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A computational approach to digital hand-painted printing patterns on cloth

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Abstract This paper presented a novel computational approach to simulating hand-painted printing patterns on cloth, according to the real process of this ancient folk handicraft. A contour grid based method was specially designed so as to generate the contours of the printing patterns by inputting a contour image or a color image. Considering both the anisotropic structure of cloth and the influence from user's strokes, we proposed the main direction guided anisotropic diffusion model (MDGADM) to compute the diffusion of dyes on cloth. Other interactions between dyes and cloth including the adsorption and evaporation were also incorporated to improve the accuracy and the realism. The algorithms of the boundary restriction and the contour enhancement were further developed to optimize the method. Various experiment results showed that our method can produce vivid hand-painted printing patterns on cloth of different woven structures. Our method provides users with a flexible artistic designing tool, and has great potential to protect and inherit this traditional handicraft.

Keywords Hand-painted printing patterns · Cloth · Dye diffusion · Physically based simulation

1 Introduction

The skill of painting printing patterns on cloth is a type of ancient, traditional folk handicraft. The hand-painted printing technique, capable of generating rich patterns and abundant colors, has a unique and characteristic style in its arts. However, it has low production efficiency due to the complex traditional process, and it also produces many waste materials posing a great pollution threat to the environment. Developing a computational approach to designing printing patterns on computer, therefore, can not only help designers improve the production efficiency but also have the potential to protect and inherit this traditional handicraft.

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According to different making processes, the painting printing patterns can be classified into two types, namely the plate-marked painting patterns and the hand-painted painting patterns on cloth [17]. The former are generated using some particular plates; while the latter, guided by user's interactive painting strokes, can be created more freely and thus has the concise, colorful, and unique design styles, which is also the focus of this paper. It is hence important to incorporate user's interactions with dyes and cloth so as to develop a computational method for realistic simulation of hand-painted printing patterns on cloth. However, little attention has been paid to this area.

1.1 Related work

Painting printing patterns on cloth belong to the category of computationally modeling fluid-structure interactions. Particularly, watercolor painting and ink painting share the similarity with hand-painted printing patterns with respect to the making processes. Let us then briefly review the progress in this field.

Physical theory based methods and procedural methods Curtis et al. [3] introduced a three-layer cloth model to simulate the flowing and the diffusion of dyes, including the shallow water layer, the pigment deposition layer, and the capillary layer. Laerhoven et al. [7] presented a watery painting simulation method based on a distributed paper model. This method is effective and can produce convincing results in real-time. Kunii et al. [6] used the Fick's second law of diffusion to describe the pigment movement in water on dry paper, aiming to obtain realistic ink painting results. Laerhoven et al. [8] designed a new system for real-time, interactive reproduction of images with thin watery paint. This system can achieve the effects of watercolor, gouache, and Oriental black ink at a great balance between the simulation speed and the simulation complexity. Although the above physical theory based methods can produce realistic watercolor or ink-painting effects, they are all computationally prohibitive from a large resolution of the simulation grids. In recent years, some researchers extend the 2D diffusion simulation to surface flow simulation. Auer et al. [1] developed the numerical solution of the wave equation and the incompressible Navier-Stokes equations on surfaces via the Closet Point Method (CPM). Djado et al. [5] simulated the motion of water drops on a surface. Jeong and Kim [4] introduced a combustion model of heat transfer and fuel consumption for the propagation of a fire front on a point cloud surface.

Geometry based methods and image based methods Wilson and Ma [16] combined the two- and three-dimensional geometry processing techniques in a mix pipeline to simulate pen-and-ink illustrations. By mixing several layers of semi-transparent paint textures, Lum et al. [12] proposed a new lighting model to achieve the watercolor effects, more effectively communicating the shape and texture information than any of previous physical theory based methods. Burgess et al. [2] generated watercolor-style images through a hybrid of object space rendering techniques and image plane post processing. This method is fast owing to the acceleration of Graphics Processing Units (GPU) and the exploration of noise textures. Focusing on an efficient image space based simulation rather than a physically accurate simulation, Luft and Deussen [11] presented a method for rendering 3D scenes with a watercolor painting appearance. The animation with visual pleasing time coherence can also be realized by incorporating a stable segmentation scheme. To eliminate the limitation to the black ink domain, of conventional Chinese ink simulation, Wang et al. [15] proposed an image-based painterly rendering system which can automatically synthesize an image with color ink diffusion. The geometry/image based methods improve the simulation efficiency to some extent, but at the cost of ignoring the natural textures generated due to the diffusion of dyes.

