a previous stroke has not completely evaporated out and a following stroke is then painted over the same area, ink from the two strokes will be mixed with each other, resulting in numerous color changes for various artistic effects. This is a skill by painters for Chinese paintings, commonly known as "ink breaking" technique. However, when a stroke is painted on a completely dried stroke on paper, due to re-deposit of ink particles, color in the overlapped region may be darkened, which is commonly called as "ink accumulation" technique (Fig.9). Simulation of "Ink breaking" technique involves rather complex physical behavior of ink on paper, which is not to be discussed via the image processing method here. In this paper, we intend to focus on the simulation of "ink accumulation" effect in Chinese painting.

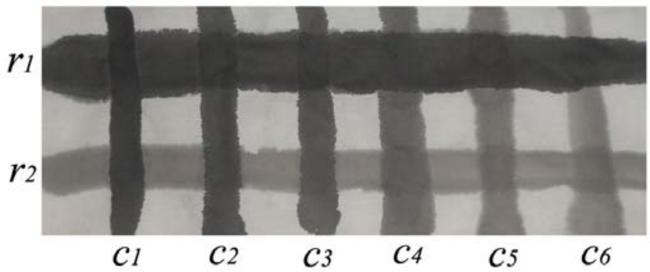


Fig.9 An image showing blending of brush strokes with different ink densities.

When two brush strokes were overlapped at the same spot on paper, due to secondary absorption of ink by the paper, the amount of black carbon particles in the overlapped regions shall be larger than any one of the two strokes applied separately at different spots. Because of that, the color of the overlapped region will become darker in a normal circumstance. Nevertheless, as shown in Fig.9, if ink densities of the two strokes were different significantly from each other, the overlapped region will mainly show the ink color of the darker stroke. For instance, the overlapped regions of stroke r1 and stroke c5 and c6 mainly show the color of stroke r1. If the difference between ink colors (ink densities) of two strokes is very narrow, the overlapped region looks generally darker than any one of the two strokes applied separately, such as that of r2 and c6 in Fig.9.

For two overlapped strokes, assuming that the average luminance of the darker stroke is C_{dark} , and the brighter stroke is C_{light} , average luminance of the overlapped region is $C_{overlap}$, the average color difference of the two strokes is ΔC_{stroke} and the overlapped region is $\Delta C_{overlap}$, ΔC_{stroke} and $\Delta C_{overlap}$ can then be calculated as following:

$$\Delta C_{stroke}=C_{light}-C_{dark} \quad (5)$$

$$\Delta C_{overlap}=C_{dark}-C_{overlap} \quad (6)$$

We investigated 200 image samples from the hand-painted stroke images to analyze the variety of $\Delta C_{overlap}$ corresponding to ΔC_{stroke} on the basis of statistic analysis. These samples were painted by experienced Chinese painters. Fig.10 shows the distributions of $\Delta C_{overlap}$ when C_{light} is 160 or 60 respectively, in which the solid line curve are approximate curves constructed via the average values of $\Delta C_{overlap}$ corresponding to every ΔC_{stroke}. It can be seen in the figure that with the increase of ΔC_{stroke}, $\Delta C_{overlap}$ decreases gradually. In addition, when C_{light} is at a relatively small value, $\Delta C_{overlap}$ becomes relatively larger. This finding could explain why the degree of color darkening in the overlapped regions is related to ink density of the strokes. The larger the ink density is, the more carbon particles will deposit in the overlapped regions, and the darker the overlapped regions will be.

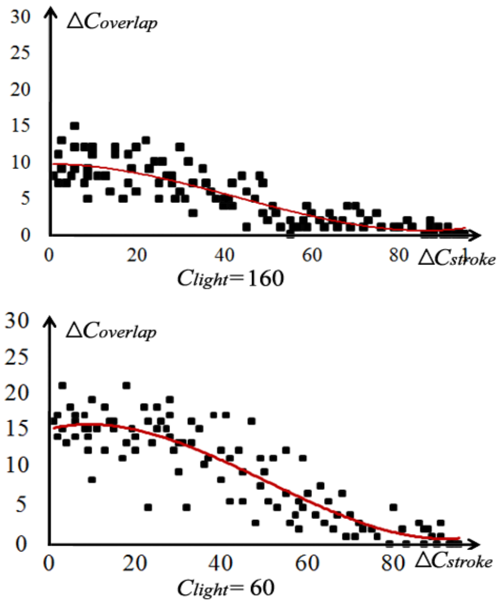


Fig.10 Distribution map of $\Delta C_{overlap}$。

We use a cubic polynomial to construct the relation curve between $\Delta C_{overlap}$ and ΔC_{stroke}.

