國立交通大學

資訊科學系

碩士論文

具有以物理模式為基礎色彩渲染效果的電腦合成中國水墨畫之研究

Computer-Generated Chinese Painting with Physically-Based Ink and Color Diffusion

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摘　　要

在中國水墨畫中，除了使用墨與水調和出各種不同濃淡的墨色之外，色彩也扮演了一個很重要的角色。要描繪一幅景物時，除了用墨色表現出明暗對比之外，若加入了物體本身的色彩，更可以顯現出物體的本質，進而提升整幅畫的生命力。在本篇論文中，利用真實的物理理論來模擬水與墨/顏料在畫紙上的流動，接著在色彩的表現上，利用 Kubelka-Munk 的理論，考慮顏料與畫紙之間光線的折射與反射來表現出擬真的顏色，同時使用 tablet pen 作為輸入裝置，建立了一個可供使用者以各種顏色描繪一幅中國水墨畫的互動式系統。

Computer-Generated Chinese Painting with Physically-Based Ink and Color Diffusion

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ABSTRACT

Water and ink are two important elements in Chinese Ink Painting. By mixing water and ink, we can get different concentrations to show the contrast of an object. To make a painting more vivid, we can also apply the third element, color, to display the nature of an object.

In this thesis, we simulate the ink diffusion effects based on observations and analysis of the physical phenomenon, such as the flows of water and ink/pigment on paper. Then we display realistic colors by taking the light reflection and transmission between pigments and paper, namely the Kubelka-Munk theory [15], into consideration. We also use tablet pen as an input device to create an interactive painting system for users to draw a Chinese Ink Painting with color pigments.

Acknowledgements

First of all, I would like to show my gratitude to my advisor, Prof. Zen-Chung Shih for his patience and guidance. Also, I am grateful to all the members in Computer Graphics and Virtual Reality Laboratory for their useful suggestion and encouragement in these days.

I want to dedicate the achievement of this work to my family. Without their support, I couldn’t fully focus on my study.

Special thanks to my girl friend who helps to correct and typeset this thesis.

Contents

List of Figures

Chapter 1

Introduction

Ink and color are equally important in Chinese Ink Painting. Unlike western paintings which explore the changes of light and color, Chinese Ink Painting focuses mainly on the combination of shape and color. Ink depicts the frame and the substantial spirit of a painting. Color on the other side acts as a supporting role to flesh as well as glorify the frame. The perfect chemistry of their combination is shown in Figure 1.1. With shape and color, we can catch the whole spirit of Chinese Ink Painting.

Figure 1.1 *Ling-chih Plants, Symbols Of Longevity* by Chang Dai-chien [7]. The painting shows shape with ink and the nature of the object with colors.

1.1 Shapes and Colors in Chinese Ink Paintings

In Chinese Ink Painting, shape is constructed by drawing dots and lines with brushes, while colors are diffused layer by layer with different thickness of ink or different colors of pigments. These techniques together create the unique quality and effects in Chinese Ink Painting. With the observations of the shapes and colors in Chinese Ink Painting, we simulate different kinds of effects according to real physical characteristics.

To deal with shapes, we propose two types of brushes and various quantities of water to simulate not only dry and wet strokes, but contour effects.

In western paintings, take watercolor for example, the absorbency of paper is not so high that water and color pigment both flow on paper. Therefore, a shallow water simulation is needed to simulate the color pigments flowing on paper [9]. However, the paper used in Chinese Ink Painting is different from that used in western paintings. The absorbency of Hsuan paper is very high, so the water in the brush will immediately sink into the paper and bring the ink and color with it to flow among the paper fibers once the brush touches the paper. To express the unigue characteristics of Chinese Ink Painting, a diffusion model should be proposed to simulate the flow of particles in paper instead of the shallow water flow on paper.

As to color, we consider ink and color pigments separately. First, in ink diffusion simulation, water and carbon particles are moved in paper according to real physical properties. By adjusting parameters in our proposed system, we can also simulate many different ink diffusion effects. Second, in simulating pigments behaviors, pigment particles are moved the same as carbon particles in ink diffusion process. We display the colors of the pigments by applying Kubelka-Munk (KM) theory, which models the light reflection and transmission between pigments and paper. According to KM theory, we can simulate how pigments show their colors on different background colors.

1.2 Overview

We proposed an interactive painting system with tablet pen as its input device. Users can create a Chinese Ink Painting simply by adjusting the parameters of brushes.

Giving thoughts to system processing speed, we use multiple threads to handle the diffusion process. In this way, we can decrease the idle time for screen display, which has been a major problem in traditional computer painting system.

To create a simulative painting environment as close to the real world as possible, we also simulate the actual painting sequence of Chinese Ink Painting, such as applying colors after dampening the paper to achieve the diffusion effects and stacking ink from thin to thick concentration.

1.3 Thesis Organization

This thesis is organized as follows. In chapter 2, we review the previous related researches about brush models, ink diffusion and color display. Then we compare the proposed system with current commercialized painting packages. We describe the system overview, including system framework and user interface in chapter 3. Chapter 4 describes models and algorithms for color ink painting, dividing into three sections: brush models, ink diffusion and color display. We show some implementation results in chapter 5, including some imitated paintings and original paintings using the proposed system. Then we have some discussions on these results. Finally, chapter 6 concludes this work and addresses some future works to improve our work.

Chapter 2

Related Works

We will discuss some previous works related to Chinese Ink Painting on three main topics, which are brush model, ink diffusion and color representation. Then we will compare our system with current commercial painting packages.

2.1 Brush Model

To simulate brush motions and to get realistic results on the paper, an appropriate brush model should be defined. Strassmann [20] proposed a brush model to simulate the traditional Japanese art of sumi-e, where brush strokes are created by sweeping a one-dimensional brush bristle over a skeleton. Suguru Saito and Masayuki Nakajima [18] provided a three-dimensional physically-based brush model that allows users to draw strokes on a computer with a pen-type input device. A two-dimensional brush model was proposed by Shan-Zan Weng at el. [25].The region where the brush contacts the canvas is circle-shaped (which can be considered as a footprint) and the bristles are distributed uniformly in it. To create a stroke, they proposed an algorithm to extract the skeleton of a stroke and let the center of the brush model move along with it. The orientation of the brush during movement was taken into consideration to make the generated strokes look natural and smooth. Finally, the footprints of the bristles would be taken as the path of ink contribution on the canvas. With different types of brush selected, different styles of strokes can be generated. Wong and Ip [27] used an inverse cone to represent the virtual brush. In the DAB [8] project, they used a particle system to represent their brush geometry. Xu et al. [28] proposed a two-level hierarchical geometry model. They used three B-spline curves to control the three-dimensional brush geometry.

Some of the brush models mentioned above are defined in 2D while the others are defined in 3D. As to the brush models defined in 2D, another curve need to be defined to represent the path of the brush: a spline curve evaluated by control points. Since the proposed system in this thesis is an interactive system, the brush path is determined by users. We don't need to define another skeleton to represent the path. Besides, brush models defined in 3D often have to simulate the brush motion, which will require a lot of system resources. After considering system speed and the presented effects, we define our brush model in 2D. The detailed brush model will be discussed in section 4.1.

2.2 Ink Diffusion

The special effect of ink diffusion is produced by the incredible absorbency of Hsuan paper. Ink diffusion is widely used in Chinese ink painting and it is also what differentiates Chinese ink painting from western painting. A technique proposed by Lee [17] efficiently rendered oriental black ink paintings with realistic diffusion effects. The system proposed by Lee can simulate ink diffusion based on a variety of paper types and ink properties. However, there has been no mechanism presented about the simulation of blending effects of two or more strokes. Small [19] proposed a parallel approach to predict the motion of pigment and water on the paper, which computes the status in each paper cell repeatedly to achieve realistic diffusion effects. A more sophisticated paper model was proposed by Curtis and Anderson [9]. With a more complex shallow water simulation, they can simulate realistic diffusion effects of watercolor. Sheng-Wen Huang et al. [13] proposed a physically-based ink diffusion model by simulating the interaction among water particles, carbon particles and paper. This model is the main reference for the ink diffusion simulation in this thesis. By making some modifications and extensions to Huang's model, we can achieve the requirement for an interactive system. Detailed ink diffusion model will be discussed in section 4.2.

2.3 Color Representation

The importance of colors in Chinese Ink Painting is no less than ink diffusion effects. Previous researches on Chinese Ink Painting all focus on black ink painting, and they rarely discuss the simulation of color pigments. In DAB project [8], they simulated color mixture on the canvas and used a simple alpha blending to get the colors from two different pigments in two layers. The system proposed by Xu [28] also used a simple alpha blending to show the color mixture. Curtis and Anderson [9] used Kubelka-Munk theory, which researches on the light reflection and transmission between pigments and paper, to compute the color of a stroke painted on another stroke. Another work that used KM theory is proposed by Chet S. Haase et al. [12]. They used this theory to compute a variety of color mixtures of pigments. Since KM theory can display the color of the mixed pigments realistically, our system also use it to compute the display of colors. Details will be discussed in section 4.3.

2.4 Survey of Commercialized Painting Packages

Among current commercial painting packages, a system similar to ours is COREL's Painter, which doesn't need stroke skeleton information such as spline curve. This is why we compare our system with Painter on the simulation of Chinese Ink Painting. In Painter, the simulation results of watercolor and oil painting effects are realistic, but there is only a calligraphic brush Sumi-e that simulates the effects of Chinese writing brushes. The Sumi-e brush in Painter can create calligraphic strokes but it is unable to achieve the ink diffusion effects in Chinese Ink Painting. Our system, however, complements this defect.