All the above methods model the dye diffusion effects on paper, a type of isotropic medium with respect to the diffusion process, and therefore they cannot be directly used for simulation of painting effects on anisotropic materials such as cloth, which is still a rarely studied area. Another related topic is the simulation of dyeing and staining effects on cloth. Morimoto et al. [13] visualized the dyeing effects by describing cloth as a cellular model. They considered the influence of dye adsorption effects in order to reproduce fine details such as thin colored threads. They further improved their work by introducing more flexible physical parameters of threads and dyes, and extended the simulation to achieve 3D tie-dyeing effects.

Although the dyeing and the staining effects on cloth can be simulated by considering the anisotropic structure of cloth, the above methods cannot be adopted for simulation of hand-painted printing patterns on cloth. This is mainly because of the rich pattern textures and the complex user interactions. To reproduce the specific and colorful hand-painted printing patterns on cloth, not only should we consider the interactions between dyes and cloth, but also we should account for the influence from the hand painting tools during the interactive process.

1.2 Overview

As reported in [17], the actual process of hand-painted printing on cloth is as follows: firstly, cloth is fixed on a frame or clamped by the sticks, so as to make it uptight and flat for the following dyeing process. The dye resisting agent is then employed to draw the closed outline of the printing design. Finally, the artist fills dyes in the regions surrounded by the closed contours. Since dyes diffuse automatically in cloth, the freehand tool can be kept a certain distance from the contours during the dyeing process.

Based upon the above actual process, we proposed a novel approach to simulating hand-painted printing patterns on cloth. As illustrated in Fig. 1, our algorithm mainly consists of the following procedures:

- Construction of the cloth grid: Cloth, woven from crossing threads, is a type of anisotropic fabric regarding the dye diffusion in it. We specially designed the cloth grid model to represent the interwoven structure of cloth. The details will be introduced in Section 2.1.
- Generation of the contour grid and the interaction areas: Our method allows users to input a contour image, which can either be a stick picture or a picture drawn by users. As it will take much time as well as need strong skills to create a contour image for non-professionals, and sometimes it is not easy to obtain a suitable stick picture, our system provides users with a selective function of generating the contour image by extracting contours from a color image which can more easily be found than a stick image, see the dotted lines areas in Fig. 1. The details of the generation of the contour grid and the interaction areas using the contour image and the color image are respectively discussed in Section 2.2.
- Simulation of the dyes' filling: Aiming to achieve the realistic hand-painted printing patterns on cloth, we take into account both the anisotropic property of cloth and the influence from user's strokes, and propose the main direction guided anisotropic diffusion model (MDGADM) to simulate the diffusion of dyes on cloth in Section 2.3. Section 2.3 includes the calculation of other interactions such as the adsorption and evaporation between dyes and cloth. Another difference between hand-painted printing patterns on cloth and paintings on paper lies in the boundary restriction, i.e., the designing of the

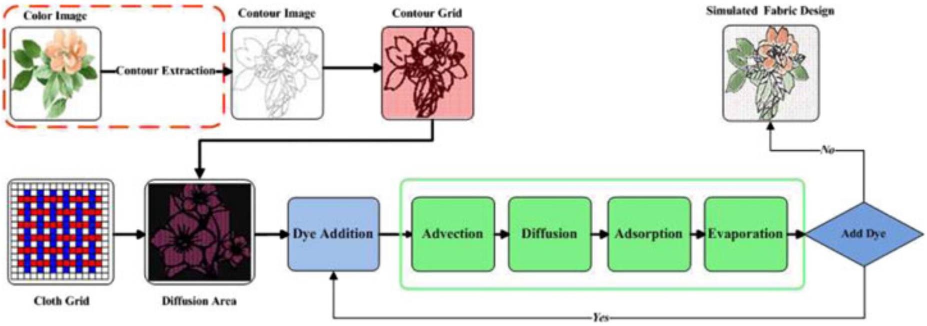


Fig. 1 The framework of our algorithm

former is limited to the areas surrounded by the contours while the latter has no restriction. We address the issue of the boundary restriction in Section 2.4. The main contributions of our paper can be summarized as follows:

