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Computer-generated Chinese color ink paintings

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PLEASE SCROLL DOWN FOR ARTICLE

COMPUTER-GENERATED CHINESE COLOR INK PAINTINGS

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ABSTRACT

Chinese color ink painting is a traditional art form, a non-photorealistic rendering, that is over three thousand years old. Simulating the behavior of Chinese ink is challenging. Various artistic effects of color ink diffusion are analyzed, and a scheme presents how they can be simulated automatically for their computer-generated simulation. The proposed method simulates various tonal expressions on different papers, by employing a Kubelka-Munk model to simulate optical effects. Elucidation of the effect of mixing simulated strokes with different brushes is a significant contribution of the proposed method. Finally, results of this study demonstrate the effectiveness of an interactive painting system. Also, results are compared with genuine ink paintings.

Key Words: non-photorealistic rendering (NPR), Chinese ink painting, color ink diffusion, Kubelka-Munk model.

I. INTRODUCTION

Several studies in recent years have focused on western painting techniques and styles, including watercolor, impressionistic, pencil sketching and hatching (Elberg, 1999; Freudenberg, 2001; Hertzmann and Zorin 2000; Markosian *et al.*, 1997; Sousa and Buchanan, 1999). Although, these methods yield good results for Western painting, these methods are not suited to Chinese ink painting. Generally, a Chinese-ink artist can apply thousands of styles while painting, by combining different brush strokes with rich ink gradations. Ink and color diffusion is crucial in Chinese ink painting, It generates numerous effects such as the fluffy-edged effect, a variety of ink intensities, blurring the boundaries of a stroke, and merging of two strokes, among other effects. Unlike western paintings that generally explore changes in light and color, Chinese ink paintings focus primarily on the combination of shape and color. Ink brush strokes delineate the subject. Color,

on the other hand, is utilized to flesh out the subject. An example of Chinese ink painting, by Chang Dai-chien, is shown in Fig. 1 (Gao, 1998).

In watercolor paintings, paper absorbency is not so high that water and color pigment both flow on paper. Therefore, a shallow water simulation is required to simulate color pigments flowing on paper. Small (1990) proposed a parallel approach to derive the action of pigment and water on paper fibers. Curtis *et al.* (1997) employed a more sophisticated paper model to simulate watercolors more realistically. It adopted a more sophisticated paper model, a more complex shallow water simulation, and a more faithful rendering and optical composition of pigmented layers, based on the Kubelka-Munk model. Unfortunately, the characteristics of Chinese ink painting differ from those of watercolors. The physical behavior of watercolor differs from that of Chinese ink. Furthermore, the paper used in Chinese ink painting is different from that used in watercolor painting. The absorbency of Hsuan paper used for ink paintings is very high. Consequently, water in a brush is immediately absorbed by the paper once the brush touches the paper and the ink and color then flow among the paper fibers. To express the unique characteristics of Chinese ink painting, a diffusion model was proposed to simulate the flow of particles in paper.

The rest of this paper is organized as follows. Sec. II describes previous work. In section III, the

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Fig. 1 "Ling-chih Plants, Symbols of Longevity" by Chang Dai-chien

properties of Chinese ink painting are introduced. A detailed description of the motion of the water is described in Sec. IV. Ink diffusion is analyzed in Sec. V. The color representation of Chinese ink painting, introducing a Kubelka-Munk model is shown in Sec. VI. In Sec. VII, the results generated by the proposed system are discussed. Finally, conclusions and possible directions for future work are provided in Sec. VIII.

II. PREVIOUS WORK

Little research has addressed methods for simulating brush strokes (Lee, 1999; Strassmann, 1986; Wong and Ip, 2000; Yeh *et al.*, 2002; Zhang *et al.*, 1999) and the behavior of ink (Guo and Kunii, 1991; Lee, 2001) in color ink painting (Chu and Tai, 2005). The brush has been modeled as a collection of bristles that move in the course of the stroke. Wong and Ip (2000) modeled a calligraphy brush as an inverted cone. Strassmann (1986) first described the hairy brush as a 1D array of bristles. Jintae Lee (1999) presented a model for elastic bristles governed by Hooke's law. Guo and Kunii (1991) first addressed ink diffusion in 1991. The diffusion of ink into absorbent paper is one of the most notable features of black ink painting (called Sumie in Japanese). Zhang *et al.* (1999) presented a 2D simple cellular automaton-based simulation model ink behavior. Lee (2001) rendered black ink paintings that applied new paper and ink diffusion models. Although these methods for simulating brush strokes and the diffusion of ink realistically reproduced the diffusion of a single stroke, no mechanism has been presented to simulate the blending of two or more different brush strokes and color diffusion. Accordingly, the simulated results in the above papers were not compared to real ink paintings.

