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Droplet: A Virtual Brush Model to Simulate Chinese Calligraphy and Painting

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Abstract This paper proposes a virtual brush model based on droplet operation to simulate Chinese calligraphy and traditional Chinese painting in real time. Two ways of applying droplet model to virtual calligraphy and painting are discussed in detail. The second droplet model is more elaborated and can produce more vivid results while being slightly more time-consuming. The novel feature of the proposed droplet virtual brush model successfully enables the simulation painting system to overcome the poor expressional ability of virtual brush based on particle system and avoids the complex evaluation of physical brush with solid model. The model, derived from the actual calligraphy and painting experience, due to the simplicity of the droplet operation and its powerful expressive ability, considerably improves the performance of the simulation system and maintains painting effect comparable with real brush by supporting special Chinese brush effect such as dry brush, feng and stroke diffusion.

Keywords NPR, virtual brush, painting system, droplet model

1 Introduction

Chinese calligraphy, the ancient Chinese art of writing, has been around for so long as the history of China. Numerous calligraphers have been producing countless of masterpieces since Chinese characters appeared. The hair bristle brush, which has long starched natural bristles narrowing to a pointed tip and serves as the tool of Chinese calligraphy or traditional Chinese painting, is convenient to use and has its special expressive ability. However, this characteristic of hair brush has also imposed difficulties in its simulation by computer. Most researchers implement their simulations as soft brushes, which usually lead to lack of the ability to express some special effects of Chinese brush, such as dry brush, feng (explained in Subsection 2.2), etc.

1.1 Related Work

Various brush models have been built by many researchers. One of the earliest attempts is that of Strassmann's. In his paper[1], he analyzed the effects a virtual brush can produce and developed a method for drawing lines as brush strokes. He actually simulated the behavior of a brush with wet paint on paper. The paper by Henmi and Yoshikawa[2] described some aspects of such kind of virtual brush system. Wong and Ip[3] simulated the physical process of brush stroke creation using a parameterized model which captures the writing brush's 3D geometric parameters, the brush hair properties and the variations of ink deposition along a stroke trajectory. Another approach is that of Xu and Tang's[4]. In this model, clusters of hairs are represented as solid models and the imitation of the calligraphy includes some geometric operations on the model. Nelson S. H. Chu recently developed a similar 3D model[5]. Chan presented a method to create 3D Chinese painting animation using existing software packages by modeling and special lightening model[6].

There are also hardware approaches to implement the virtual brush model such as the one by Greene[7]. This model, as well as Chu's[5] and Bill Baxter's[8], presented paradigms of hardware-based user interface for stroke input.

Another challenging and critical problem to address is the interactive model between the paper and ink or pigment. Curtis[9] presented an excellent model for watercolor painting, which is roughly the same as the ink-brush model in Chinese calligraphy or traditional painting. An elaborated dis-

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cussion of the ink diffusion effect in Chinese calligraphy or painting is presented by Jintae Lee[10]. Some ink diffusion models have been proposed for different ink spreading effects[11−13]. Classical artificial intelligence, fuzzy logic, and knowledge engineering have been found to be useful in creating beautiful calligraphic artwork with a virtual hairy brush[14−16].

Simulation of the Chinese traditional calligraphy or painting is a kind of non-photorealistic rendering[17−19]. But it is distinct from general non-photorealistic rendering such as digital painting, picture retouching, or illustration generation. The methods involve a wide range of colors, rich editing functions, and various brush patterns, but generally do not care the brush models that are essential in simulation of the hair brush.

Simulation of the Chinese traditional calligraphy also includes the extraction of the profiles of the character strokes. Shamir and Rappoport introduced a parametric method to compactly represent existing outline-based oriental fonts[20]. Wong and Ip developed a fractal-based outline font technology which is able to capture the outline characteristics of calligraphy writing[21]. They also proposed an alternative method in [3] to capture the stroke outline, which is better than the traditional approaches[12−24] of expressing vividness of calligraphy writing.

1.2 Overview of Our Brush Model

Pure hardware approaches such as Greene's[7] tend to be expensive and not generally applicable. The most significant drawback of the current hair brush model is its complexity due to pixel-by-pixel evaluation. The model proposed in [3] can produce rather vivid calligraphy result when simulating some cases of the "dry-brush" effect. However, the simulation ability is limited because of the model's coarseness when stroke forks and the interactive manner of the model is not so convenient and straightforward.

This paper proposes a parameterized physical brush model which is consistent with the real procedure of calligraphy or traditional painting. This model uses a simplified evaluation algorithm to approximate the effect while maintaining the ability to express most of the special effects of Chinese calligraphy. By using the approximation, the time needed is greatly reduced, which enables our model to produce result in real time.

Though omitting some of the minor details, our model has actually enhanced the traditional "soft brush" model by introducing a novel stroke model called droplet. This model, discussed in detail in Sections 2, 3 and 4, is essential to produce the "feng" effect, which is a characteristic feature of the Chinese calligraphy. It also helps to produce the stroke boundary, without losing the power of expressing the "dry brush" effect and this is very difficult for the previous brush models.