Chapter 3

System Overview

3.1 System Architecture

OpenGL is the graphic API used in our proposed system. We use glDrawPixels to render the final color of each pixel. The flow of the whole process is shown in Figure 3.1 below. When strokes are drawn on the screen using tablet, the system will put all the pixels drawn into a queue. Then the system serves the queue as an input for the ink diffusion thread. At this time, the system processes the ink diffusion thread and render the color of each pixel computed by KM model in a parallel process way. By processing the ink diffusion thread and refreshing screen at the same time, the current progress of the system is noticeable and the idle time is greatly reduced.

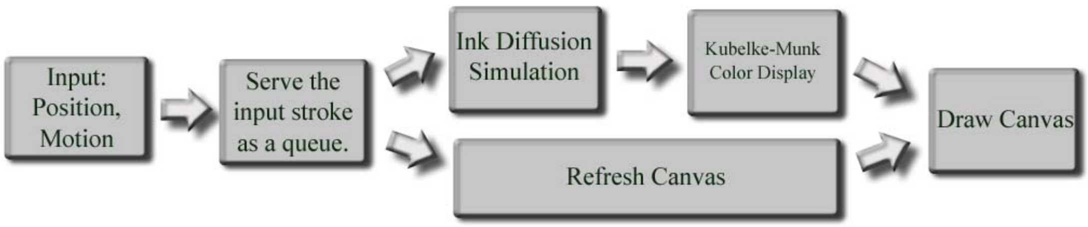

Figure 3.1 System Architecture, the system processes the ink diffusion thread and computes the color by KM model in a parallel process way.

3.2 User Interface

The system provides a user interface using the GLUI user interface library. Users can choose brush type, pigment type and different ink concentrations. The basic functions such as load canvas, save canvas and save canvas as a bitmap file (*.bmp), and undo the last stroke are provided. Besides, by adjusting the stroke parameters such as colors, size, water volume, and carbon volume, users can achieve various painting effects.

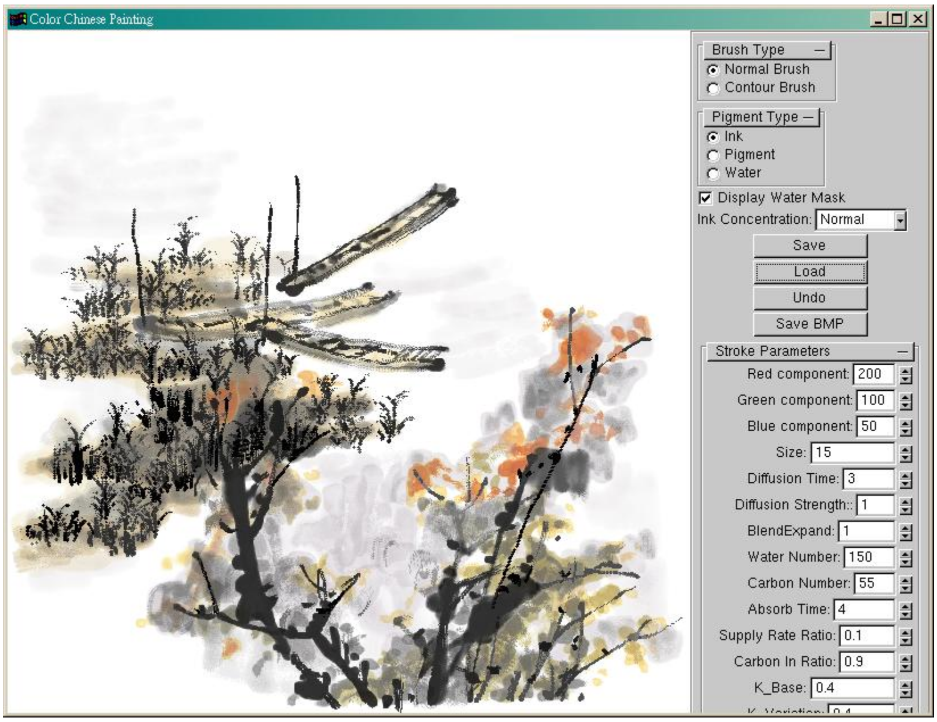

Figure 3.2 User Interface

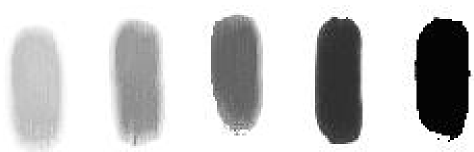

Figure 3.3 Strokes with different concentrations.
Left to right: from thin to thick.

(a) Simulated image.

(b) Real image.

Figure 3.4 Comparison between real and simulated various ink concentration.

We also simulate the painting sequence from observations of real painting behaviors, such as drawing after dampening the paper to achieve the diffusion effects. In real world, if we apply water on paper, the wet area would appear darker because of the light reflection and transmission in paper. The water effect is provided for users to show whether an area on the paper is wet or not. Also, the wet area would dry out gradually as time elapses, as shown in Figure 3.5.

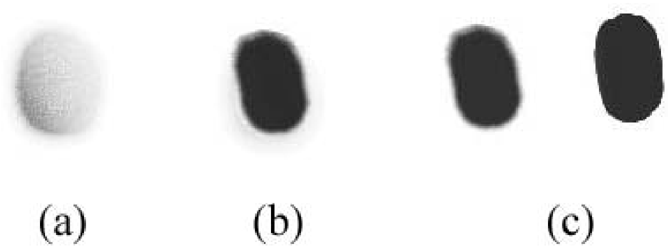

Figure 3.5 (a) The effect of wet area on paper. (b) Dry brush drawn on a wet area. (c) Left: the stroke of (b) after the canvas dries. Right: Dry brush drawn on dry area.

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Chapter 4

Models and Algorithms for Color Ink Painting

The painting media (Chinese writing brush and Hsuan paper) used in Chinese Ink Painting are very different from those in western painting. In order to create the combining effects of these two media, we have to simulate their properties. We propose a simple brush model with two different types to simulate the strokes of Chinese writing brush. In ink diffusion, we reference Huang's [13] ink diffusion model but makes some modifications. As to the color display of the pigments, we adopt the KM theory.

4.1 Brush Model

There are two types of brush model in our system, both of them are simple models defined in 2D. The first type is **normal brush**, which includes median thick brush and thick brush in Chinese writing brushes. The brush bristle are randomly distributed in a circle of radius *size* (an integer value; the radius of the largest pressure of input) and the number of points representing the bristle is the area of the circle ($\pi r^2 = \pi \cdot size^2$). Users can change the size of the circle by applying different input pressures while dragging the circle to form the bristle effects at the same time, as shown in Figure 4.1.

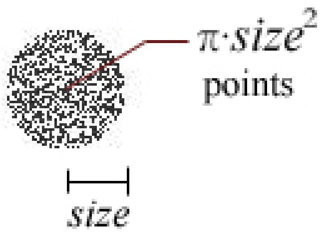


Figure 4.1 Normal brush. The brush bristle are randomly distributed in a circle of radius *size* (the radius of the largest pressure of input) and the number of points representing the bristle is the area of the circle ($\pi r^2 = \pi \cdot size^2$)

The second type is **contour brush**, which is the thin brush of Chinese writing brush and is used to depict the contours or details of an object. **Contour brush** is constructed by filling every pixel in a circle of radius *size* to represent the brush bristle. Also, users can input different pressures to change the size of the circle and drag the circle to form the effect of contour strokes. Since there are some coarse results from extremely small stroke size, e.g. smaller than 3, we apply a simple anti-aliasing process to smooth the strokes with a mask to filter all the pixels in the strokes. Figure 4.2 shows the strokes of the two brush types and Figure 4.3 shows the corresponding mask.

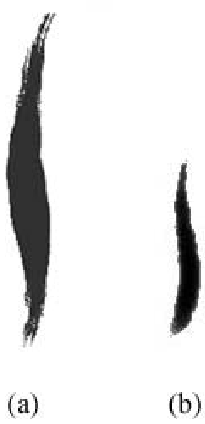


Figure 4.2 (a) Normal Brush and (b) Contour Brush.

2	4	2
4	20	4
2	4	2

Figure 4.3 Anti-aliasing mask. The coefficients are the most appropriate results for contour brush strokes.

4.2 Physically-based Model of Ink Diffusion

When the brush bristles touch the surface of the paper, the ink in the bristles begins to flow inside the paper. The high absorbency of the paper and different quantity of water cause different diffusion effects, such as strokes with their edges flurry and blurred. These diffusion features represent complex physical phenomena which cannot be completely simulated by conventional graphical techniques such as texture mapping or the creation of degradation functions, since purely mathematical method generally results in flatly blurred images which are different from realistic diffusion images.

4.2.1 Ink Diffusion Phenomena

Capillary phenomenon, a physical mechanism, is an important factor that causes the ink diffusion in the paper structure. In Figure 4.4, a thin tube is placed in a container filled with water with one end in the water and the other end in the air. The liquid will rise inside the tube and the liquid surface inside the tube is higher than the surface of the outside water. This phenomenon can also be observed in the ink diffusion in paper. The typical paper is composed of fibers which are positioned in random position and random direction in which small holes and spaces between fibers act as thin capillary tubes for carrying water away from the initial area, and create diffusion, as shown in Figure 4.5.