Chu and Tai (2004) designed a deformable brush model as a single tuft. The brush geometry includes a spine and some lateral nodes. The spine handles the general bending of the entire tuft; the lateral nodes model the tuft's lateral deformation and spreading. A static split map was applied to the single tuft. The split map is an alpha map for making part of the tuft surface transparent. They also investigated three ink-depositing variations: a dry brush, a soaked brush, and grain texture. However, their brush model certainly can't mimic every way real brushes respond to artists' manipulations. A good behavior function should include parameters that the user can adjust intuitively to derive brush variants.

Chu and Tai (2005) extended their previous work to simulate ink painting in real time with the lattice Boltzmann equation. They modify the basic equation for the physics of ink flow in absorbent paper. The modifications include the incorporation of variable permeability, modulated advection, and boundary roughening. Various ink effects, including complex branching patterns, and spontaneous shape evolution are achievable under this unified model. Very beautiful ink paintings were simulated. But the resulting images should be compared with actual paintings.

Way and Shih (2001, 2002) have implemented the effects of brush strokes and developed a brush model that combines two mechanisms: stroke geometry and brush profile. We (Way *et al.,* 2003) also provided a new method for simulating the diffusion of black ink in different types of paper. Our previous method was based on a physical mechanism and an observational model for interaction among real drawing materials used in Chinese ink painting and the diffusion of ink in the real world.

This paper improves on previous works by simulating color ink diffusion. The proposed method has the following advantages. First, it simulates the physical behavior of color ink diffusion, and can thus generate strokes that exhibit feathery effects. Second, it can blend two strokes with different thicknesses. This method can generate highly realistic blending effects in Chinese color ink paintings. Third, in order to capture the essential physical properties and behaviors of Chinese ink painting, users can apply a high-quality ink diffusion model to generate a Chinese color ink painting.

III. PROPERTIES OF CHINESE INK PAINTING

Chinese ink painting uses four tools commonly called the four treasures: brush, ink stick, ink stone and paper; all are used in calligraphy, writing and

Fig. 2 An example of ink diffusion in Hsuan paper

(a) 0.1   (b) 0.4   (c) 0.7

Fig. 3   Three simulated ink diffusion images represent different kinds of paper with different degrees of absorbency

painting in China. Typically, when the brush bristles touch the surface of the paper, the ink from the bristles seeps into the highly absorbent paper, creating a stroke whose edge is fluffy and blurred. These diffusion characteristics are complex physical phenomena that cannot be accurately simulated by conventional graphical techniques, such as texture mapping or degradation functions, as purely mathematical approaches generally result in flat blurred images that are unlike real diffusion images (Chiu and Chow, 1979; Liu, 1984).

The ink is a colloidal liquid. Diffusion phenomena are considered typical instances of the diffusion of a colloidal liquid in a highly absorbent paper. The capillary effect in the paper causes ink to diffuse into the structure of the paper. Typical paper consists of fibers layered in random positions and directions; small holes and spaces among the fibers act as thin capillary tubes that carry ink away from the area where it was initially applied and causes diffusion, as shown in Fig. 2.