2 Parameters and Brush Model

The brush model proposed in this paper is a parameterized one. First, we define a set of interactive actions to simulate actual calligraphy/painting actions, and then we define a series of brush parameters, and discuss how these actions affect the variation of the parameters and how the parameters determine the final stroke model.

2.1 Basic Actions and Parameters

2.1.1 Basic Actions

There are four kinds of basic interactions defined in our model. *Dipping brush* is the initial action and this action will reset the parameters to initial values; *Lift and press the brush* is the action of modifying the pressure the brush imposes on the paper; *Brush movement* scratches the brush on the paper and produces strokes; *Rotate brush-holder*, the fourth action type, is often performed by the calligraphers when they want to change the direction of the hair brush tip.

2.1.2 Normalized Brush Parameters

Basic actions decide the modification of properties of the brush, and thus the simulation of actual calligraphy or Chinese traditional painting in hair bristle brush can be performed. The most important parameters are listed as follows.

1) Fundamental brush parameters. This set includes brush length L, diameter D and hair number.

2) Brush velocity V. This parameter denotes the speed of brush movement and it is detected by the system through user interaction.

3) Humidity of the brush H. The initial value is given by the user and is detected automatically by the system when the brush movement action is performed.

4) Thickness of pigment T. This parameter denotes the proportion of the amount of ink or Chi-

nese traditional painting pigment to the amount of water. This value is important when strokes overlap and are blended.

5) Brush *pressure* is decided by the lift and press brush action. The press action increases brush pressure whereas the lift of brush will decrease the parameter.

6) Tip direction V_{tip}.

To make our model simple, all the parameters of the brush model are normalized except those in the fundamental brush model parameter set, that is, their domains all lie in the interval $(0, 1)$. How to derive proper tangent area between the brush and the paper given the parameters is one of the main purposes of the paper.

2.2 Stroke Area Models

In our approach, we use the "droplet" model to simulate the tangent area between the brush and the paper because this kind of model resembles real model better than previous ones[1,3,4]. There are different variations of the "droplet" model besides the standard droplet shown in Fig.1(a). All the droplet models apply the same rules in affecting the result and the rules of transformation among droplets under the driving of actions are derived from actual brush wielding experience.

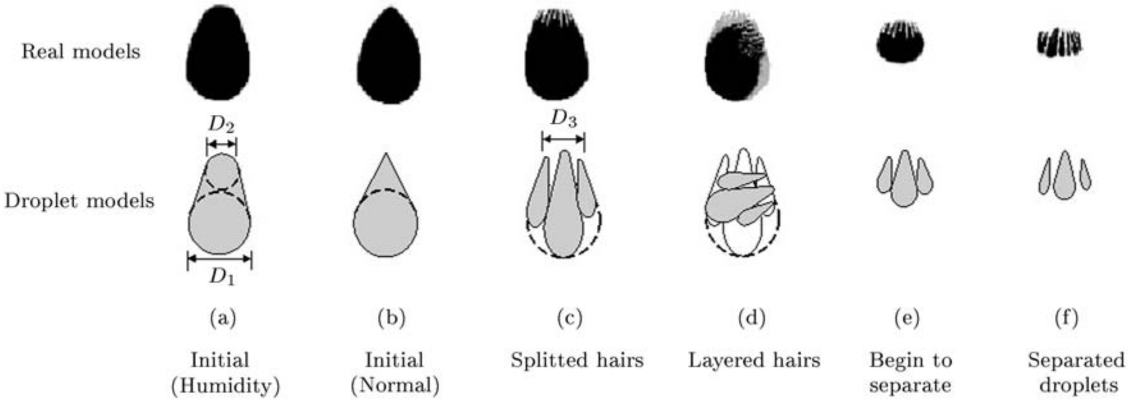


Fig.1. Variations of the droplet models to simulate real tangent area between brush and paper.

The "droplet" model is a kind of 2D model. As just mentioned, the standard droplet is the region enclosed by two circles, with diameters D_1 and D_2 respectively, and the two common tangent lines of them. The final result of our system proves that representation of brush in this model, instead of a soft solid of a bunch of hairs, needs no complex computation and still maintains as good simulative results as others. Both the standard droplet model and the variation 2 contain a single droplet, whereas the remainder may consist of more than one.

The standard model and the variation 2 are two droplets used as the initial model when the brush is dropped. In fact, variation 2 is a special form of the standard model with $D2$ being 0. The value of $D2$ is decided by the brush humidity and the fundamental brush parameters, including brush length and diameter. Detailed description of the calculation of the model will be presented in Subsection 3.1.

The droplet model is important to simulate the peculiar and important hair brush effect "feng" in Chinese calligraphy. There are different styles of fengs. Zhong feng, or the central cutting power of the brush, refers to keeping the brush point always in the middle of the stroke and the tip direction V_{tip} is parallel to the stroke motion direction; Ce feng means the writer uses the brush point one-sidedly or in a sidelong manner, with the angle between the two directions being an obtuse one; Pian feng is a special kind of Ce feng with the angle being a right one. Fig.2 shows three kinds of fengs commonly used in Chinese calligraphy or painting.