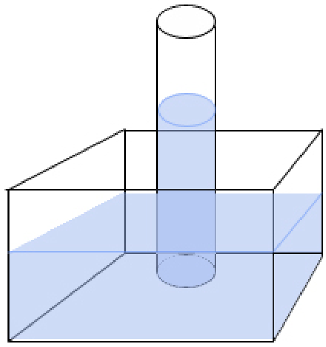


Figure 4.4 The capillary phenomenon.

Figure 4.5 The real ink diffusion effect.

4.2.2 Discrete Paper Model

Although the diffusion phenomenon is a continuous physical phenomenon, the simulation of the diffusion phenomenon in computer is discrete. Therefore, the paper model is defined in a discrete 2D array of [X $\times$ Y] paper cells. Each paper cell is called a papel [16], as shown in Figure 4.6. The papel is a basic unit of the paper structure and corresponding to a pixel on the screen.

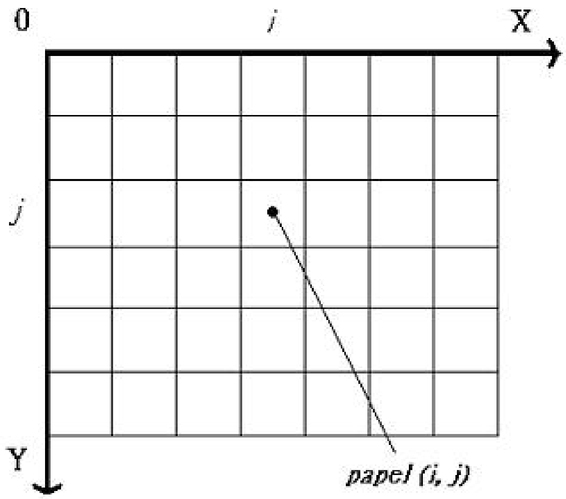


Figure 4.6 Discrete paper model. The paper cells are named *papels* (Courtesy of Huang).

According to Huang's [13] definition, each papel has some properties. *Absorbency (p)*, the ability of absorbency of the papel p is defined as following. When the moving ink pass through p with N fibers lay in, the quantity of water left and deposited in p is Q. The relationship between Q and N can be represented as

$$Q \propto N . \tag{1}$$

According to the previous research proposed by Lee [16], the number of the cross points of fibers in the paper is the most important factor to the ability of absorbency. If the number of cross points of fibers is *Cn*, then the relationship between *Cn* and *Absorbency (p)* is

$$Cn \propto Abosorbency(p) . \tag{2}$$

We can approximate the relationship between *N* and *Cn* from (1) and (2) as

$$N \propto Cn\,, \tag{3}$$

Then we obtain the following relationship:

$$Absorbency(p) \propto N \propto Q\,. \tag{4}$$

Based on the relationship of (4), we can define many kinds of paper model with different ability of water absorbency with different densities of paper fibers. The initial ability of absorbency of each papel can be described as

$$Absorbency(p) = Base + Var \times rand() \tag{5}$$

where *Base* and *Var* are real numbers between zero and one, and *rand*() is a function which produces number between 0 and 32767. In Figure 4.7, we simulate different ink diffusion effects with different kinds of absorbency of paper. The coefficient of the ability of water absorbency is represented as a real number between zero and one.

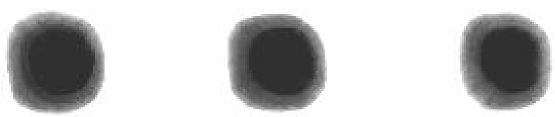


Figure 4.7 Three simulated ink diffusion image represent different kinds of paper.

4.2.3 Discrete Ink Model and Ink Flow

The black ink in Chinese ink painting is a dilute mixture of water and colloidal carbon particles. The carbon particles are much smaller than those of watercolor paints such that they can diffuse into paper along with the absorbed water. Besides the capillarity, the forces acting on the motion of ink involve the interaction between waters and waters, waters and carbons and the gravity, etc. To simulate chaotic and complex motion of ink in fibers, we separate the ink into two kinds of particles: *water particles* and *carbon particles*. [26]

Water Particle

In Huang's [13] definition of water, the water volume is divided into particles for the characteristic of discrete-computing ability of computers. All of the water particles are defined as objects that have uniform volume and uniform mass. The only different property of the water particles is their positions, which recorded the index of the papel they are at.

With the definition of water particles, we can decide the movement of these particles on paper. When the water in a certain papel is decided to flow out, the *quantity* and *direction* of the water to flow out are the two characters must be figured out. Based on some physical knowledge and hypothesis, the approximate equation of *K(p)*, the ratio of the quantity of water to flow out to the quantity of water contained in the papel *p* is represented as

$$K(p) = Base + Var \times \left(1 - \left(1 - Absorbency(p)\right)^2\right), \tag{6}$$

where *Base* is a real number between zero and one to represent the basic flow rate of *p*, and

Var is a real number between zero and one to represent the difference between the highest flow rate and the lowest flow rate.

The reason for the ability of ink diffused in paper is the capillarity only on water particles, not on carbon particles. Based on this phenomenon, we have to decide the direction of the diffused water flowing out, which is decided by predicting the probabilities of the water particles. This method will be discussed in section 4.2.4.

Carbon Particle

Carbon particles don't move like water particles. Instead, if the force produced by the energy of the movements of the water particles is larger than the force produced by the friction of the carbon particles, the carbon particles move with the water particles. According to Huang's [13] definition, carbon particles have some attributes such as mass, position, diameter and color. But all of these attributes are not uniform, which is different from water particles. The diameter and mass of a carbon particle is decided according to the fineness when grinding the ink initially. If the initial ink grinding is coarse, the ink contains small and large particles which produce an observable change of color intensity along the border line of the initial brush area. On the other hand, if the carbon particles are homogeneous, small, and uniform, most carbon particles move with water unhindered by the fibers, such that a continuous and smooth intensity change appears across the diffusion area. This occurs because only sufficiently small carbon particles can seep into the fiber mesh and flow along with water particles, large carbon particles are left without flowing away.

Under the influence of the motion of water particles, suspended carbon particles move in a manner called *Brownian motion* [21]. According to this physical mechanism, the quantity of carbon flow is proportional to the quantity of water flow. A phenomenon occurs because only those carbon particles whose granule size is smaller than the space between fibers can seep into the mesh along with water. Particles whose granule size is bigger than the space remain at the initial position, as shown in Figure 4.8. This phenomenon is referred as a “***filtering effect***” [11, 16] of the fiber mesh, and can be represented as the following, where *p* is the papel the carbon particle lays in and *Hole_Diameter* is defined as the average length of diameter of the holes between fibers in the papel.

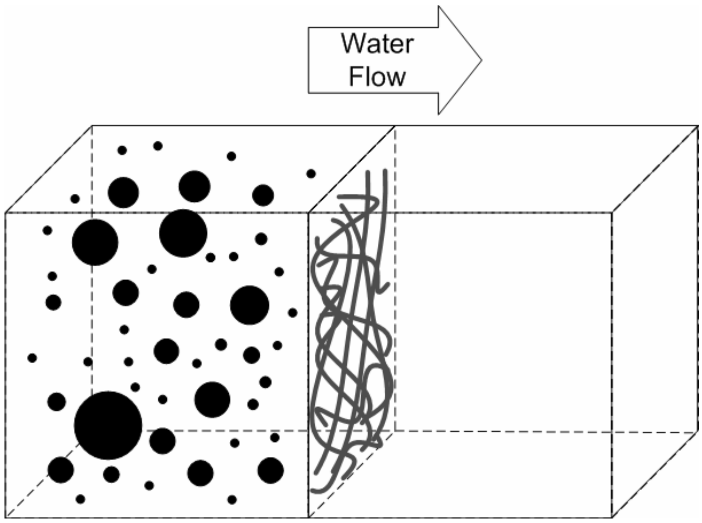
if (Carbon_Diameter > Hole_Diameter(*p*)) then

  Carbon_Position ← *p*

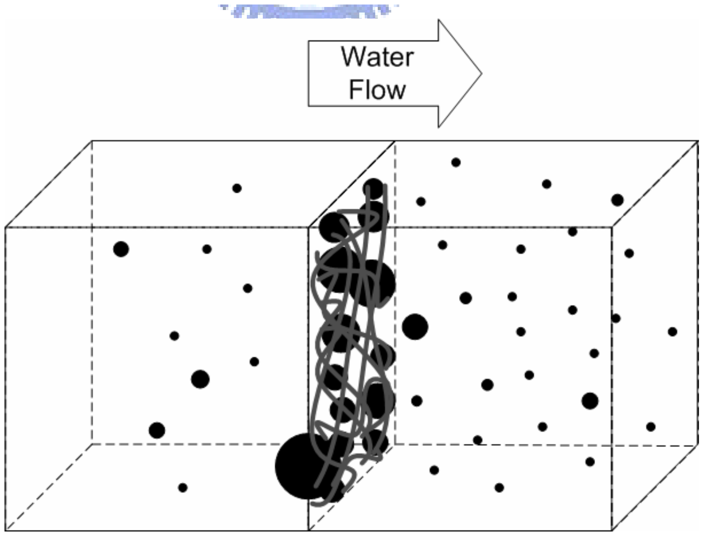
else

  Carbon_Position ← Water_OutFlow_Direction(*p*),

(a)



(b) Two adjacent cubes represent two neighbor papels. Black grains in papels are carbon particles in different sizes. The chaos strings on the face between two papels represent fibers. The arrow represents the direction of water flow which carbon particles are moving along with.



(c) Larger diameter of carbon particles can not pass the holes between fibers results in a filtering effect and be left in the original papel.