(1) A novel simulation framework for digital hand-painted printing patterns on cloth is developed. To the best of our knowledge, it is the first attempt for simulation of digital hand-painted printing patterns on cloth in the field of multimedia.
(2) The main direction guided anisotropic diffusion model (MDGADM) is designed to simulate the diffusion of dyes on cloth, which takes the anisotropic property of cloth and the influence from user's strokes into account.
(3) Our method can simulate the interactions such as the adsorption and evaporation between dyes and cloth, and can correctly model the dye filling effects by introducing the technique of boundary restriction.

2 Algorithm

In this section, we will introduce our algorithm in detail including building up the cloth model, generating the interaction areas between dyes and cloth, solving the interactions between dyes and cloth, and handling the boundary restriction.

2.1 The cloth grid model

In order to represent the special structure of cloth (Fig. 2a), woven from the weft and the warp, we designed a two-dimensional cloth grid model (Fig. 2b), in which the grid cells can be classified into three types: the warp grid cell, the weft grid cell, and the gap grid cell. Users can specify the grid cell to be on either the top layer or the bottom layer, and thus approximate the interwoven structure of the real cloth. In addition, according to different distributions of the adjacent grid cells, we defined five kinds of position relations between the adjacent grid cells, namely the position relation between the warp grid cell and the warp grid cell I, the weft grid cell and the weft grid cell II, the warp grid cell and the weft grid cell III, the warp/weft grid cell and the gap grid cell IV, the gap grid cell and the gap grid cell V. These position relations between the grid cells will be utilized to

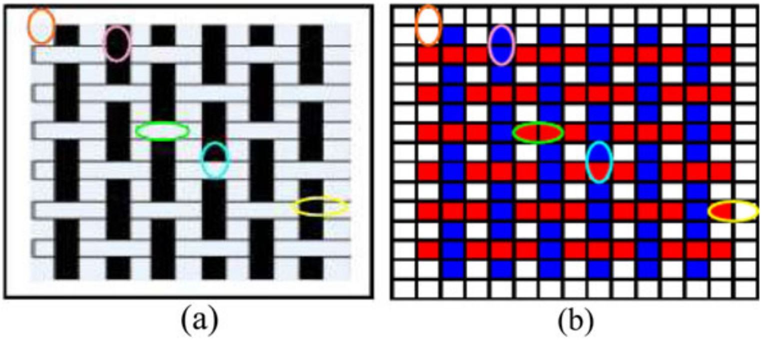


Fig. 2 The structure of (**a**) the real cloth and (**b**) our cloth grid model. The ellipses in *five different colors* represent five different relations between the adjacent grid cells, I: the *pink ellipse*, II: the *green ellipse*, III: the *blue ellipse*, IV: the *yellow ellipse*, and V: the *orange ellipse*. In (**b**), the grid cells marked in *red*, *blue*, and *white* are respectively denote the weft grid cell, the warp grid cell, and the gap grid cell

determine different diffusion rates of dyes in different positions and different directions. These five position relations between the grid cells affect the diffusion of dyes on cloth (see Section 2.3.2).

2.2 Generation of contour grid and interaction areas

In the real designing process of hand-painted printing patterns, the artist needs to interactively draw the contour of the printing patterns on cloth using dye resisting agent. This process, however, requires the artist to be very good at painting and be very careful in handling strokes; if the artist makes a mistake in the process of drawing, it will lead to a re-drawing which is tedious and time-consuming. Alternatively, we allow users to input a contour image such as a stick picture, to mark the contours efficiently. Our method also provides users with another selection of using a color image as the input.

For the boundary extraction of a color image with rich textures,it often generates discontinuous contours using traditional boundary extraction algorithms in image processing. These discontinuous contours will greatly influence the diffusion calculation and thus lead to the artificial phenomenon of dyes' penetrating through the boundaries. So, we can use some successful boundary extraction method in the field of image processing to extract the contour image.