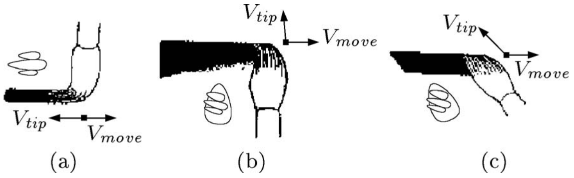


Fig.2. (a) Zhong feng. (b) Pian feng. (c) Ce feng. (Corresponding droplet models are also given.)

The variation 4 of the droplet models is called a layered droplet, which is used when simulating the special effect "feng". When wielding brush in Ce feng or Pian feng manner, the friction of the paper against the bottom part of the brush hairs is inconsistent with the tip direction of the upper part of brush hairs, thus the layered droplet model is adopted.

More detailed explanation is given in Fig.3. V_{move} denotes the direction of the brush movement; F is the paper's friction against the bottom hairs; V_{tip_0} is the initial direction of the brush tip; V_{tip_1} and V_{tip_2} are tip directions of the bottom and upper hairs respectively. The following formula gives the calculation of V_{tip_1} and V_{tip_2}. The parameter p is a user-specified factor which represents the user's intention of wielding brush. When $p = 1$, the virtual brush expresses the effect of Pian feng whereas it expresses Zhong feng when $p \to 0$.

$$V_{tip\_x} = normalize(p_{tip\_x} V_{tip\_0} + (1 - p_{tip\_x})F), \\ x = 1, 2;\ p_{tip\_x} \in [0, 1]$$

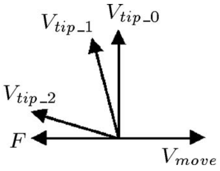


Fig.3. Inconsistence and interaction between the directions of brush tip and brush movement.

In the layered droplet model, V_{tip_1} and V_{tip_2} are specified with different values and $p_{tip\_1} \gg p_{tip\_2}$. When the brush moves fast, the ink in the upper hairs cannot have enough time to deposit to the paper and thus the lower droplet model of variation 4 is applied; otherwise, the upper model is applied.

2.3 Transformations Between Droplet Variations

In the brush model under discussion, except for the fundamental brush parameters, all other parameters are determined according to the brush actions and thus the transformations between variations of the model are driven. The "state machine" can be achieved from experience. The possible transformations between droplet model variations are listed below.

1) From variations 1, 2 to variation 3. The reduction of ink is the cause of this transfer. D_1 is determined by the value of brush *pressure* and the value of D_2 is a function of brush humidity. When the parameter H is lower than a predefined value, the hair of brush cannot be concentrated in a single bunch and would split to more than one and the model is transformed to 3. In this model, D_3 is decided by the parameter *pressure* and the manner of holding brush. When the stress point of the brush is moved to the tip area, D_3 is increased.

2) From variation 3 to variation 4. As described in Subsection 2.2, when the direction of brush movement and the tip direction are not the same (in Pian feng or Ce feng), inconsistence between the upper and lower parts of the brush hair will occur.

3) From variations 3, 4 to variation 5 then 6. When the value of *pressure* decreases, overlapped droplets will at last become separated from each other.

4) From variation 5 to variations 3 and 4. This is an inverse transformation of the previous one. When the pressure increases, the previously separated droplets will again be overlapped.

5) From variations 3, 4 to variation 2. When the calligrapher rotates the brush-holder, the split droplets will unite into a single one and the layered structure in variation 4 will also be eliminated.

Fig.4 shows the possible transformations between the standard droplet model and variations of it.

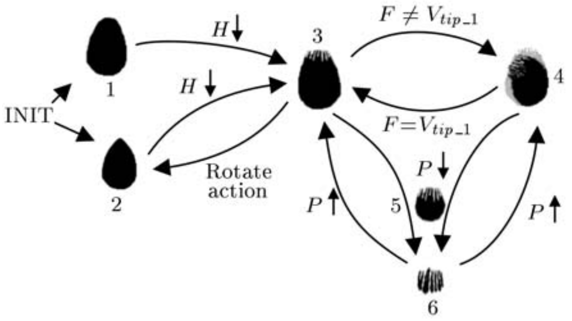


Fig.4. Action-driven transformation of the droplet model.

3 Computation of Stroke Area

The stroke area is the tangent area between the brush and the paper when the calligrapher writes characters with a brush and a droplet is the stroke area at a given moment. The entire stroke area is assumed as the trail the droplets have swept.

3.1 Computation of the Droplets

The computation of the droplet model can be divided into two steps: evaluating the droplets in its local coordinate system and then transforming it to paper coordinate system. Given the location of the brush and the tip orientation, it is simple to get the transformation T and the sequent work is straightforward. So in this section we focus on the evaluation of the droplet in its local coordinate system.

Because most of the brush parameters are normalized, we do not intend to and cannot calculate the physical model of the brush precisely. Besides, the introduction of various random variables into the calculations adds to the impossibility. Furthermore, to give an aesthetically beautiful result, it is of no sense being precise. In fact, in our brush model, we have used a lot of simplification of evaluation without loss of expressive power.