Figure 4.8 An illustration to explain the phenomenon called "*filter effect*" (Courtesy of Huang).

Besides the diameter-filtering mechanism, the mass-filtering mechanism is proposed. Suppose V_c is the velocity of the carbon *c* suspended in the water in papel *p*, and W_p is the quantity of out-flowing water in *p*. The relationship between V_c, W_p and the diameter of holes in *p*, *Hole_Diameter(p)*, is described as

$$V_c \propto W_p, \; V_c \propto \frac{1}{(Hole\_Diameter(p))^2}. \tag{7}$$

If the carbon *c* is too heavy to moved out from papel *p* and then deposited in *p*, then $V_c \leftarrow 0$. On account of this physical phenomenon [21], we define an upper-bounded threshold T_p for papel *p*, to decide whether the carbon particle can move out or not. If the mass of carbon *c* is larger than T_p, then $V_c \leftarrow 0$. The value of T_p is decided depending on V_c. The relationship between T_p and V_c is represented as

$$T_p = T(V_c) = T(W_p \times \frac{1}{(Hole\_Diameter(p))^2}), \tag{8}$$

where *T* is a transform function from V_c to T_p.

4.2.4 The Moving Direction of Water Flow

The water in a papel may flow to some of its eight neighboring papels. The directions of this movement are determined by taking the following dominant factors that affect the flow of water into account.

1. The gradient of water between neighboring papels based on Brownian motion.

2. Degree of *Absorbency* for water of the neighboring papels.

3. Factor of paper texture of the neighboring papels.

4. Factor of inertia acting on water flow.

All of these factors are about the relationship between some papels and their neighboring papels. Therefore, we classify neighboring papels into eight directions, d_k (k = 1, 2, …, 8), that point to the center of the neighboring eight papels p_k (k = 1, 2, …, 8) from c_0, respectively, as shown in Figure 4.9. By considering all the factors described above, we can obtain the probability of each direction and decide the quantity of the water flowing out according to these calculated probabilities, which will be shown in Equation 17.

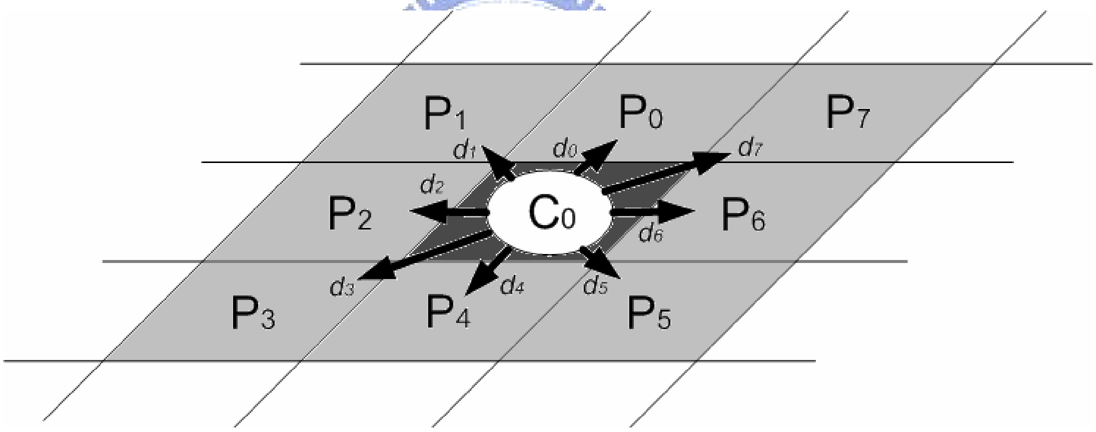


Figure 4.9 Determine directions of water flowing into neighboring papels, p_k (k = 1, 2, …, 8), according to the probabilities in eight directions calculated based on four factors (Courtesy of Huang).

Besides, the static friction can affect the flow of water also. *Static friction* is a resistance that prevents water from moving and originates from the interfacial tension between water particles and fibers in the given area, even the tension among water particles. It increases linearly when the water particles intend to flow until it reaches the maximum static friction. Then water starts to flow and the static friction transfers to the dynamic friction, as shown in

Figure 4.10.

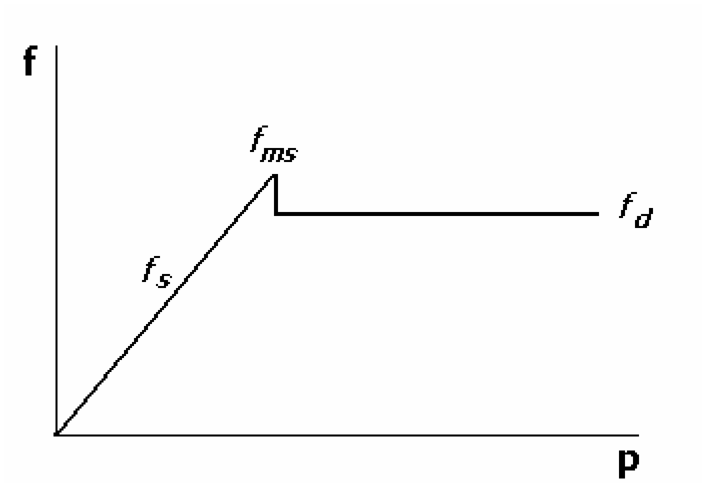


Figure 4.10 The relationship among static friction f_s, maximum static friction f_{ms}, and dynamic friction f_d. **P** is the external force, such as interfacial tensions. **f** is the friction changed corresponding to **P** (Courtesy of Huang).

In Huang's [13] method, the *critical threshold* CT_p, which is defined as the minimum quantity of water in a papel p corresponding to the maximum static friction, is calculated using the degree of absorbency, a_p, as

$$CT_p = \gamma_s a_p, \tag{9}$$

where γ_s is a coefficient for converting the degree of absorbency into the quantity of water corresponding to maximum static friction and is set experimentally. When the quantity of water in p is larger than CT_p, water is free to flow out from p. Otherwise, water is left in p.

If water particles are decided to flow out, we calculate the probability of the flowing direction. The following paragraph describes how to transfer the four factors that affect the direction of water flow into probabilities.

The Factor of Gradient

It is assumed that the movement of water particles in a paper obeys Brownian motion. A mixture of two sets of water particles, each has different number of water particles, will produce an irreversible diffusion process in which water particles transfering from the set with larger number to the other one with smaller one. This movement continues until the difference of particle's numbers of two sets reach a value expressing the balance of forces acting on these two sets in tolerance. *Gradient* here is used to represent the difference of number of water particles between two sets.

Let us assume that the number of water particles in c_0 and p_k are W_c and W_k, respectively. The probability based on Brownian motion is determined by the equation

$$G_k = \frac{u(W_c - W_k)}{G_{sum}}$$

(10)

$$G_{sum} = \sum_{i=1}^{8} u(W_c - W_i)$$

where G_k (k = 1, 2, …, 8) is a probability based on *gradient*. $u(x)$ is the unit function, i.e. if $x \geq 0$, then $u(x) = x$, otherwise $u(x) = 0$.

The Factor of Absorbency

When the water particles intend to flow out into the neighboring papels, attractions from each neighboring papels result in different kinds of quantity of water flow. When the water particles intend to flow, the static friction f_s continuously acts on them and grows linearly until the maximum static friction f_{ms} is reached, as shown in Figure 4.10. Based on *Newton's Second Law Of Motions*, we figure out the equation as

$$f_d = M \times a, \tag{11}$$

where f_d is the *dynamic friction*, which cannot be changed by any forces or interfacial tensions, is usually a constant force in ideal between the flowing water and fibers. a is the acceleration of those flowing water particles in water flow. Based on the theorem discussed by Theo [21], we figure out that a is usually much smaller than g, the acceleration of gravity. Therefore, we can regard it as a constant value of acceleration acting on those water particles. M is the mass of the flowing water. Because of the pre-defined uniformity of mass of water particle, the quantity of water flow is proportional to M. Assume N_w is the number of water particles in the water flow, the relationship between M and N_w can be described as

$$N_w \propto M. \tag{12}$$

From Equation 11 and 12, we can conclude that

$$f_d \propto N_w \times a. \tag{13}$$

According to the equations deduced above and the constant a, the relationship between f_d and N_w is represented as

$$f_d \propto N_w. \quad (14)$$

This important deduction indicates that larger f_d makes larger N_w. Based on the relationship in Equation 8, we conclude that

$$f_d \propto a_p \rightarrow N_w \propto a_p, \quad (15)$$

where a_p is the degree of absorbency of papel p.

We assume that the eight neighbors of center papel c_0 are p_k (k = 1, 2,…, 8), and the degree of absorbency of c_0 and p_k are $Absorbency(c_0)$ and $Absorbency(p_k)$, respectively. Probabilities based on absorbency are distributed to the eight directions and calculated by the equations

$$A_k = \frac{Absorbency(p_k)}{A_{sum}} \quad (16)$$

$$A_{sum} = \sum_{i=1}^{8} Absorbency(p_i)$$

where A_k (k = 1, 2,…, 8) is a probability based on absorbency.

The Factor of Paper Texture

While water pulled by capillarity and flowing in the holes of fibers, fibers in the trajectory of water flow are saturated with water. For this phenomena of capillarity, different kinds of alignment of fibers result in different trajectories of water flow. The texture of Hsuan paper was, as a rule, solid, firm, unblemished, white and most hospitable to ink. After material choosing, steaming, bleaching, stamping, and baking, the paper was made with dense, fixed, irregularly distributed, and interlocked fibers of the material we use. According to those processes of manufacturing, the alignments of fibers in the paper structure are chaotic. In other words, the distribution of fibers in paper structure is uniform. When water in a certain papel determines the next papels to flow in, the probabilities of its eight candidate neighbors are almost the same for uniform distribution of fibers in paper mesh based on the factor of paper texture.