Then, we map the contour image onto a grid, called the contour grid, with the same size of the cloth grid and be adopted to record the positions of the contours. In order to determine the interaction areas between dyes and cloth, we next map the contour grid onto the cloth grid, by the scan-line algorithm to mark the interior grid cells.

2.3 Simulation of interactions between dyes and cloth

When dyes are added onto cloth, the dyes begin to flow. As a kind of fluid, the dyes should comply the law of the fluid's motion when they flow on the cloth. In the field of the computer graphics, the Navier-Stokes equation are usually used to compute the fluid's motion, when simulating the interactions between dyes and cloth will occur four processes which describe the generation of the hand-painted printing patterns, including the advection, the diffusion, the adsorption, and the evaporation. So, the mass of the dyes at any time t should be calculated through five terms, namely:

$$C(t) \Rightarrow S + adevct(t) + diffu(t) + adsop(t) + vapor(t), \tag{1}$$

where $C(t)$ is the mass of dyes, S is the initial mass of dyes, the other four terms on the right of Eq. (1) represent the dyes' addition term, the advection term, the diffusion term, the adsorption term, and the evaporation term, respectively.

Dyes consist of color pigment and a certain proportion of water. Color pigment flows only in the moist areas, that is, it flows along with the water and finally attaches on the cloth, while water will be evaporated. In our model, we respectively calculated the change of pigment and water as follows:

$$C(t) = p(t) + w(t), \tag{2}$$

where $C(t)$, $p(t)$, and $w(t)$ are the mass of dyes, color pigment, and water, respectively. Below we will introduce the solving of this interaction equation.

2.3.1 Initializing the concentration of dyes

There are several types of brush shapes for hand-painted printing on cloth such as the circle-style shape and the line-style shape. In order to simulate the brush shapes for hand-painted printing on cloth vividly, we define the circle-style shape as the primitive, of which the line-style shape can be made up of (Fig. 3a). The mass of the added pigment p_{init} and the added mass of water w_{init} are respectively initialized as,

$$p_{init} = (R - d(x, x_0)) \cdot p_0, \tag{3}$$

$$w_{init} = (R - d(x, x_0)) \cdot w_0, \tag{4}$$

where p_0 and w_0 are the standard mass of pigment and water respectively, $d(x,x_0)$ denotes the distance from each position x to the center of the circle x_0 and R is the radius of the circle which describes the brush size. R changes accordingly with the variation of the size of the filling area, i.e., the larger the filling area is, the larger R will be, and vice versa. In all of our experiments, the value of R ranges between 1 and 30.

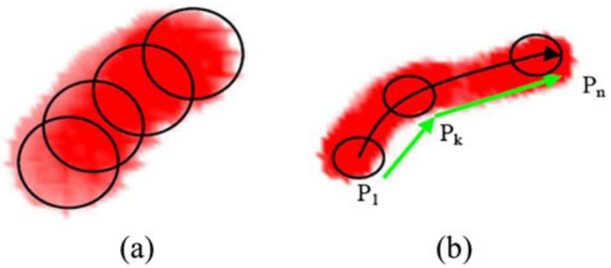


Fig. 3 (**a**) Dyes with the *line-style shape*, and (**b**) calculation of the main diffusion direction. The *arrow* in *black* stands for the brush trajectory, and the *arrows in green* represent the main diffusion direction determined by our algorithm

2.3.2 The advection term and the diffusion term-MDGADM

In the field of the computer graphics, the fluid's motion is usually modelled by the Navier-Stokes Equations [14]:

As known, the dyes belong to one kind of the fluids. Color pigment flows along with the water, so we should compute the velocity filed of the water at any time and then compute the dyes' motion on dye cloth, so we simulate the velocity of the dyes based on the Navier-Stokes Equations, namely:

$$\frac{\partial u(t)}{\partial t} = -(u(t)\cdot\nabla)u(t) + D\nabla^2 u(t), \tag{7}$$

where $u(t)$ is the velocity of water and color pigment at time t, D denotes the diffusion coefficient for each grid cell, and it is a variable which is influenced by the weft and warp structure of the cloth and the main direction of the user's brush. We will focus on the description of the solving process of the diffusion coefficient D in the following context. We solve the advection term based on Stam [14], and the initial velocity of the dyes is set by the constant of the diffusion coefficient, if one area is added by the dyes, the velocity of the area is set as 1.0, and the direction of the velocity is set by the direction of brush.