Moreover the forces that move the ink include interactions among water molecules, water and carbons, and the force of gravity, among others. Color ink is a dilute mixture of water, colloidal black carbon particles and pigment that diffuse into paper. Water and carbon are the two main components of Chinese ink. The motion of ink among fibers is discussed in section III.2 and III.3

1. Paper Cell

Several kinds of paper are used in Chinese ink painting. Typically papers are one of two fiber mesh types. The first is a regular fiber mesh, such as in silk paper, whose fibers are uniformly aligned as woven. The second type is an irregularly distributed fiber mesh, such as in Hsuan paper, that consists of a mesh of randomly positioned fibers.
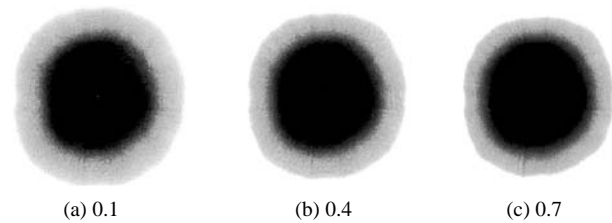
Constructing a mesh, such as that in Hsuan paper, requires an appropriate data format that represents a mesh structure. Traditionally, a network format was applied to represent papers with random fiber networks (Guo and Kunii, 1991). The continuous interaction between water and fiber was discretely simulated by computers; a two-dimensional array, whose entries specify the structural attributes of the mesh, was employed. A papel (paper element) is a basic unit of paper structure and corresponds to a pixel.

The ink seeps into the paper and is then pulled away from the application area by capillary attraction and then is absorbed by the fibers. Some of the diffused ink is deposited in the holes or spaces between fibers and the remaining ink continues to flow along the fibers until it is completely absorbed.

Let $Absorbency(p)$ of papel p be defined as follows. When the moving ink passes through p with N fibers, the amount of water deposited in p is Q. The relationship between Q and N can be expressed as $Absorbench(p) \propto N \propto Q$. Based on this relationship, several techniques can be defined for paper with various absorbencies and with fibers of various densities. An equation for the absorbency of each papel is

$$Absorbench(p) = Base + Var \times random() \quad (1)$$

Figure 3 illustrates the resulting ink diffusion in three types of paper, each with a different absorbency. The coefficient of absorbency is a real number between 0 and 1.

2. Water Particles

Capillary forces can move water anywhere on the paper. All water particles are defined as having the same volume, mass, color and response to forces. The water only differs in position, recorded as papel coordinates. The quantity of water governs the span of the diffusion image or the number of diffusion steps. When the water in a certain papel flows out, its quantity and direction must be determined.

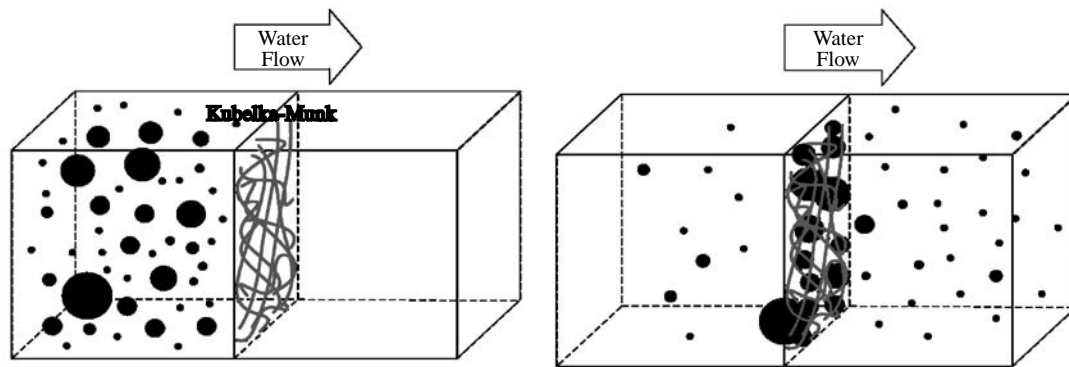The approximate equation for $K(p)$, the ratio of the quantity of out-flowing water of a papel p is represented as

Fig. 4 An illustration to explain the phenomenon called "*filter effect*"

$$K(p) = F_{base} + F_{diff} \times (1 - (1 - Absorbency(p)^2)) \tag{2}$$

where F_{base} is a real number between 0 and 1 that represents the basic flow rate of p, and F_{diff} is a real number between 0 and 1 that represents the difference between the highest and lowest flow rates. The quantity of water that flows to neighboring papels is determined by associated probabilities. Details will be discussed in section IV.