$$2\left(\frac{\Delta C_{storke}}{100}\right)^3-3\left(\frac{\Delta C_{storke}}{100}\right)^2+1=\frac{\Delta C_{overlap}}{20} \quad (7)$$

Considering the impact of stroke colors on the overlapped regions, the following formula is adopted to calculate $\Delta C_{overlap}$:

$$\Delta C_{overlap}=\left(40\left(\frac{\Delta C_{stroke}}{100}\right)^3-60\left(\frac{\Delta C_{storke}}{100}\right)^2+20\right)\frac{255-C_{light}}{255} \quad (8)$$

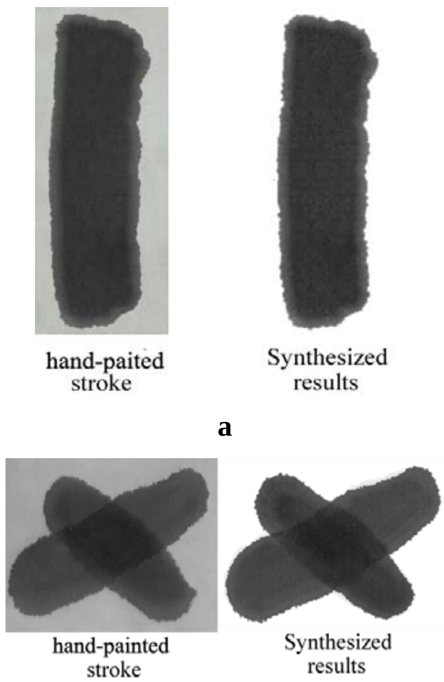
Color of overlapped region is calculated as follows:

$$C_{overlap}=C_{dark}-\Delta C_{overlap} \quad (9)$$

3.6 Rendering Results

In our study, the simulation of ink diffusion effects mainly based on image processing method without considering the influence of carbon particle quantity on stroke color at present. So the color of diffusion areas depends on the color of the corresponding primary stroke areas. When dealing with irregular boundary of diffusion areas, an image template of grayscale is used to represent the density and distribution of natural fibers in Chinese art paper to control ink absorption. Therefore, rendering results are depend on a number of parameters, such as diffusion distance d, attenuation coefficient f, ink residual volume I_r and fiber pattern in the paper used. Should those parameters remain unchanged, the rendering results would maintain great frame-to-frame coherence.

As shown in Fig.11, the results of images between our synthesized ones and the hand painted strokes have been comparable showing realistic wash-ink strokes.



b

Fig.11 Comparison of images between hand-painted brush strokes and synthesized results of our method.

A comparison between our method and two other algorithms is given in Fig.12. It demonstrates that our method is more close to the hand-painted image.

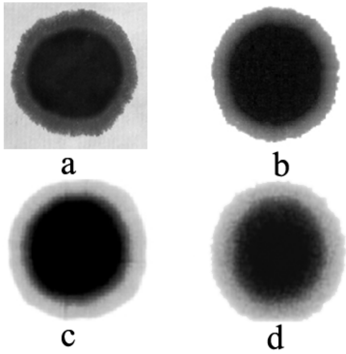


Fig.12 Comparison of our method with others.
(a) hand-painted image. (b) our result.
(c) Huang's result. (d) Zhang's result.

Our method is efficient and easy to code. It is necessary to search the whole image to determine the initial boundary of a primary stroke area and adjust the ink color. To generate a diffusion area, we should search all boundary pixels along the diffusion boundary. Therefore, the total time consumed for rendering a single brush stroke is related to the size of the stroke image, length of the stroke boundary and diffusion range. Table 1 illustrates the time taken to synthesize the stroke of Fig.11.a in the case of different sizes and diffusion distances. The experimental platform is a laptop with *Intel CPU/2.3GHz* and *Windows XP* operating system. Table 2 lists the time taken to render the images of fig.12 using our algorithm and the ones of Huang *et al*. [3]and Zhang *et al*.[19] on the same experimental platform.