The changes of dye pigment and water are related to the above velocity field, written as,

$$\frac{\partial p(t)}{\partial t} = -(u(t)\cdot\nabla)p(t) + D\nabla^2 p(t), \tag{8}$$

$$\frac{\partial w(t)}{\partial t} = -(u(t)\cdot\nabla)w(t) + D\nabla^2 w(t), \tag{9}$$

For the diffusion of dyes in the process of hand-painting on cloth, it is not as simple as the dyeing [13]; for example, when a blot drops onto cloth, it will uniformly diffuse to the surrounding areas with no restriction, while the diffusion of dyes for the hand-painting on cloth will be restricted by the pattern boundaries. In order to simulate the dyes' diffusion for hand-painted printing patterns on cloth, on one hand, like the simulation of the dyeing, we should consider the interwoven structure of cloth, which means that dyes in different types of grid cells have different diffusion coefficients, and we thus define five kinds of diffusion coefficients (DI, DII, DIII, DIV, and DV) for different position relations; on the other hand, during initializing dyes using strokes, the brush would exert a force on dyes which will influence their diffusion in cloth, guiding dyes preferentially move along the direction of the exerted force. We call this guided direction as the main diffusion direction, and compute it using a special piecewise linear approximation method as shown in Algorithm 1.

Algorithm I: Main-Diffusion-Direction Calculation

1: Input the center of each circle-style shaped dye: $P_1 P_{k_i} P_{k_{i+1}}$;

2: Calculate the angle $_i$(0<i<n) between $P_i P_{i+1}$ and the forward direction of the horizontal axis, and the minus between two adjacent angles $_i$

($_i$= $_i$− $_{i-1}$)(0<i<n)

3: for i=1:n-1

4: if i=n-1 then

5: Output $P_1 P_n$ and end the calculation;

6: else

7: while i=n-1 do
8: Calculate $_{i+1}$, $_{i+1}$;
9: if $_{i+1}$ is larger than the threshold $_{0}$ then
10: Output $P_{k_i}P_{k_{i+1}}$ and end the calculation;
11: else
12: Calculate $_{i+2}$, $_{i+2}$;
13: end if
14: end while
16: end if
16: end for
17: Output the main diffusion direction vector list: $P_iP_{k1},\ P_{k_1}P_{k_2}, \ldots, P_{k_n}P_n$.

As shown in Fig. 4, we define four directional diffusion coefficients $D_{up(i,j)}$, $D_{down(i,j)}$, $D_{left(i,j)}$ and $D_{right(i,j)}$ (Fig. 4b) for each grid cell. By incorporating the influence of the main diffusion direction, the above four coefficients are updated as follows:

$$\begin{aligned} D_{up(i,j)} &= D_{\text{stand}} - \frac{dy}{\sqrt{dx^2+dy^2}} \cdot D_{\text{stand}}, \quad D_{down(i,j)} = D_{\text{stand}} + \frac{dy}{\sqrt{dx^2+dy^2}} \cdot D_{\text{stand}}, \\ D_{left(i,j)} &= D_{\text{stand}} - \frac{dx}{\sqrt{dx^2+dy^2}} \cdot D_{\text{stand}}, \quad D_{right(i,j)} = D_{\text{stand}} + \frac{dx}{\sqrt{dx^2+dy^2}} \cdot D_{\text{stand}}, \end{aligned} \tag{10}$$