3. Carbon Particles

Carbon particles are black and solid-grained. They cannot move alone, but are suspended in water and carried by the moving water particles. Suspended carbon particles are affected by Brownian motion and buffeted water particles. The simulation of carbon particles is similar to the simulation of water. However, the movement of small and uniform carbon particles in water is unhindered by fibers, and, as such, the ink's intensity changes smoothly across the diffusion area. Carbon particles that are smaller than the spaces between fibers can seep into the mesh. Particles larger than these spaces remain in their initial positions, as shown in Fig. 4. This phenomenon is referred to as the filtering effect of the fiber mesh, and can be represented as follows.

if (Carbon_Diameter > Hole_Diameter(p)) then
    Carbon_Position ← p
else
    Carbon_Position ← Water_OutFlow_Direction(p)

where p is the papel in which the carbon particle is located.

In Fig. 4, black grains in papels are carbon particles of different sizes. Larger carbon particles cannot pass through holes in the paper. As well as the diameter-filtering mechanism, a mass-filtering mechanism is proposed. Suppose V_c is the velocity of a carbon particle c, suspended in water in papel p, and W_p is the quantity of out-flowing water from p. The relationship between V_c, W_p, and the diameter of holes in p ($Hole\_Diameter(p)$), is given by $V_c \propto W_p$, $V_c \propto \frac{1}{(Hole\_Diameter(p))^2}$. If a carbon particle c is too heavy to exit papel p and is deposited in p, then $V_c \leftarrow 0$. An upper-bounded threshold T_p for papel p determines whether the carbon particle can move out. If the mass of a carbon particle c exceeds T_p, then $V_c \leftarrow 0$. The value of T_p is determined derived depending on V_c. The relationship between T_p and V_c is represented as

$$T_p = T(V_c) = T(W_p \times \frac{1}{(Hole\_Diameter(p))^2}) \tag{3}$$

Where T is a transformation from V_c to T_p.

IV. MOTION OF WATER

Water flows from one papel to one of its neighboring eight papels. The flow directions are measured by considering the following factors that dominate the flow of water.
1. Gradient of water between neighboring papels, based on Brownian motion.
2. Absorbency of neighboring papels.
3. Paper texture of neighboring papels.
4. Inertia of water.

Figure 5 shows that a papel C_0 has eight neighboring cells p_k defining eight directions, d_k ($k = 1, 2, \cdots, 8$). The probabilities of motion in each direction are calculated according to the four factors listed. The number of water particles that flow into a neighboring papel is proportional to the calculated probability.

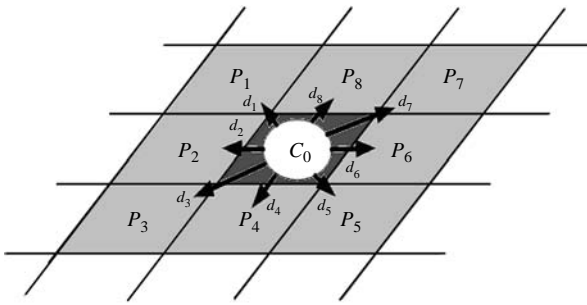### 1. Gradient

A mixture of two sets of different numbers of

Fig. 5 Determine directions of water flowing into neighboring papels, p_k ($k = 1, 2, \cdots, 8$), according to the probabilities in eight directions calculated based on four factors

water particles produces irreversible diffusion in which water particles are transferred from the set with more particles to that with fewer particles. Gradient represents the difference between the numbers of water particles in the two sets. The number of water particles in C_0 and p_k are assumed to be W_c and W_k, respectively. The probability, based on Brownian motion, is determined by the equations

$$G_k = \frac{u(W_c - W_k)}{G_{sum}} , \; G_{sum} = \sum_{i=1}^{8} u(W_c - W_i) \qquad (4)$$

where G_k is a probability determined by gradient, and $u(x)$ is the unit function; that is, if $x \geq 0$, then $u(x) = x$, otherwise $u(x) = 0$. Diffusion continues until the gradient is 0.