The evaluation of the standard droplet model is quite simple. $D_1 = D \cdot pressure$, and it means that the size of the tangent stroke area varies according to the variation of the pressure the calligrapher imposes on the paper. The range of D_1 is $(0, D)$. $D_2 = D_1 \cdot kH$, k lies in the interval $(0, 1)$ and is specified by the user at the initial time. A relatively bigger k means that the "virtual calligrapher" tilts his brush holder to the side of the brush tip. $h = L \cdot pressure$. (See Fig.5(a)).

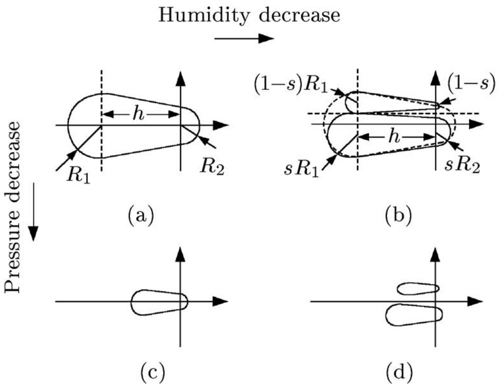


Fig.5. Evaluation of droplets.

Fig.5(b) shows how the variation model 1 or variation model 2 transforms to variation model 3 or 4. Here, we introduce a random number s. The circle with radius R on either end of the droplet is divided into two circles with radius $(1 - s)R_1$ and sR_1 respectively.

Figs.(c) and (d) in Fig.5 shows the droplets when pressure decreases. We can see from the figure that, when the brush is lifted, the droplet variation 3 or 4 transforms to variation 6 ultimately.

Note that in Fig.5, all Rs are half the value of the corresponding Ds mentioned; R stands for radius and D for diameter.

The reunion and merging of the droplets are inverses of the course of droplet separating and splitting, so we omit explaining the evaluation of them here.

3.2 Hull of Droplets

When the parameters of the brush model are modified, for example, lifting or pressing the brush, moving the brush etc., the droplet model must be reevaluated. The brush moves continuously in real calligraphy, but this is impossible in computer. In our model, we simply evaluate droplets periodically and use the hull of the two sequentially evaluated droplet models to approximate the stroke in this interval.

Before further discussion, we first define some terms. We say that the droplets retrieved in the same evaluation are *sibling droplets* with one another. When evaluating droplet model, each droplet can be derived by one of the three cases: inheritor from previous droplet, merged one from several droplets or otherwise one of the resulting droplets from a split. In any case, the previous droplet(s) is(are) the *parent*(*s*) of the result droplet and the latter is called a *descendant* of the former. After sorting the droplets in a droplet model by the Y coordinate value in the droplet model's local coordinate system, where some droplets are called *neighboring* ones if there are no other droplets between them in the sorted sequence.

As for the case shown in Fig.6, in the generation of the shown stroke, there are 5 evaluations of droplet model, i.e., $a - e$. As explained in Fig.1, models a, b and e belong to the standard droplet model whereas model c or d belongs to variation 6. (In interactive calligraphy, the system will execute much more than 5 evaluations, and by our model, the standard model cannot transform to variation 6, but this does not affect the explanation of the terms.) There are more than one droplet in both c and d. c_1, c_2 and c_3 are siblings with one another, so are d_1 and d_2. c_2 and c_3 are the parents of d_2 and the latter is a descendant of them. c_1, c_2 are neighboring droplets, so are c_2 and c_3, however, this is not true for c_1 and c_3.

The evaluation of the hull is not so straightforward because there may be case that the two droplet models are topologically inconsistent. Occurrence of such inconsistence may be during the time when droplet model 1 or 2 transforms to model

3. To avoid extreme complexity, we hold two assumptions.

Assumption 1. *Only neighboring sibling droplets can be merged into one new droplet and the droplets' order of one evaluation keeps the same as the order of the droplets' parents in the previous evaluation.*

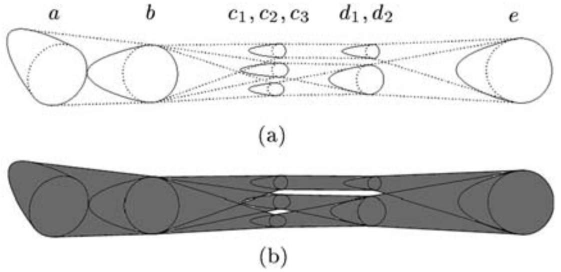


Fig.6. Hull rule. The hull of separated droplets elegantly expresses the "dry brush" effect. (a) The droplets and the hull rule. (b) The resulting stroke area.

For example, suppose $drop_{k-1}$, $drop_k$ and $drop_{k+1}$ are three neighboring droplets. In the next evaluation of the droplet model, the droplet(s) transformed from $drop_k$ is bound to lie between the droplets transformed from $drop_{k-1}$ and $drop_{k+1}$.

Assumption 2. *In two sequentially evaluated droplets, a single droplet cannot split into several while in the same time part of them merge with other droplets.*

Now we give the *hull rule: each of the descendants or the parents of a droplet participates in the evaluation of the hull with this droplet.*

Fig.6 shows an example of applying the hull rule to evaluate the stroke area of a "dash" stroke, including the case of topologically difference.