Table 1 Time consumed to render the stroke in Figure 11.a

Image size	Diffusion distance	Time (ms)
256×256	6	68
256×256	12	78
512×512	6	93
512×512	12	110
1024×1024	6	123
1024×1024	12	150

Table 2 Comparison on time consuming between our algorithm and others

Image size	Diffusion distance	Our method	Huang's method	Zhang's method
256×256	12	57ms	289ms	504ms
512×512	12	99ms	401ms	898ms
1024×1024	12	143ms	742ms	1572ms

4 Rendering of 3D Wash-ink Landscape Paintings

The following sections provide details on application of our method to 3D scenes in order to generate "XIEYI" Chinese wash-ink paintings of landscape. We firstly rendered each 3D model in the scene to a picture showing wash-ink wash diffusion effects, and then compiled individual pictures into one to mimic the hand-painted Chinese landscape painting.

4.1Rendering Process of Single Model

When painting, painters usually repeat strokes using brushes with different ink quantities to achieve various ink colors. These strokes are mostly overlapped each other. Therefore, a Chinese wash-ink painting can be considered in a simple concept as superposition of many brush strokes with various ink colors. To render 3D scenes of Chinese paintings, we firstly render photorealistic grayscale images for every object in 3D scenes, then divide the grayscale picture into several sub-pictures with different color regions (see Fig.13), which reflect "stroke area" in hand-painted Chinese painting. Each stroke area represents a cluster of strokes with similar color. The segmentation of stroke areas is discussed in section 4.2. Finally, we generate ink diffusion effects on these sub-pictures and blend all sub-pictures using the method discussed in section 3. Figure 13 shows the rendering process of a single 3D model.

In wash-ink landscape painting, ink density at the bottom of mountain fades gradually, which expresses clouds or frogs around the mountains (This can be seen clearly in Fig.1). This is called as "Lacuna Remaining" in Chinese paintings. To mimic the technique of "Lacuna Remaining", like [7] we change pixel transparency at the bottom of mountains to form color fading according to the height of each mountain (Fig.13).

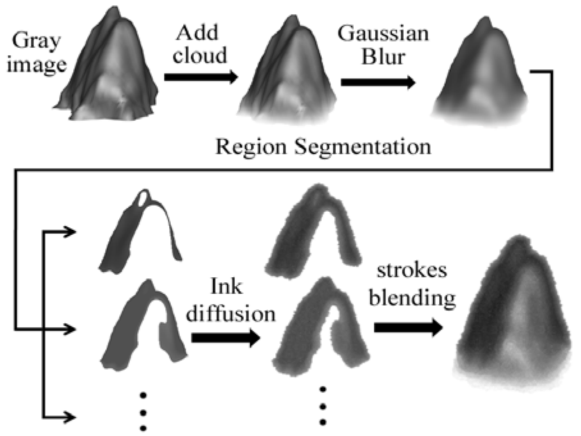


Fig.13 Rendering process of a single 3D model.

Photorealistic gray picture often includes extensive details of objects. However, in "XIEYI" wash-ink Chinese paintings, generally painters would ignore the exact shape of objects to meet the needs of their personalized impression and feeling. Because of that there is no obvious boundary between different brush strokes in such art products. To achieve more close results to hand-painted "XIEYI" wash-ink paintings, prior to segmenting stroke areas, Gaussian low-pass filtering is applied.

Subsequently the filtered image is segmented into several stroke areas, which will be regarded as the primary stroke area to synthesize ink diffusion effect via the method introduced in Section 3. At last, we blend all strokes using the method discussed in Section 3.5, and then get the final wash-ink effects of a single object.

4.2 Segmentation of Stroke Areas

In "XIEYI" wash-ink paintings, although painters do not draw the exact shape details of objects, but they prefer to use the changes of ink color for depicting object appearances. So a "XIEYI" wash-ink painting can be seen as a picture consists of several stroke areas. Each stroke area represents a group of brush strokes with similar ink color.

We segment the gray picture using five color ranges, which are [0, 70], [70,120], [120,160], [160,210] and [210,255]. Such arrangement is consistent with the old saying that "Chinese black ink possess five elemental colors" in wash-ink paintings. Pixels in each color interval make up a stroke area. The stroke areas of lighter color intervals also include all the stroke areas of deeper color intervals. In a lighter stroke area, colors of the pixels located in the darker color intervals are set as the minimum of the lighter color interval. For instance, in Fig.13, the stroke area in color interval [120,160] includes the areas in color interval [0, 70] and [70, 120], in which the pixels are set as 120. The purpose of such setting is to avoid the colors of the overlapped regions turns to extreme dark after strokes blending. Fig.14 shows four stroke areas after region segmentation on the gray picture in Fig.13.