2. Absorbency

Attraction to each neighboring papel causes different amounts of water to flow into each. Newton's Second Law of Motion is $f_d = M \times \alpha$ (5) Dynamic friction f_d is ideally a constant force between the flowing water and the fibers. The term α is the acceleration of the flowing water particles. Based on the theorem of Theo, α is usually significantly smaller than g, the acceleration due to gravity. Therefore, α is regarded as constant. M is the mass of the flowing water particles. The pre-defined uniformity of the mass of water particles is such that the amount of flowing water is proportional to M. Assume N_w is the number of water particles in the flowing water.

From Eqs. (4) and (5), $f_d \propto N_w \times \alpha$. This important derivation verifies that N_w increases with f_d, based on the relationship in Eq. (3), $f_d \propto \alpha_p \rightarrow N_w \propto \alpha_p$, where α_p is the absorbency of papel p. Assume that the eight neighbors of the central papel C_0 are p_k, and the absorbency of C_0 and p_k are $Absorbency(C_0)$ and, $Absorbency(p_k)$ respectively. Probabilities, based on absorbency, are attributed to the eight directions, according to

$$A_k = \frac{Absorbency(p_k)}{A_{sum}} , \; A_{sum} = \sum_{i=1}^{8} Absorbency(p_i)$$

$$(6)$$

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

3. Paper Texture

The texture of the paper also determines the directions where water flows. When water undergoes capillary action, fibers in the trajectory of the flowing water become saturated. Various alignments of fibers promote different trajectories of flowing water.

Papers with different distributions of fibers have different textures. When the water particles flow out from papel C_0, C_0 becomes the center of a 3-by-3 texture mask, M_{direct}, with a central element m_0 at C_0. The eight elements at the periphery of M_{direct}, m_k ($k = 1, 2, \cdots, 8$), are assigned weights that represent the alignment of the fibers.

4. Inertia

Inertia is another important physical mechanism. According to Newton's First Law of Motion, inertia increases as the mass of an object increases. During painting, water is treated as a moving object. Assume that water in papel p_0^t in the t-th time interval originates from papels p_k^{t-1} in the t-1-th time interval, and the quantity of water particles flowing in the direction d_i^{t-1}, from p_k^{t-1} to p_0 is w_k^{t-1}. Based on the relationship between inertia and the mass of an object, water in p_0^t will flow in the same direction as w_k^{t-1}. The flow probabilities associated with the eight directions of p_0^t, I_k^t, are proportional to w_k^{t-1} in direction d_i^{t-1}.

The probabilities of inertia are used to identify the directions of water flow. A high probability of a neighboring cell corresponds to more water flowing into it. The probabilities are,

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

$$R_{sum} = \sum_{i=1}^{8} (\alpha_1 G_i + \alpha_2 A_i + \alpha_3 m_i + \alpha_4 I_i^t) \qquad (7)$$

where R_k ($k = 1, 2, \cdots, 8$) is the probability governed by four main factors for each neighboring papel and α_1, α_2, α_3, and α_4 are weights that guide the behavior and movement of water.

The directions of water particles and the points in the mesh to which water will flow are determined by adopting these probabilities. The quantity of water that flows to a neighboring papel p_k ($k = 1, 2, \cdots, 8$) is proportional to the probability R_k.
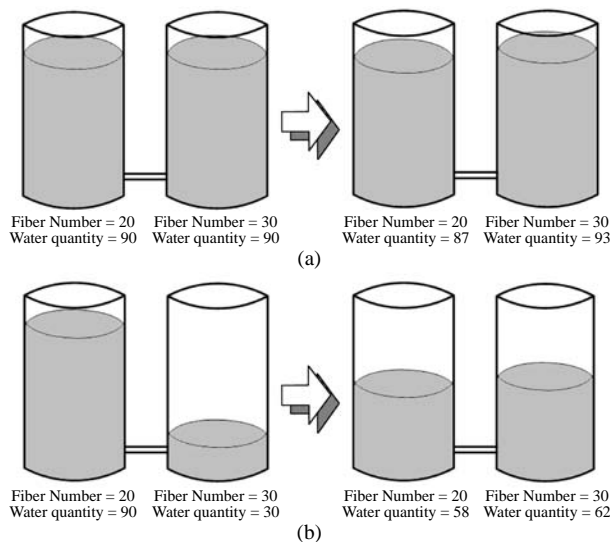
Fig. 6 Two illustrations are given to describe the water propagation influenced by capillary force and gradient of quantity of water, relatively

Fig. 7 Function $h(x)$ for determining the quantity of water evaporated

V. INK DIFFUSION

The diffusion of ink in paper is complex. It is regarded as continuous and time-dependent. Evaporation of water and absorption of ink remaining on the surface of the paper are also considered.