4 Simulation of Various Brush Effects

The droplets computed using the algorithm described in previous sections represent the tangent areas between the brush and the paper. The final result after virtual "calligraphy" with this model depends on how to deal with the tangent area. As the first application of the model, by hatching the generated tangent areas with proper textures, together with the consideration of ink diffusion, we can retrieve fairly good painting results.

4.1 Hull Hatching

Proper hatching of the calculated hulls will present vivid calligraphy effect. The solid hatching style as shown in Fig.6 is not good enough as far as the real "dry brush" or "diffusion" effect is to be simulated.

When the value of humidity divided by brush velocity (as an indication of the deposit amount of the ink) is lower than a predefined value, the produced strokes should be rendered in "dry brush" style. To express this effect, Helena T.F. Wong and Horace H.S. Ip[3] have developed an *ink depositing model* in their virtual brush system to attach the texture to the produced stroke pixel by pixel and the resulting effect is fairly vivid. However, this is a time consuming process. In our implementation, we import the texture image from a proper part of a predefined texture library according to the brush humidity, hair number and the pressure distribution in the stroke area.

In most cases, the pressure the brush imposes on the paper distributes equally along the direction v as shown in Fig.7. While in some occasion, the calligrapher may choose to tilt his brush to stress some part of the stroke and leave the other part white, then the pressure may not distribute equally along the tangent area between the hair brush and the paper. Fig.7 shows the process of hatching the stroke area with predefined texture according to the humidity, pressure and velocity.

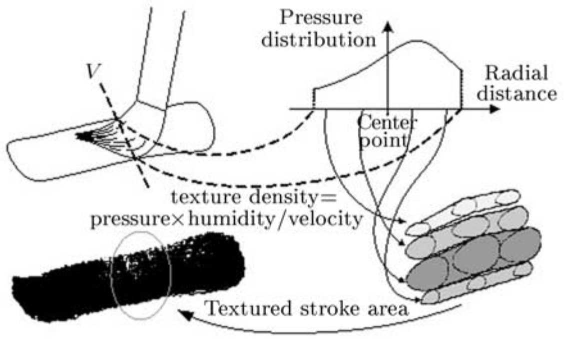


Fig.7. The process of stroke hatching according to the pressure, humidity and velocity.

In the case of Fig.7, when the variation 4 of the droplet model is applied, due to the scarceness of deposited ink, we should apply the bottom part of the model to evaluate the stroke area. However, when the brush is wet enough, the upper layer of the droplets is applied. In this case, a diffusion effect of the stroke is needed. The directions of the droplets are computed according to the discussion presented in Subsection 2.2. Fig.8 shows the resulting image and the detailed discussion of stroke diffusion is presented in the next section.

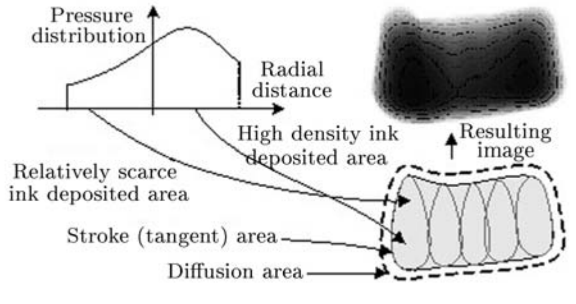


Fig.8. The process of stroke hatching when ink is densely deposited and the upper layer of droplet variation 4 is adopted.

4.2 Stroke Diffusion

4.2.1 *Basic Diffusion Model*

Basic diffusion is to be applied when the whole brush is soaked with ink, or pigment and water, equally. For this simple model, Jintae Lee[10] has already proposed a stroke diffusion model based on the color intensity observation on real circular diffusion images. Here, we adopt this diffusion model to our system, except that we omit the paper model to get simplicity. Based on our experiment on rice paper, we retrieve the pixel grayscale function of radial distance from the center of the droplet that contributes pigment to that pixel. Fig.9(a) shows the experimental data from the sample shown in Fig.9(c), and Fig.9(b) shows the retrieved function curves. The meanings of the reference value r_0 and the variable r are indicated in Fig.9(d). From the experimental result, the diffusion area is divided into two zones: the "diminish zone", where the ink (or pigment) density gradually decreases and the ensuing "vanish zone", where the density is weak and fluctuates. The whole rendered area can be divided into the "stroke area", where the brush is tangent to the paper, and the "diffusion area", as indicated in Fig.9(c). Following this model, the calculated diminish zone and vanished zone when simulating the sample stroke in Fig.9(c) are shown in Fig.9(d), and Fig.9(e) is the final rendering result using a gradient brush.

We use five control points, P_0 to P_4, for the evaluation of the spline in Fig.9(b), whose coordinates in the radial-grayscale plane are as indicated.