The second kind of representative paper usually used in ink painting is silk paper. Because of the drawback of difficult preservation, the ancients discovered that silk paper is a good substitute for Hsuan paper. Besides the convenience of preservation, it has good ability of absorbency the same as Hsuan paper. Silk paper is handmade and woven in perpendicular directions. The special process of manufacture differing from the Hsuan paper results in different kinds of distribution of fibers. For the reason, the directions of water flow are mainly vertical or horizontal when the water flowing in the holes of fibers in a piece of silk paper.

Huang [13] took the texture of paper into account as a factor determining the directions of water flow. Since the distributions of fibers in paper structure are not the same, the textures of paper are different. When the water particles in a papel c_0 decided to flow out, we cover c_0 with a 3×3 *texture mask*, denoted as M_{direct}, with the center element m_0 positioned at c_0. The eight elements in periphery of M_{direct}, denoted as m_k (k = 1, 2, …, 8), are weights used to represent the alignment of fibers of different kinds of papers. For a simple instance, we use two kinds of M_{direct} to represent the texture of Hsuan paper and silk paper, as shown in Figure 4.11.

In Figure 4.11(b), all of the elements in periphery set to 1 express that all the eight probabilities of flowing direction of neighboring papels are equal because of random, uniform distribution of fibers. Elements in horizontal and vertical directions given larger value than those in diagonal direction, as shown in Figure 4.11(c), expresses the regular distribution of fibers in silk paper.

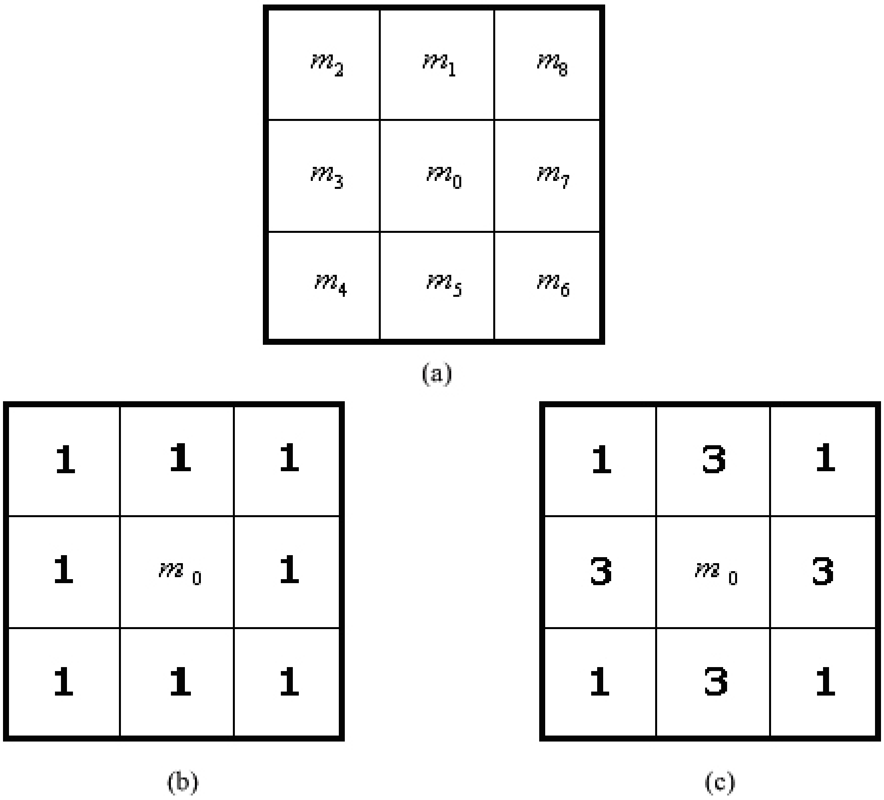


Figure 4.11 (a) Texture mask; (b) One example of texture mask for Hsuan paper; (c) One example of texture mask for silk paper. m_0 is the center element in the mask positioned at c_0 (Courtesy of Huang).

The Factor of Inertia

Besides those three factors we have mentioned above, there is still an important physical mechanism we need to take into consider. Every moving object without actively motive power could not be moved to the next area without inertia. With inertia, object will move to next place by the remaining power acted on it and will not stop moving immediately. According to the conception of *Newton's First Law Of Motions*, we discover that inertia increases when the weight of object increases. In the other hand, decreasing inertia decreases the weight of object. In our case, water is treated as moving object. Assume that water in papel p_0^t in (t)-th time interval is originated from papels p_k^{t-1} (k = 1, 2, …, 8) in (t-1)-th time interval, and the quantity of water particles flowing along with direction d_i^{t-1} (i = 1, 2, …, 8), from p_k^{t-1} to p_0 is w_k^{t-1}. Based on the conception about the relationship between inertia and weight of object, we conclude that water in p_0^t will intend to flow out in the same direction with which w_k^{t-1} flowing along. The probabilities of the eight neighboring flowing directions from p_0^t, denoted as I_k^t (k = 1, 2, …, 8), is proportional to the quantity of w_k^{t-1} in direction d_i^{t-1}, as shown in Figure 4.12.

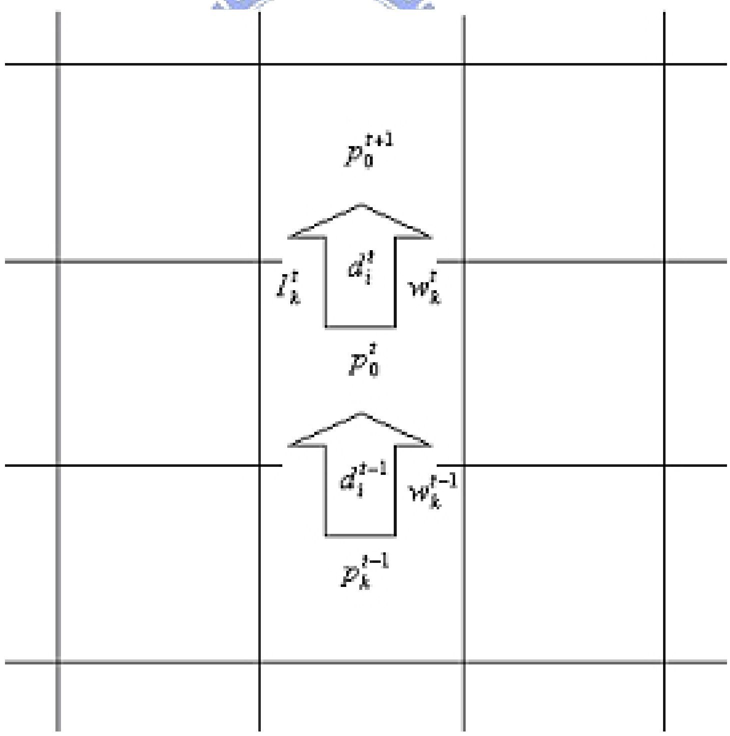


Figure 4.12 The direction of flow due to inertia and the probability of flow direction is proportional to the quantity of incoming water flow (Courtesy of Huang).

The probabilities used for determining the directions of water flow movement, i.e. the next area to flow into, are determined by using the four factors described above. The higher the probability of the neighbor cell has, the more the water flow toward it. The probabilities can be described as

$$R_k = \frac{\alpha_1 G_k + \alpha_2 A_k + \alpha_3 m_k + \alpha_4 I_k^t}{R_{sum}}$$

(17)

$$R_{sum} = \sum_{i=1}^{8} (\alpha_1 G_i + \alpha_2 A_i + \alpha_3 m_i + \alpha_4 I_i^t)$$

where R_k (k = 1, 2, …, 8) is the probability involving four dominant factors of each neighboring papels and α_1, α_2, α_3, and α_4 are weights for controlling behavior and movement of water flow resulting in different kinds of effects.

The directions of water particles, i.e. the meshes water flow will move to next, are determined by using these probabilities. The quantity of water flowing to neighbor papel p_k (k = 1, 2, …, 8) is proportional to the probability R_k been counted.

4.2.5 Ink Diffusion Process

In Huang's [13] ink diffusion process, the whole process includes skeleton finding, initial area pipelining and propagation process. Since the input of our proposed system is constructed by the user, there is no need to find the input skeleton. If we draw a stroke on paper in real world, we can observe that the ink diffusion process starts at the beginning of the stroke and then continues to the path the stroke is drawn. We therefore apply this phenomenon into our proposed system. That is, when the user input a stroke, we put all the pixels in the stroke into a queue in proper order. Then we do the diffusion process in proper order to every pixel (papel) in the queue, as shown in Figure 4.13, which is, move the water particles in the papels and then move the carbon particles according to the methods described in the last four sections.