1. Ink Diffusion Schema

Ink diffusion is effected by the capillary action of water between fibers and the gradient for paper cells. Given two neighboring papels saturated with water, as shown in Fig. 6(a), only the strength of the capillary forces in these two papels influence the flow directions of the water. In contrast, if only one papel is saturated with water and the other is absolutely dry, as shown in Fig. 6(b), the water gradient between these two papels is maximal and results in an obvious propagation of water from the papel with substantial water to that with little.

2. Evaporation

In the real world, water evaporates continuously from paper. The evaporation of water is a complex process governed by many parameters. The area of contact with the atmosphere is an important parameter. When other parameters are fixed, a large contact area increases the rate of evaporation. Assume that the contact area of each papel with atmosphere is the same. The rate of evaporation from each papel is, then, approximately equal.

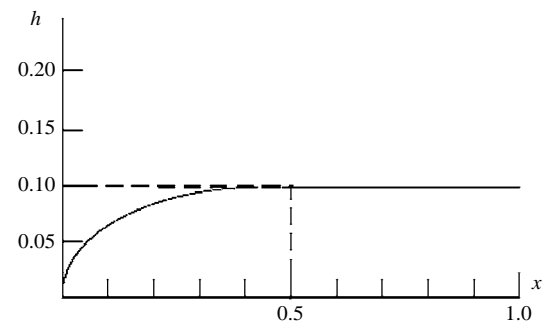Humidity slows the evaporation of water. For the sake of simplicity, assume that the number of water particles that evaporate from papel p at the t-th step, E_p^t, depends on the humidity H ($0 \leq H \leq 1$) according to the equation $E_p^t = h(1 - H) \times Water_p$, where $Water_p$ is the number of water particles in papel p, and function $h(x)$ yields a coefficient for the evaporation of water, where $0 \leq x \leq 1$.

VI. COLOUR REPRESENTATION

In the proposed system, the pigments are classified into three types: ink, color and water. Although there are three different pigment types, they all share the same diffusion process. The colors of the first two types, ink and color pigment, are represented according to Kubelka-Munk theory (Curtis *et al.*, 1997). As for the third pigment, water, its color is represented by another model, which is discussed in section VI.2.

1. The Colors of Ink and Color Pigment

The Kubelka-Munk (KM) model is applied to perform the optical composition of pigment layers. The KM model defines two coefficients for each pigment: absorption coefficient K, and scattering coefficient S. A particular proportion, K, of the light traveling in each direction is absorbed by the pigment, and another portion, S, is scattered. In fact, the K and S coefficients for a given pigment are determined experimentally by utilizing spectral measurements in typical applications of KM theory. However, the ratio of these two coefficients, not their individual values in the KM model is important. Therefore, the scattering coefficient S was set to 1 and only the absorption coefficient K was computed with the following equation.

$$\frac{K}{S} = \frac{(1 - R)^2}{2R} \tag{8}$$

where R is the reflectance of the pigment in each RGB color channel and its value is between 0 and 1.

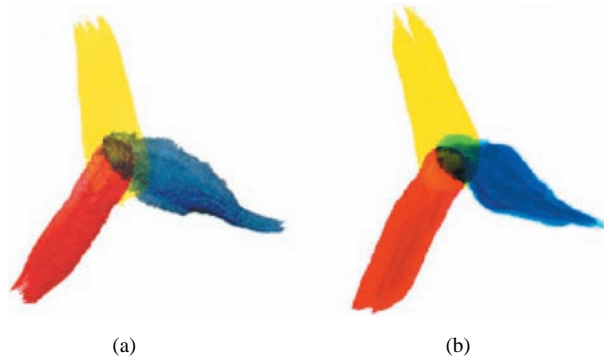For a pigment layer of given thickness x (where