Among the coordinate values, r_d denotes the width of the diffusion area; P_2 is the critical point where the grayscale begins to decrease dramatically and we record the grayscale value there as G_1. G_2 is the grayscale on the boundary between the diminish zone and the vanish zone. We give the formulas to evaluate these coordinate values.

$$\begin{aligned} &r_d = s_{pigment} \cdot s_{paper} \cdot H \cdot r_0 \\ &G_1 = e_1 G_0, \quad G_2 = e_2 G_0 \\ &G_0 = T \cdot Grayscale(C_{pigment}) \end{aligned}$$

$s_{pigment}$ and s_{paper} denote the diffusion ratios of the pigment and the paper respectively and the value of them is given when the user has chosen a kind

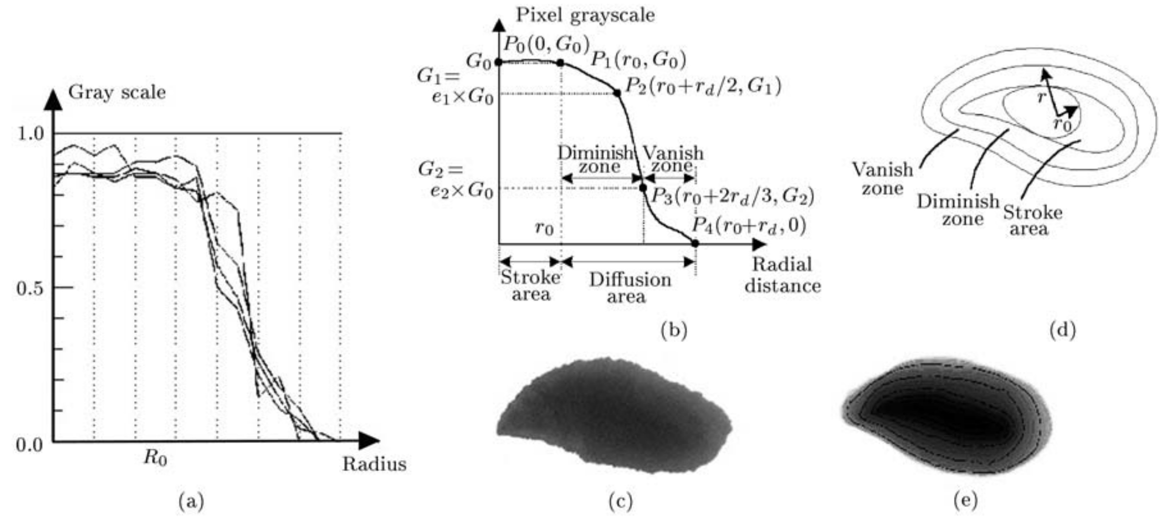


Fig.9. (a) Corresponding experimental density function. (b) Synthesized function curve. (c) Actual pigment diffusion images generated on rice paper. (d) Calculated diminish zone and vanish zone. (e) Imitation result.

of pigment and a paper. e_1 and e_2 are called diffusion variables and the values of them are 0.8 and 0.2 in our system. G_0 is the grayscale value of the center of the stroke area and its value is determined according to the pigment color and the pigment thickness T. The value of r_0 is retrieved using the algorithm discussed in previous sections.

The decreasing of the grayscale in diffusion is based on the physical phenomenon: the water flows more quickly than that in the pigment particles. Thus it is true that the thickness of the ink (or pigment) in the diffusion area is lower than that in the stroke area. We draw the *color distribution* formula as follows:

$$C = Color(G * C_{pigment} \cdot alpha, C_{pigment} \cdot red, \\ C_{pigment} \cdot green, C_{pigment} \cdot blue).$$

The formula implies that the color in the diffusion area is the same as that in the stroke area but more transparent since the alpha value of the color is lower.

4.2.2 Non-Equal Diffusion

The discussion in the previous section is based on the assumption that the ink distributes equally all over the brush. However, sometimes, especially in the case of Chinese traditional painting, the painter may choose to unequally dispose the pigment throughout the brush. For example, he may let the pigment around the brush tip thicker than that of the other part. We use a simple strategy, multi-pass diffusion model, to deal with this case. In this model, we establish a set of thickness values $\{T_i\}$ and a corresponding set of radius values $\{r_i\}$, then apply the equal diffusion model to each pair of (T_i, r_i) and retrieve the grayscale distribution G_i. For each (T_i, r_i), the grayscale function curve is evaluated and the evaluation of the value G_i at a given point is executed with the function. The final value G at a point is the maximum of the set $\{G_i\}$ on that point.

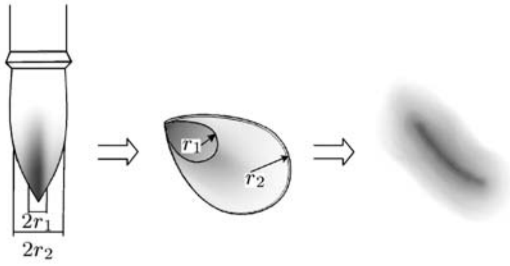


Fig.10. Non-equal diffusion using multi-pass diffusion model.

Fig.10 shows our non-equal diffusion model and the rendering result in this model.