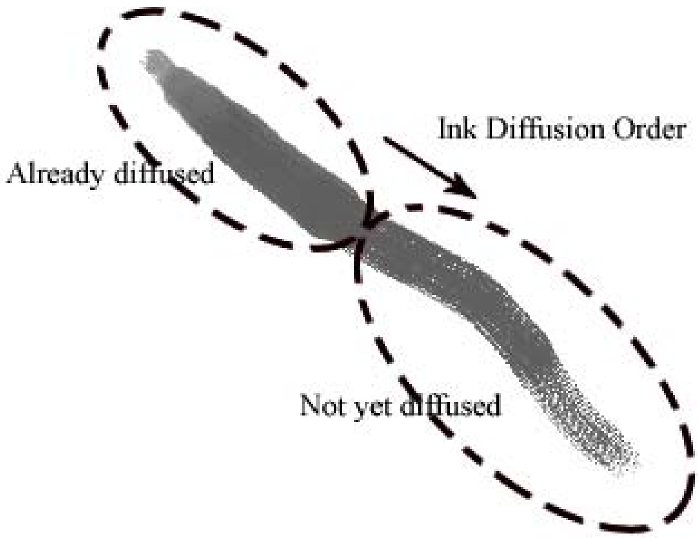


Figure 4.13 Ink diffusion order.

In real world, after drawing a stroke on paper, the wet stroke will dry out gradually. This phenomenon is called **evaporation**. The evaporation of water is a complicated process in which many factors play a role. One important factor is the contact area with atmosphere [20].

When other factors are almost fixed, larger contact area results in higher rate of water evaporation. In Huang's [13] thesis, the contact area of each papel with atmosphere is equal. Based on the equality of the contact area of all papels, the rate of water evaporation in each papel of the paper is approximately equal. There is another important factor which is in opposite to the evaporation of water, called *humidity* [20]. For the simplicity and the demand of our theorem, we assume that the number of water particles evaporated in papel p at step t-th, E_p^t, depends on the humidity H ($0 \le H \le 1$) and is expressed by the equation

$$E_p^t = h(1-H) \times Water_p, \tag{18}$$

where $Water_p$ is the number of water particles in papel p, and function $h(x)$ yields a coefficient for the evaporation of water, where $0 \le x \le 1$. Figure 4.14 shows an example of the function h. The less the humidity, the greater is the amount of water evaporated.

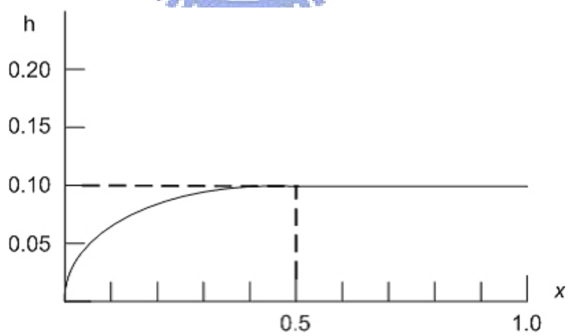


Figure 4.14 Function $h(x)$ for determining the quantity of water evaporated (Courtesy of Huang).

4.3 Color Representation

In the proposed system, we classify the pigments into three types: **ink**, **color** and **water pigment**. Although there are three different types of pigments, they share the same diffusion process. The colors of the first two types, **ink** and **color pigment**, are represented according to Kubelka-Munk theory [9, 15]. As for the third type of pigment, **water**, its color is represented by another model, which will be discussed in section 4.3.2.

4.3.1 The Colors of Ink and Color Pigment

Kubelka-Munk (KM) model is to perform the optical composition of pigment layers. In KM model, there are two coefficients to be defined for each pigment, namely absorption coefficient K and scattering coefficient S. A certain fraction, K, of the light traveling in each direction will be absorbed by the pigment material, and another portion, S, will be scattered. In fact, the K and S coefficients for a given pigment are determined experimentally using spectral measurements in typical applications of KM theory. But we can observe that all that matters in KM model is the ratio of these two coefficients, not the values. Therefore, we set the scattering coefficient S to 1 and only compute the absorption coefficient K by the following equation, which is referred in KM theory.

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \tag{19}$$

where R is the reflectance of the pigment in each RGB color channel and its value is between zero and one.

For a pigmented layer of given thickness x (where x is the ratio of the number of the remaining carbon particles to the maximum carbon capacity in each papel) with absorption and scattering coefficients K and S, the KM model can compute reflectance R and transmittance T through the layer [15]:

$$R = \sinh bSx / c$$

$$T = b/c \tag{20}$$

where $c = a \sinh bSx + b \cosh bSx$, $a = (S+K)/S$ and $b = \sqrt{a^2 - 1}$. Then we use the optical compositing equations in KM model [20] to determine the overall reflectance R and transmittance T of two layers with reflectances R_1, R_2 and T_1, T_2, respectively:

$$R = R_1 + \frac{T_1^2 R_2}{1 - R_1 R_2}$$

$$T = \frac{T_1 T_2}{1 - R_1 R_2} \tag{21}$$

When a new stroke is drawn on the canvas, the computation of Equation 21 is repeated to get the overall reflectance R of each pixel to render. Note that for more than one pigment of thickness $x^1, \ldots, x^k$, the K and S coefficients of each pigment are weighted in proportion to that pigment's relative thickness x^k and the overall thickness of each papel is accumulated with the pigment's thickness painted on it. Figure 4.15 shows the mixture result of three colors. Note that the colors in the accumulated pigment area in the simulated result (b) resemble to the correspondent area in the real image (a).

Figure 4.15 Color mixing. (a) The real image. (b) The simulated result.

For the color representation of pigment type **ink**, the reflectance R in each RGB channel are set to the same value. Since we divide the concentration of ink into five levels in our proposed system, the reflectance of each level are 0.01, 0.1, 0.2, 0.3 and 0.4, respectively.

4.3.2 The Water Effect on Paper

When we apply water on paper, the wet area looks darker than the dry area. This phenomenon is caused by the reflection and scattering of light on the paper surface. In our proposed system, we simulate the water effect in a simple way and define the wet area as a mask. When users choose pigment type **water** to draw an area, the diffusion process works the same as that for **ink** and **color pigment**. Once the diffusion process is over, the number of carbon particles in each papel is use to construct an alpha mask; that is, the alpha value of each papel is in proportion to the number of the remaining carbon particles. We use this mask to filter the canvas and create an effect of water flowing into paper, as shown in Figure 3.4 in Chapter 3.

Chapter 5

Implementation Results

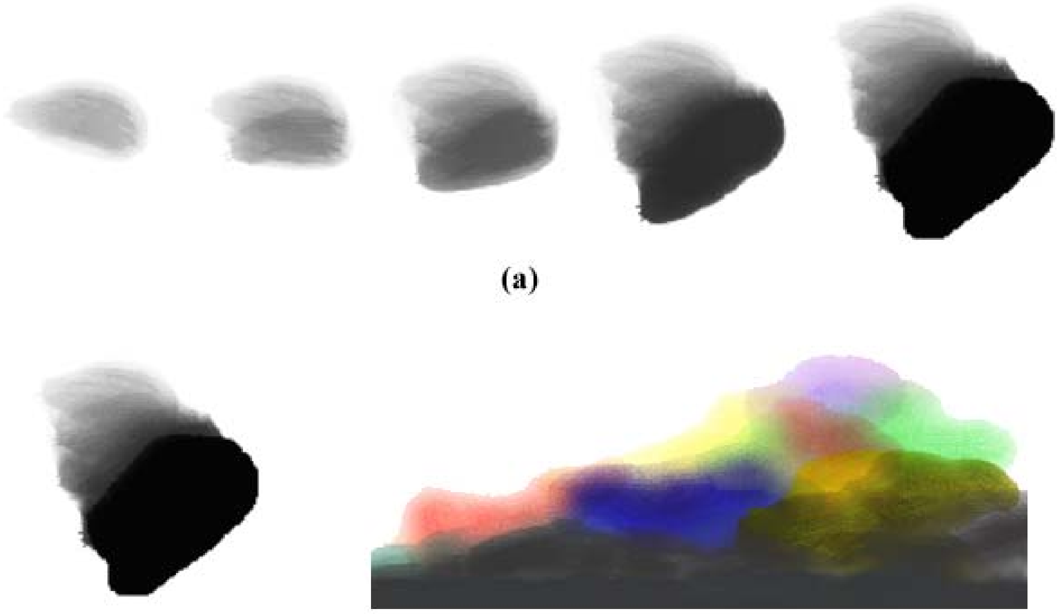
The implementation results of our proposed system are presented in this chapter. The system is written in C++ language and runs OpenGL on the PC platform with an AMD 1.4GHz CPU and 256 MB RAM.

Figure 5.1 shows the results of using our proposed system as Huang [13] did. Figure 5.1 (a) is the simulating result of dripping a drop of ink on Hsuan paper, which is done in interactive rate (within one second). And the effect of blending two brush, “dense brush following dilute brush” (濃墨破淡墨) process, is presented in Figure 5.1 (b). It is done by applying a dense brush stroke on the area where you have previously drawn a dilute brush stroke. And the dense stroke must be drawn before the dilute stroke is dried. Figure 5.1 (c) displays the stroke of dry brush by decreasing the water quantity of the brush (set the water number to be under 50).


(a) (b) (c)

Figure 5.1 Basic effects in Chinese Ink Painting. (a) A drop of ink. (b) Dense brush following dilute brush. (c) Strokes of dry brush.

Figure 5.2 (a) shows the blending result of several strokes with different concentrations. By accumulating several strokes from thin to thick, users can get their desired ink blending effects in Chinese Ink Painting. Figure 5.3 (b) shows the blending effect of color pigments and ink.


(a)

(b) (c)

Figure 5.2 (a) The sequence of several strokes. (b) The blending effect of several strokes. (c) The blending effect of color pigments and ink.