(a) (b)

Fig. 8 Color mixing. (a) The real image. (b) The simulated result
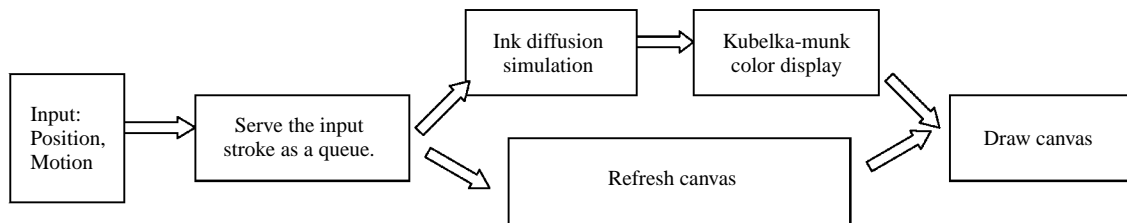

Fig. 9 System Architecture, the system processes the ink diffusion thread and computes the color by KM model in a parallel process way

x is the ratio of the number of the remaining carbon particles to the maximum carbon capacity of each papel) with absorption and scattering coefficients K and S, the KM model can compute reflectance R and transmittance T through the layer (Kortum, 1969):

$$R = \sinh bSx/c, \; T = b/c \tag{9}$$

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

$$R = R_1 + \frac{T_1^2 R_2}{1 - R_1 R_2} \; , \; T = \frac{T_1 T_2}{1 - R_1 R_2} \; . \tag{10}$$

When a new stroke is drawn on the paper, the computation of Eq. (10) is repeated to derive the overall reflectance R of each pixel to be rendered. For more than one pigment of thickness x^1, $\cdots$, x^k, the K and S coefficients of each pigment are weighted in proportion to that pigment's relative thickness x^k, and the whole thickness of each paper cell is accumulated with each pigment's thickness painted. Fig. 8 shows the result of mixing the three colors. Colors in the pigment area in the simulated result (b) resembled the corresponding area in the real image (a).

For the color representation of ink, the reflectance R in each RGB channel was set to the same value.

Since the concentration of ink was divided into five levels in the proposed system, the reflectance of each level was 0.01, 0.1, 0.2, 0.3 and 0.4, respectively.

2. The Water Effect on Paper

When water is applied to 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 the proposed system, the water effect is simulated in a simple way and the wet area is defined as a mask. When users choose pigment type water to draw, 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 used to construct an alpha mask; on the other hand, the alpha value of each papel is in proportion to the number of remaining carbon particles. The alpha mask is used to filter the canvas and create an effect of water flowing into paper.

VII. INTERACTIVE PAINTING SYSTEM

1. System Architecture

The complete proposed model is shown in Fig. 9. When strokes are drawn on the screen tablet, the system places all drawn pixels into a queue. The system then process the input queue for the ink diffusion thread. Simultaneously, the system processes
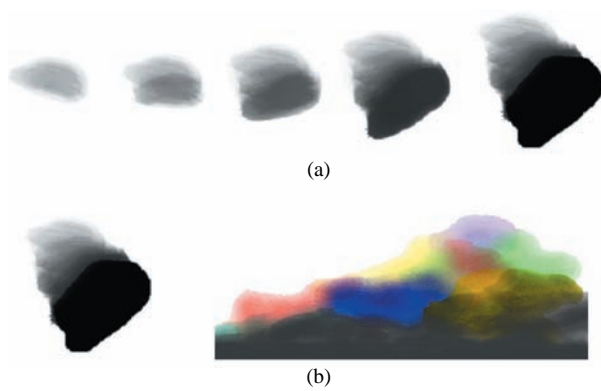
Fig. 10 (a) The sequence of several strokes. (b) The blending effect of several strokes. (c) The blending effect of color pigments and ink

Fig. 11 Left: The original painting "Ling-chih Plants, Symbols of Longevity" by Chang Dai-chien. Right: The simulated result