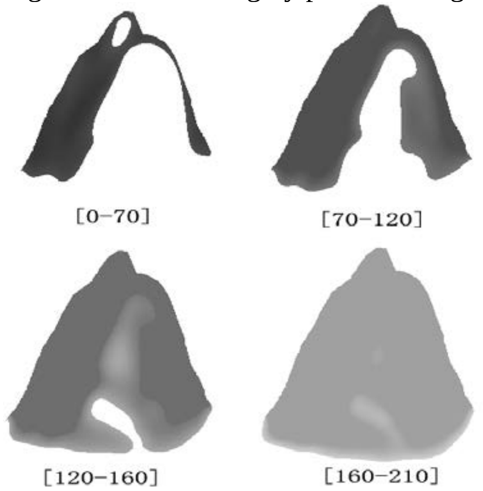


Fig.14 Stroke areas of different color intervals.

4.3 Stroke Occluding and Depth of Field

In normal rendering process, Z-buffer can be utilized to judge pixel visibility, because Z-buffer recorded depth values of the pixels corresponding to the points on model surfaces when the model was projected to the screen. When we render every 3D model separately, depth values in Z-buffer shall be copied at the same time so that the visibility of every pixel can be determined when all pictures were combined into one picture. However, when ink diffusion is implemented for the stroke areas, the outline of each object will be magnified correspondingly, and pixels in the diffusion areas are likely to be occluded by objects in far depth of the painting. In order to avoid this undesired Occluding problem, when a diffusion area is forming, the depth value of every pixel in diffusion area shall be calculated at the same time. Depth calculation has the same principles to the color calculation discussed in section 3.2. As defined in this method, depth of a newly formed boundary point is the average depth of the points on the former boundary among its 4-connected neighborhood. For example, in Fig.4, the depth of point p is:

$$depth(p) = average(depth(p_1), depth(p_2)) \quad (10)$$

In Chinese wash-ink paintings, painters utilize ink density to express the depth of field. For objects with far distance, light ink will be adopted. On the contrary, for near objects, more dense ink will be used. In order to simulate such depth-of-field effect, when rendering every model, calculate the distance from object to viewpoint, and according to the distance, enhance luminance of the grayscale image of this model. The calculation is following:

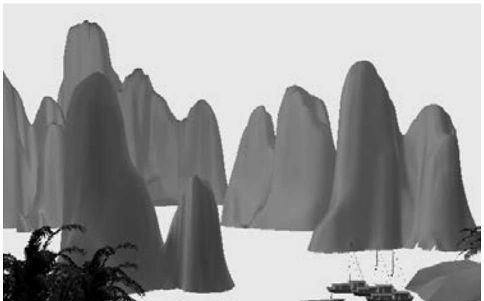
$$\begin{aligned}&C = C + 255 \times dist / D\\&if\,(C > 255) \quad C = 255\end{aligned} \quad (11)$$

C is luminance of model's grayscale picture, *dist* is distance of object, and *D* is the far clip of camera. When *dist* is nearing *D*, the object will fade out gradually.

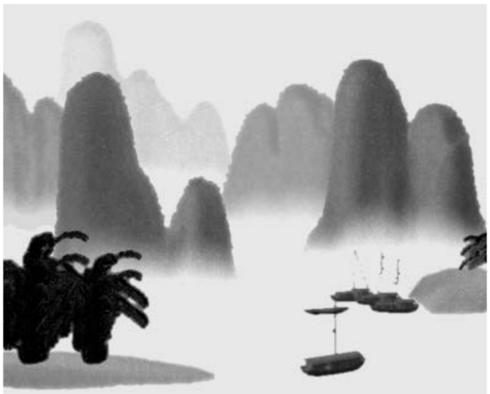
4.4 Rendering Results

As shown in Fig.15.a we built a 3D scene of the picture in Fig.1. Fig.15.b is the rendering results of this scene using our method. The whole rendering process is implemented by computer automatically. Fig.16 shows four pictures of the animation sequence when the camera moves gradually. The experimental results show that our method can maintain satisfactory frame-to-frame coherence during animation.