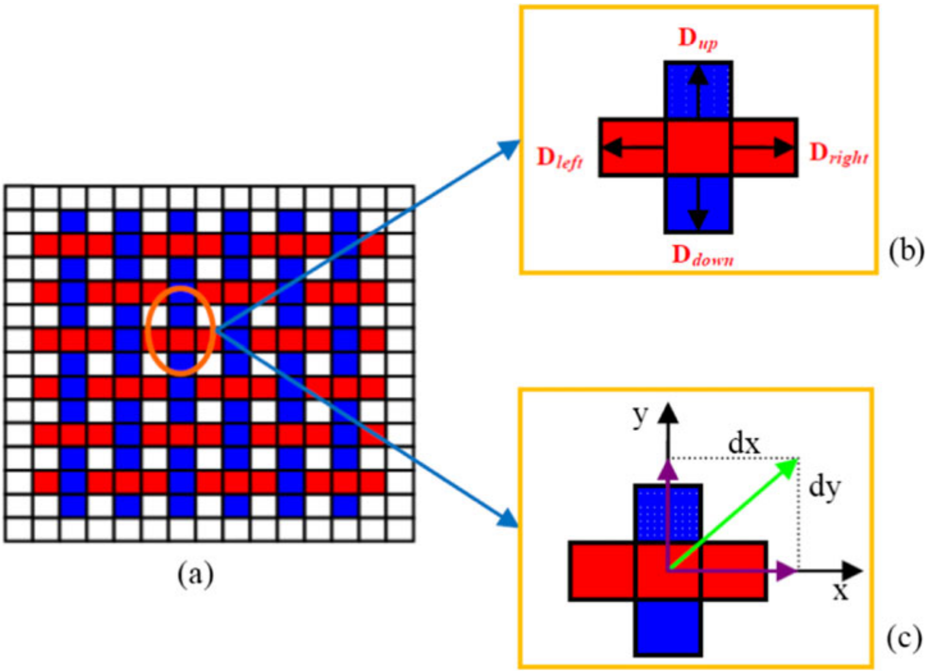


Fig. 4 Illustration of the influence of the main diffusion direction, (**a**) a cloth grid; (**b**) and (**c**) are the amplified versions of the marked grid cell in (**a**), which respectively represent (**b**) four diffusion directions without considering the influence of the main diffusion direction, and (**c**) the decomposition of the main diffusion direction (the *green arrow* shows the main diffusion direction and the *purple arrows* are the decomposed components on the coordinate axes)

where D_{stand} is the standard diffusion coefficient for each grid cell, and it shows that if the brush does not act on the grid cell (i,j), all the directional diffusion coefficients $D_{up(i,j)}$, $D_{down(i,j)}$, $D_{left(i,j)}$ and $D_{right(i,j)}$ are D_{stand}, and the value of D_{stand} is 0.5; dx and dy are the vector components of the main diffusion direction on the horizontal axis and the vertical axis, respectively.

We integrated the above techniques, and proposed a novel diffusion model-MDGADM to compute the diffusion of dyes in cloth, which can be written as,

$$D = D_{cloth} \cdot D_{direction}, \tag{11}$$

where D_{cloth} denotes one of the diffusion coefficients of DI, DII, DIII, DIV, and DV related to five kinds of position relations in the structure of the cloth; $D_{direction}$ is one of the diffusion coefficients of −, $D_{down(i,j)}$, $D_{left(i,j)}$ and $D_{right(i,j)}$ guided by the main diffusion direction of the brush.

2.3.3 The adsorption term and the evaporation term

To further improve the realism of the simulation results, we incorporated the adsorption effect of color pigment and the evaporation effect of water into our method. After dyes diffuse in cloth, the color pigment would also be adsorbed into the fabric fibers. The absorbed amount of color pigment will not diffuse any more. According to the Langmuir adsorption theory [13], we adopt the formula (12) to compute the adsorption effects after identifying whether the existing amount of adsorption is larger than the maximum adsorption amount in each cloth grid cell.

$$\frac{\partial p_{adsor}(t)}{\partial t} = a \cdot (K \cdot (V_d - p_{adsor}(t))p(t) - p_{adsor}(t)), \tag{12}$$

where $p_{adsor}(t)$ is the amount of the adsorption of color pigment; a, K, and V_d are the adsorption equilibrium constants; $p(t)$ denotes the mass of color pigment at time t. We modeled the evaporation effect of water using the following equation:

$$w(t+dt) = w(t) - vap \cdot dt, \tag{13}$$

where $w(t)$ is the mass of water, and vap denotes the average rate of evaporation.