In Figure 5.3 and Figure 5.4, we mimic two Chinese ink paintings drawn by Chang Dai-chien with the tablet pen device in our proposed system and the original paintings are attached for comparison. The painting time for the simulated images in Figure 5.3 and Figure 5.4 varies with the complexity of the original paintings: Figure 5.3 is within three hours while Figure 5.4 is about five hours. During the painting time, the ink diffusion process of each stroke is done in interactive rate (in seconds; the actual time depends on the size of the stroke: the larger the size of the stroke, the longer the processing time).

Figure 5.3 (a) The original painting “Bamboo and Chrysanthemum” by Chang Dai-chien. (b) The simulated result.

(a) (b)

Figure 5.4 (a) The original painting “Fisherman Return” by Chang Dai-chien. (b) The simulated result.

Figure 5.5 references a bird photo to draw an original Chinese Ink Painting with our proposed system. More original paintings drawn with the proposed system can be seen in Figure 5.6 to include more kinds of materials in Chinese Ink Painting.

Figure 5.5 Top: The painting using the proposed system. The photo in the right is used as a reference.

Figure 5.6 Several paintings using the proposed system.

How the Proposed System Works

Here we present a demonstration of mimicking a Chinese Ink Painting "*Ling-chih Plants, Symbols Of Longevity*" by Chang Dai-chien [7] to show how the proposed system works and how to use the proposed system. We first depict the shape of the plants by selecting the brush type "**normal brush**" and pigment type "**ink**." Note that we would like to use dry brush effect to draw the plants, so we don't need high water quantity in the brush. The quantity of water is decreased to 52, as shown in Figure 5.7.

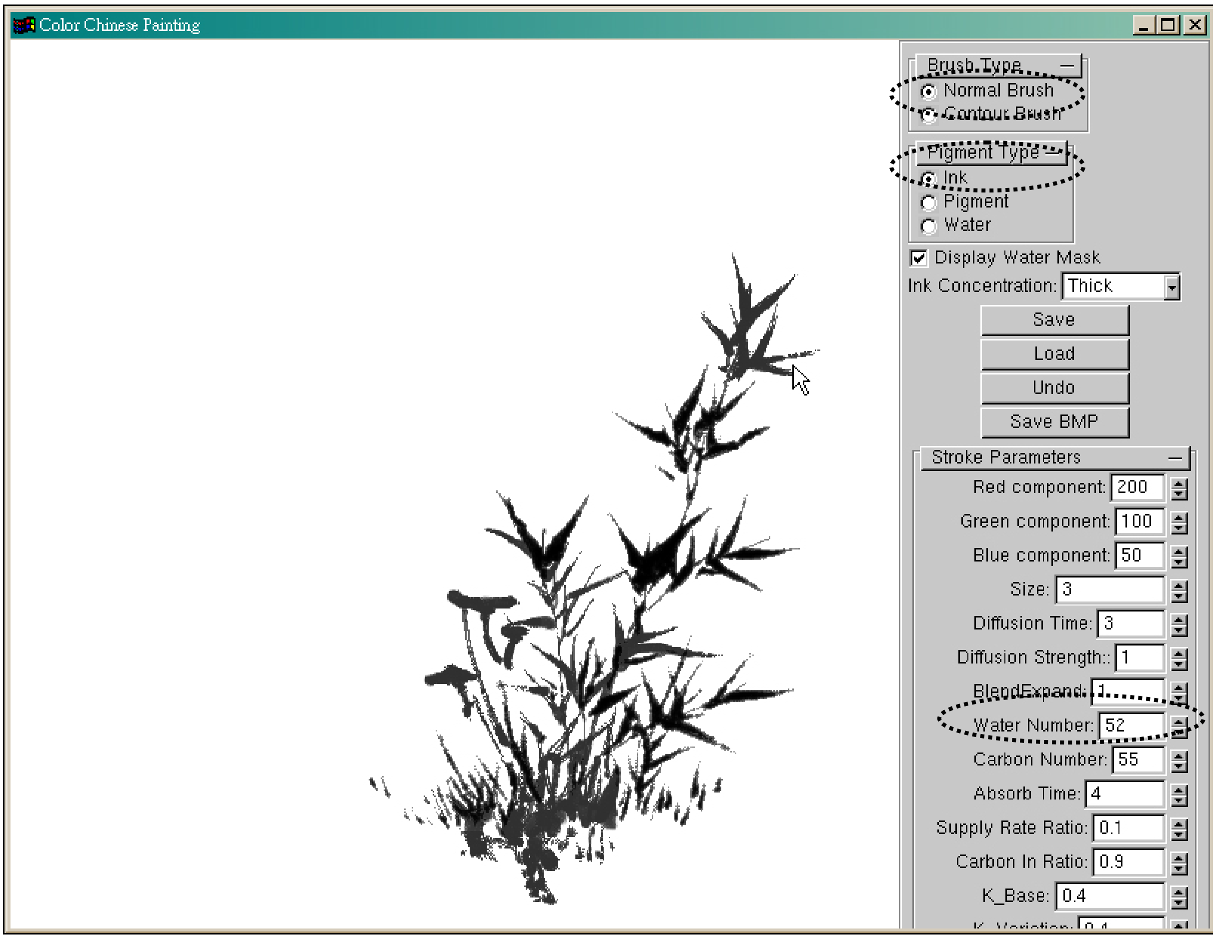


Figure 5.7 Using Dry Brush to Draw the Plants and Grass.

Next, we draw the leaves of the plants on the left by selecting the brush type "**contour brush**" and setting the stroke size to 2, as shown in Figure 5.8.

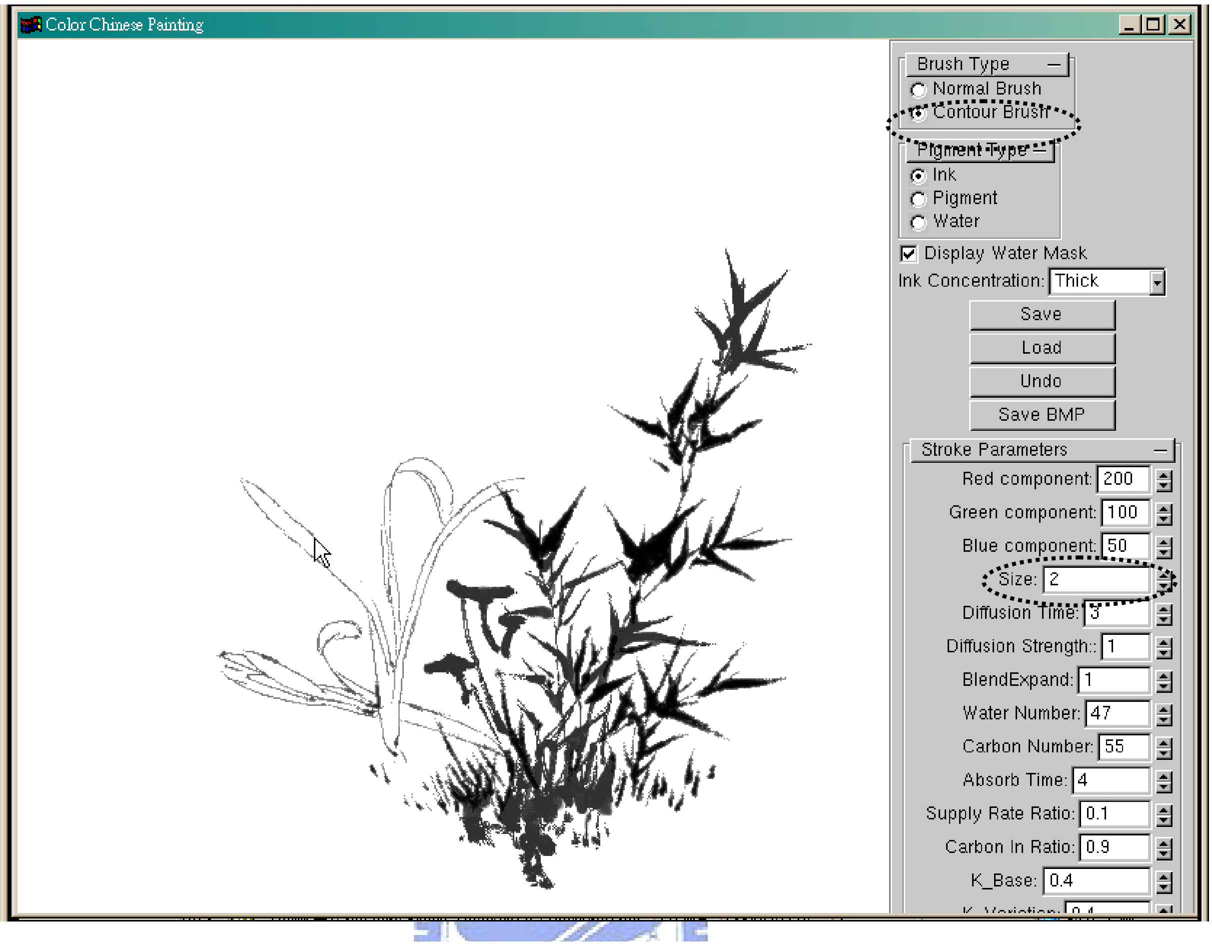


Figure 5.8 Using Contour Brush to Draw the Plants on the Left.

Then we go on drawing the rock using normal brush. By changing the ink concentration, we can depict the texture of the rock. After the shapes of all objects in the painting are drawn, we then apply color on each object. First, apply color on the rock by selecting pigment type "**color pigment**." After it is set, input the value of each RGB color channel and increase the quantity of water on brush to create more diffusion effects. Finally, we can draw the region of the rock by setting the stroke size to 6, as shown in Figure 5.9.