In this paper, the rendering process of a 3D wash-ink painting includes three steps: the first step is the normal photorealistic rendering for each object; the second step is to generate ink diffusion effect in image space; the last step is to blend all the pictures to a final picture. Comparing with common photorealistic rendering, our method includes specific time on implementing the second and the third steps. Since objects in the scene have to be processed individually, the total rendering time is not only related to image resolution, but also to the number of objects in the scene. Table 3 provides the time taken to render the scene in Fig.15.a which includes 15 objects. The experimental platform is a laptop with *Intel CPU/2.3GHz* and *Windows XP* operating system. Data in the table do not include the time for rendering photorealistic images.



a



b

Fig.15 Rendering result of a 3D scene.
(a) the scene built according to Fig.1.
(b) the rendering result.

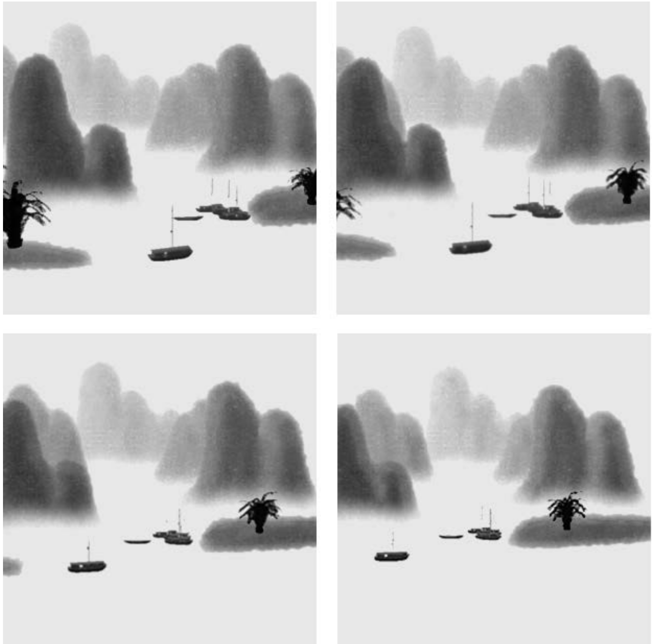


Fig.16 Four frames of pictures in animation sequence rendered using our method.

Table 3 Time taken to render the scene in Fig.15.a

Image size	Diffusion distance	Time (ms)
256×256	6	3037
256×256	12	3489
512×512	6	4205
512×512	12	5101
1024×1024	6	5839
1024×1024	12	7250

5 Discussion

By taking no account of the complicate physical properties of ink particle movement in paper, our algorithm is established with high efficiency and better simplicity. Using different stroke samples and mage templates of Chinese art paper with various natural fiber contents, different rendering effects have been obtained. Given that our method has the advantage to vary relevant parameters for different situations, our method can provide more flexibility for users. This study also experienced the difficulty issue in image-based rendering method, showing difficulty to simulate the ink diffusion between two wet strokes, which is commonly known as "Ink breaking" technique for Chinese painters. It is important to note that the blending method for overlapped strokes presented in this paper can only be applied to overlap strokes when ink is complete dry between applications.

In this paper, we applied our image-based method of rendering ink diffusion to 3D scenes to render "*XIEYI*" Chinese landscape paintings. However, we are confident that our method is also capable to render other objects, such as animals, trees and so on. Our preliminary study also demonstrated that our method can be incorporated with the methods proposed by Yuan *et al* [10] and Joo-Hyu *et al*.[11], to generate wash-ink effect at the stage of internal shading.

6 Conclusion and Future Works

In this paper, an image-based method for synthesizing wash-ink brush strokes and a method of rendering "XIEYI" Chinese wash-ink paintings for 3D landscape scene were established. The experimental results demonstrated that using our methods can render "XIEYI" Chinese wash-ink paintings effectively. However, given that skills used in Chinese wash-ink paintings are extremely complicate and delicate and are also subject to individual painters' personal experience and styles of expression, it is impossible to simulate vast Chinese paintings of different styles based on currently available computer techniques or any published non-photorealistic rendering methods.

Based on this study, the main research work we are also interested in are as follows:

- Applying the image-based method of rendering on wash-ink brush strokes to other object images of wash-ink painting, eg. to apply rendering effects on buildings, running water, animals, and flowers.
- Combining our image-based method with other physics-based methods to study ink diffusion properties on paper following repeating strokes with wet brush. Such approach would provide more options to develop further realistic simulation algorithm for ink diffusion on paper.

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