2.4 The boundary restriction

The contours of hand-painted printing patterns restrict the diffusion region to the interaction areas, and thus we need to identify if dyes flow into the boundaries, avoiding dyes' penetration through the boundaries.

As shown in Fig. 5, dyes diffuse outside the golden contours without considering the boundary restriction; while our method successfully handled this issue, benefiting from the contour grid. In each diffusion calculation cycle, we check if the current grid cell belongs to the boundaries using the boundary information recorded in the contour grid; if it is a contour grid cell, dyes will stop moving forward, i.e., the velocity of dyes in the normal direction will be 0, which can be written as $u \cdot n = 0$ (u and n are respectively the vectors velocity and the normal). On the other hand, the velocity in the tangential direction will keep unchanged. As shown in Fig. 6, the red arrow shows the current velocity of dyes; due to the boundary restriction, it will stop to diffuse in the normal direction, while the amount of velocity in the tangential direction will make dyes move along the boundary.

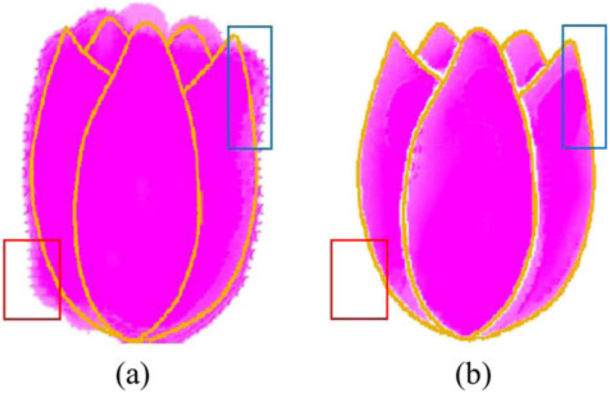


Fig. 5 The diffusion results of (**a**) without performing the boundary restriction, and (**b**) performing boundary restriction

3 Experiments and discussions

We simulated various hand-painted printing patterns on cloth of different woven structures employing the new computational method. All the experiments were run on a computer equipped with an Intel 3.07 GHz processor with 2.0 GB RAM, and an ATI display card with 1.0 GB graphics memory. The key parameters and their values in the experiments are summarized in Tables 1 and 2. In Table 1, α_0, with the value of 15.0°, is the angle threshold, used in Algorithm 1 for calculation of the main diffusion direction for dyes' initialization. The last column in Table 2 shows the simulation time for different experiments, which is the result of summing up the interaction time of users' drawing, the calculation time of solving the interactions between dyes and cloth, and the rendering timings. The timings are the total times from the initialization to the simulated result of the hand-painted printing patterns on cloth. From Table 2, we can conclude that the hand-printed painting patterns on cloth could be drawn in a fast manner using our method. The total time ranges from dozens of seconds to a few

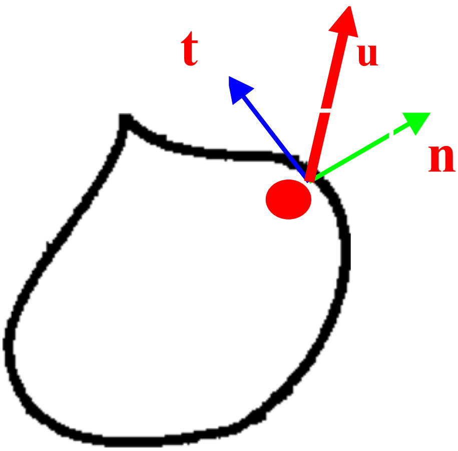


Fig. 6 Illustration of the change of the velocity when dyes collide with the boundary. The *black curve* is a boundary. The *red circle* area represents dyes colliding with the boundary. The *red arrow*, the *green arrow*, and the *blue arrow* respectively represent the direction of the velocity, the normal, and the tangent