4.3 More Elaborated Droplets

The hull-hatching rule and diffusion using a gradient brush have advantages in efficiency. Appling these models, we can interactively simulate calligraphy using the introduced virtual brush. However, the results are somehow not as good as expectation compared with the result using the model proposed by [3] or [10]. Improving the quality of real sampling stroke texture for hull hatching can improve the results to some extent; however, to get more realistic results, we must consider elaborating the droplets, though this will cost more time for stroke generation.

To mimic a real brush in various aspects, we elaborate the droplets with bristles arranged somewhat randomly within the droplet area as shown in Fig.11. This model takes the density of bristles into account and can generate strokes more vividly. Instead of droplet hulling, to visualize the strokes on the paper, this model only draws lines from the selected bristles with previous droplets to the selected corresponding ones with their descendants. The color and transparency of the line are decided by the amount of water and whether to draw the lines is decided by the humidity of the droplets.

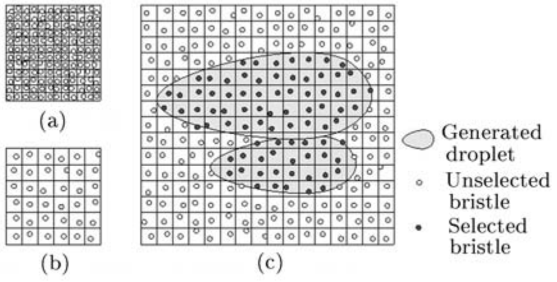


Fig.11. Elaborated droplet with bristles. (a) Densely distributed bristles. (b) Sparsely distributed bristles. (c) Elaborated droplet with bristles.

The criteria of whether to draw the line are important for expressing some special hair brush effects. One of such examples is "flying white" (or "fei bai" in Chinese). A droplet with high speed and lack of ink will give the stroke some kinds of "flying white". We express this effect by decrease the possibility of drawing the lines of the droplets.

Another improvement of the droplets is to apply Lee's model to the droplet hulls[10] to express

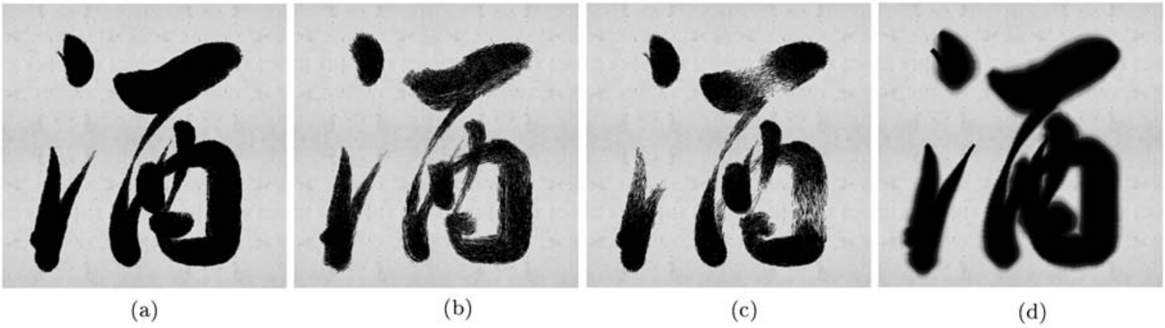
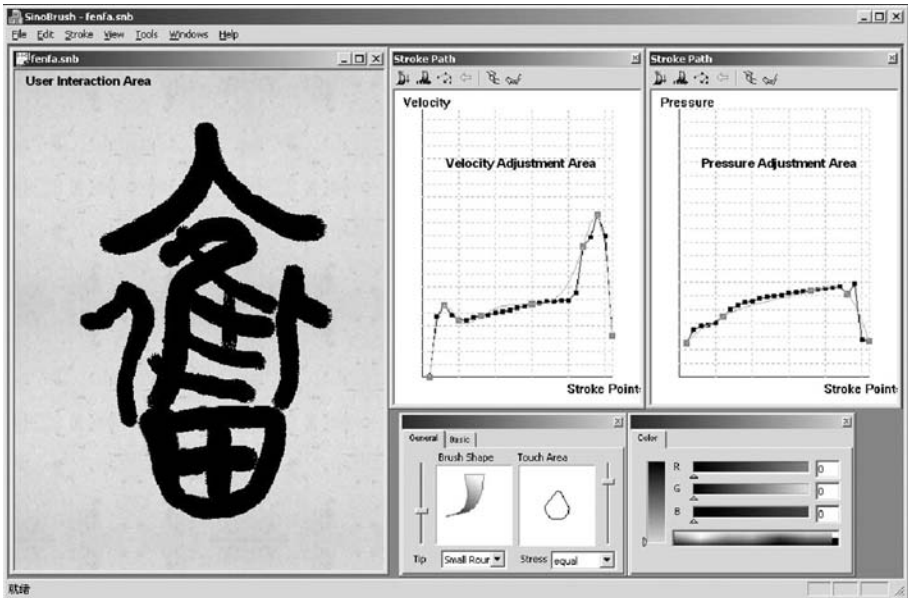


Fig.12. (a) Normal version of a calligraphy. (b) Result of a brush with more sparsely distributed bristles. (c) Stroke stress with flying white. (d) Highly diffused calligraphy. (The virtual brush used in (a), (b) and (c) has a diameter of 65 pixel equivalent, and in (d), we use a brush with a diameter of 50 to give the space for ink diffusion.)