In Figure 5.10, we continue to apply color on the plant on the left. Since the leaves of the plant are thin, we don't want the stroke to be diffused widely. The quantity of the water is decreased and another color is set to paint the leaves.

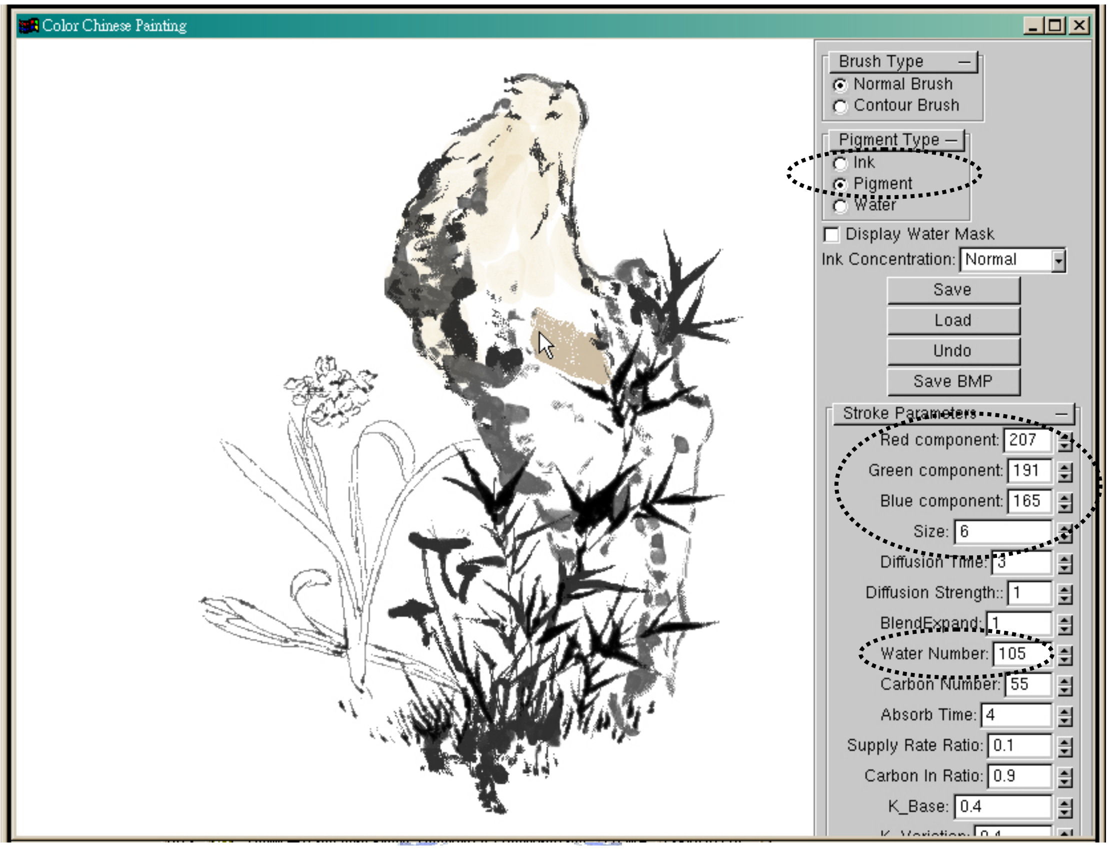


Figure 5.9 Apply color on the rock.

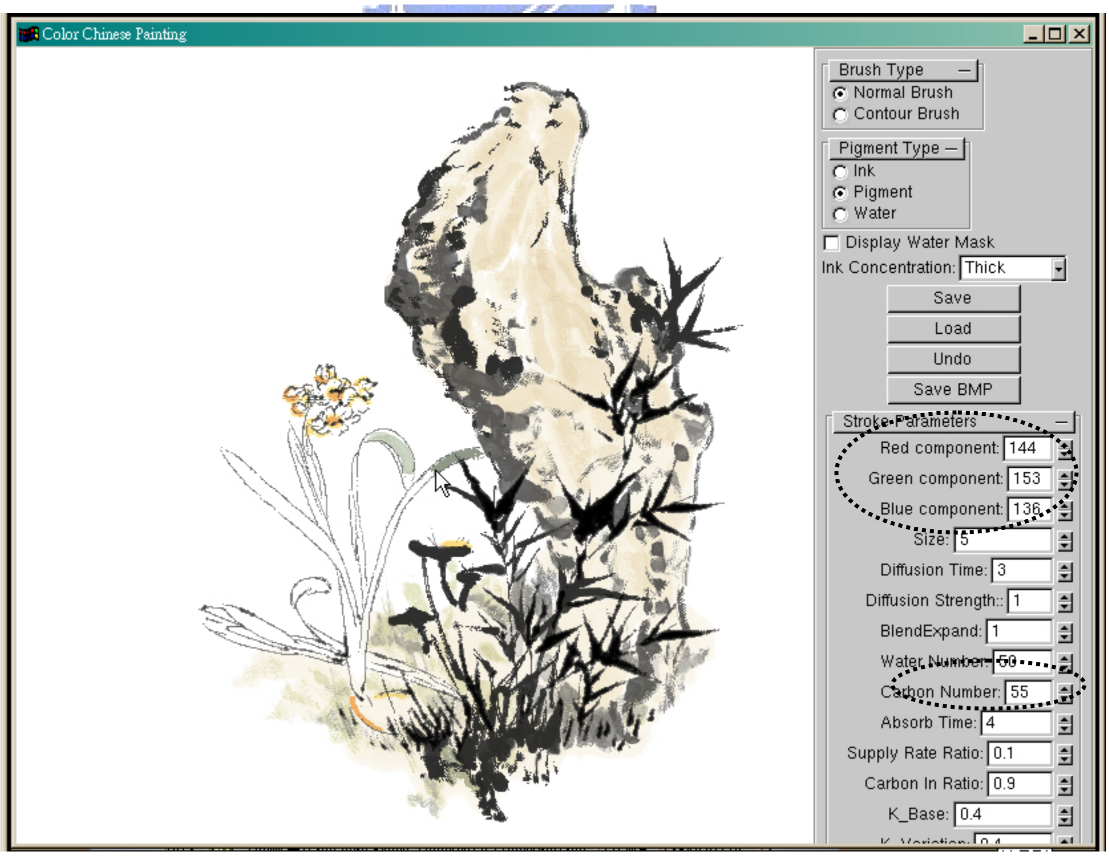


Figure 5.10 Apply color on the leaves of the plant.

Figure 5.11 shows the comparison of the final painted result (right) with the original painting (left).

Figure 5.11 Left: The original painting “Ling-chih Plants, Symbols Of Longevity” by Chang Dai-chien.
Right: The simulated result.

Chapter 6

Conclusions and Future Works

In this thesis, we propose an interactive system for Chinese color ink painting. The proposed system is composed of three main parts: a simple brush model to simulate Chinese writing brush, a method to generate ink diffusion effects in Chinese Ink Painting and a model to represent colors of pigments.

The brush model we proposed can produce good Chinese Painting strokes with tablet pen as the input device. By detecting the input pressure of the tablet pen, we can get various strokes with different shapes.

The diffusion model is based on real physical phenomenon. The paper mesh is separated into multi-layer X-Y planes, each of them divided into paper cells. Water particles flow in the holes or spaces of fibers of the paper mesh by capillarity. The carbon particles float and move in this liquid due to the collision with water particles. The directions and quantity of water flow are determined as a result of different degree of water absorbency, the alignment of fibers, and the factor of inertia of each paper cell. This ink diffusion algorithm can be used to draw lots of subjects with ink diffusion effect in Chinese Ink Painting style by controlling the user-defined stroke parameters. The most important is the effect of expressing the mixture of different kinds of brush strokes. For example, the effect of two wet brushes blend with each other. “Dense brush following dilute brush”, is a typical example in Chinese Ink Painting. Besides, since the proposed algorithms are based on physical theory and observational-based analyses, resulting images using this physical-based method are very realistic.

By adapting KM theory, the color of each pigment is correctly computed. First, we transform the user input RGB reflectance into reflection and transmission coefficients. Then we apply KM equations with the transformed coefficients to get the reflectance R in each RGB color channel on paper. The color of several overlaying pigments can also be represented accurately by computing the reflectance R in each RGB color channel with the reflection and the transmission coefficients.

Further works have to be done:

1. Although the brush model we proposed can generate fair stroke results, there are still some effects cannot be generated: the brush splitting effect and the various brush effects created by deforming the brush hair and changing the hand gesture while painting. In the future, we hope to improve our brush model by proposing a more complex one to simulate all the effects of Chinese Ink Painting.

2. The processing time of the ink diffusion process depends on the area of the input stroke. The larger the input stroke area is, the longer time the diffusion process takes. Although we can achieve interactive rate during painting, the input strokes with large area still take lots of time to finish the diffusion process. Therefore, we will implement the ink diffusion process on hardware to decrease the processing time of the proposed system.

3. The resolution of our proposed system is restricted (the current resolution is 600*600 pixels). We refresh the whole screen pixels in each time step even when the stroke only

occupies few parts of the whole screen. For the efficiency of the refreshing time, the screen resolution should not be too large. As to this problem, we will try to do some improvements in the future, such as subdivide the whole screen into several parts and only refresh the parts where the stroke occupies.

4. Currently, the color representation of our proposed system simulates the composition of color pigments. Besides the effects of overlaying color pigment, there are still some other common mixing effects created by mixing colors on canvas in real paintings. We will attach the mixing color on canvas feature to our proposed system in the future to create various mixing color effects on canvas.

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