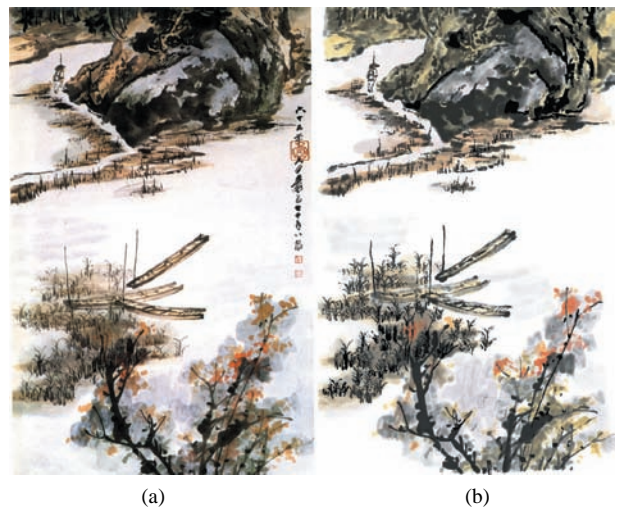Fig. 12 (a) The original painting "Bamboo and Chrysanthemum" by Chang Dai-chien. (b) The simulated result

Fig. 13 (a) The original painting "Fisherman Return" by Chang Dai-chien. (b) The simulated result

the ink diffusion thread and renders the color of each pixel computed by the KM model. By simultaneous processing, the ink diffusion threads and refreshes the screen. The idle time is also considerably reduced.

The system is written in C++ language and runs OpenGL on the PC platform with an AMD 1.4GHz CPU and 256 MB RAM. Fig. 10(a) shows the blending result of several strokes with different concentrations. By accumulating several strokes, from thin to thick, users obtain their desired ink blending effects for Chinese ink painting. Fig. 10 (c) shows the blending effect of color pigments and ink. Fig. 11 shows the painting resulting from the proposed system and the original painting.

In Figs. 12 and 13, two Chinese ink paintings were drawn using the tablet pen device in the proposed system. The painting time for the simulated images in Figs. 12 and 13 varied with the complexity of the original paintings. Fig. 12 was completed within one hour while Fig. 13 required about two hours to complete. During painting, the ink diffusion process for each stroke was completed in an interactive manner in seconds; actual time depends on the size of the stroke, i.e., the stroke size corresponds to processing time.

More paintings drawn with the proposed system are shown in Figs. 14 and 15, using the photo in 14 as an original.

VIII. CONCLUSIONS AND FUTURE WORK

This work presents a new scheme that generates the effects of ink diffusion in Chinese color ink painting. Paper is modeled as several X-Y plane layers, each divided into paper cells. Water particles flow into holes or spaces among fibers in the paper

Fig. 14   Top: The painting using the proposed system. The photo in the right is used as a reference

Fig. 15   Several paintings using the proposed system.

mesh through capillarity action. Carbon particles float and move in the ink. The direction and amount of flowing water are determined from absorbency direction and amount of flowing water. The color of each pigment has been correctly computed. First, the user input RGB reflectance was transformed into reflection and transmission coefficients. The KM equations with the transformed coefficients were applied to obtain the reflectance R for each RGB color channel on paper. The colors of several overlaying pigments were also represented accurately by computing the reflectance R for each RGB color channel reflection and transmission coefficients.

The proposed color ink diffusion algorithm can be adopted to produce Chinese ink painting style with colored ink diffusion effects. The most important contributions of this work are as follows.

(1) The resulting color ink paintings are very realistic, because the proposed algorithms are based on physical theory and analysis of observations.

(2) The most significant contribution of this proposed method is the expression of a mixture of different kinds of brush strokes, such as those of two wet brushes.

(3) The diffusion of brush strokes were easily controlled, according to experimental data, by specifying parameters. Users can easily apply these parameters to control local and global variations and achieve their desired effects.

This work has opened up a number of topics for future research. Several unknown factors affect the diffusion of pigment and should be addressed. For example, glue is a common ingredient in paper that reduces its ability to absorb water. The issue of the glue quantity added to paper should be addressed in future work. According to the proposed method, ink diffusion yielded strokes that were uniform and regular on boundary of the stroke. Mineral based pigments, which are extremely colorful, should be investigated also. This means non-uniform particles and lot of work. This also should be examined in future work.

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