Tip: Small Rour
Stress: equal
R: 0
G: 0
B: 0

Fig.13. User interface of the Sinobrush system.

stroke diffusion. Since the droplets have well defined geometrical boundary, his algorithm can easily be applied.

Fig.12 gives 4 versions of the Chinese character "wine", the first two of which have already been simulated in [3]. However, that model is somehow not so competent for the latter two effects, which need a well defined stroke boundary and more elaborated stroke area definition.

5 Implementation and Result

5.1 Implementation

Applying the ideas and algorithms discussed above, we have developed an interactive system with the proposed virtual brush model. The system's workflow is given below:

```
Brush.Initialize();
Begin: Retrieve Brush Parameters();
       Calc New Stroke Model();
       Calc Tangent Area();            //hull calculation
       Fill Tangent Area (brush parameters);
       Adjust brush parameters();      //ink decreasing, etc.
       while (!Trigger Initialize())
             goto Begin;               //move action
goto Brush.Initialize();               //brush dipping
```

In the evaluation of two sequential droplet models, random factors are introduced into the decision of droplet merging and splitting and into the location of the droplet in the paper space to add vividness to the imitational result. In the calculation of the brush model in each loop, the ink reduction model can be an iterative procedure:

$$INK_{i+1} = INK_i - INK_i \cdot S_{stroke} \cdot f(t, Ap)$$
$$\text{with } \frac{\partial f}{\partial t} \ll 1$$

Here S_{stroke} represents the area of the stroke region; $f(t, Ap)$ is a user-defined, monotonically increasing function of the duration times t between the two evaluations (an indication of the movement velocity) and the paper's absorption factor Ap. It equals 0 if and only if the value of t is 0. The range of the function is $(0, u)$, $u < 1$. And from the experiment, we find that any function that meets the constraint can be a good candidate of the function f and the simulation results are equally good. An example function can be as simple as follows:

$$f(t, Ap) = Ap \cdot a\tan(0.01t)/\pi.$$

Our implementation of the brush model is called "Sinobrush①". It is built on Windows 2000/XP platform and the developing tool is Microsoft Visual Studio.Net. The GDI+, included in the newly released platform SDK, greatly simplifies the programming work.

The mainframe of Sinobrush is shown in Fig.13. The main part of the system is the painting area with various properties setting panels on the right. The user can interactively set the fundamental parameters, such as the color, the humidity, the pigment thickness, the stress point, etc. of the virtual

Fig.14. Imitation of the masterpiece by Sha Menghai. From the image, we can see that the Sinobrush system has good expressive ability of the diffusion effect in the first character and "dry brush" effects on some strokes' endpoints. Note that the image is superimposed on an image of paper texture to improve visual effect.

Fig.15. Xu Beihong's "Running horse".

Fig.16. Pan Tianshou's "Gourd".

Fig.17. Tian Xining's "Rural".

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① You can download the system, together with the data files as the examples listed in this paper, via Internet and the URL is http://ai.zju.edu.cn/~mxf/sinobrush.htm.

brush. Since the interactive manner is the keyboard and the mouse cursor, the system has also provided extra tools and the user can edit the path, the pressure etc. of the strokes through them.

5.2 Examples

Fig.14 is a piece of calligraphy work by Sinobrush. In this work, the diffusion and "dry brush" effects are excellently expressed in some part of characters. The work shown in Fig.15 is a typical piece of Chinese traditional painting, an imitation of "Running horse", one of Xu Beihong's masterpieces and Xu is one of the greatest artists in modern China. In this imitation, most of the typical effects of hair brush, i.e., the "dry-brush" and the diffusion effect, are well expressed. Fig.16 and Fig.17 show another two pieces of imitated painting produced by our Sinobrush system.

6 Discussion and Future Work

The result of calligraphy or painting in virtual brush relies on the fundamental parameters and the actions interactively executed. This paper proposed a simplified and effective virtual brush model which focuses the concern onto the result. The introduction of variations of droplet model and the hull rule is the essential feature of the model.

The proposed model properly simulates the special effect of Chinese calligraphy, such as the "dry-brush" effect and the diffusion in much less time whereas successfully maintains good rendering result.

There is still work to do, for example:

1) Adopt an elaborated ink-paper interaction model after the interactive calligraphy or painting with the virtual brush has finished, for which the model contributed by Lee[10] is good enough;

2) Some more convenient user-interactive manner should be considered and improved. Use of neural network is an option, which can learn from the post-interactive parameter adjustment when using the Sinobrush system;

3) Due to the well-defined geometry properties of the droplets, we can easily produce the outlines of the resulting strokes in calligraphy style without losing the vividness in dry stroke area by automatically adding some indicating curves to the resulting profiles. This benefits 3D calligraphy-style character modeling. We have already developed an 3D-character modeling system from realistic calligraphy using the droplet model[25]. However, more can be done, for example, 3D-seal modeling, epigraphy modeling, etc.

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