Table 1 The parameters and their values for dyes

p_0	w_0	a	K	vap	α_0
1.0	1.0	0.2	0.01	0.01	15

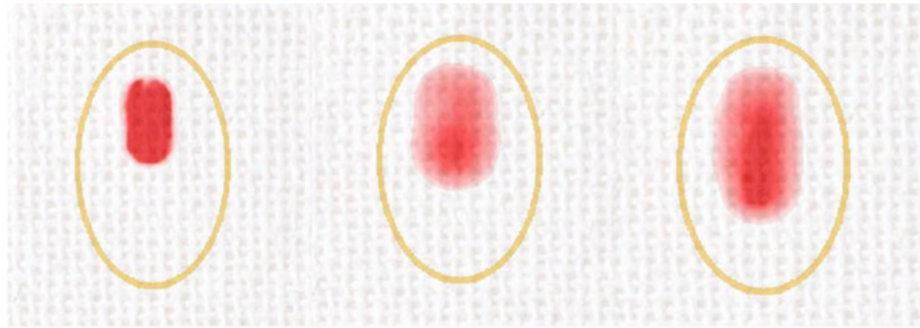
hundred seconds, and the rendering time of the whole process can be real-time. Through comparative analysis, the simulation time related to the dye-filling are and the complexity of the painting patterns. If the dye-filling area is larger and the painting patterns are more complex, the diffusion of the dyes would cost much more time.

Figure 7 shows the comparison of the filling results between different methods. In this experiment, the initialization of the concentration of dyes for different methods is identical; after the same time interval (59 s for Fig. 7a and 66 s for Fig. 7b), we see dyes cannot completely fill the lower part of the ellipse-shaped area using the methods in [13]; however, since our method accounts for the influence of the main diffusion direction introduced by user's strokes, the dyes in the third column of Fig. 7a is flowing toward downside, and the dyes in the third column of the Fig. 7b are flowing toward along the direction of the green arrow and the lower part of the same area is satisfactorily filled with diffused dyes. Our method works well for any contours with regular or irregular shapes, which can achieve visually pleasing painting results at a faster simulation rate than that of previous methods [9, 13]. Figure 8 exhibits the comparison between our result and a real recording of hand-painted printing patterns on cloth. We find that our simulation result can demonstrate different color shading effects, which is similar to the real photo in terms of the pattern shapes and the appearance of dyes on cloth, which proves the feasibility and the validity of our algorithm for the initialization of the brush shapes, the contour generation, and dyes' interaction with cloth.

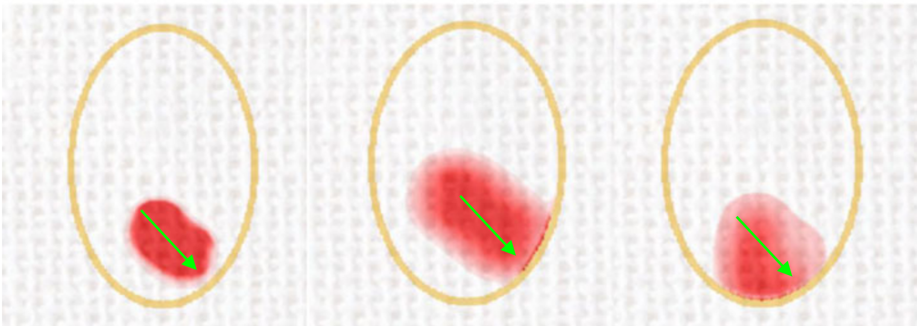
Our method can be applicable for the simulation of hand-painted printing patterns on cloth of different woven structures including the plain weave, the twill weave, and the satin weave. In plain weave, the warp and the weft are aligned to form a cross pattern; while a pattern of diagonal parallel ribs forms the twill pattern. The satin weave is another common fabric weave, with the characteristic of four or more weft yarns floating over a warp yarn or vice versa, four warp yarns floating over a single weft yarn. Figure 9 demonstrates the simulation results of hand-painted printing patterns on cloth of different woven structures, from which we can see that the diffusion of dyes is consistent with the cloth structures. Since the structure of the cloth

Table 2 The timings and the parameters for cloth and their values in the experiments

Figures	DI	DII	DIII	DIV	DV	Time(s)
Fig. 3	0.2	0.1	0.1	1.5	1.0	5
Fig. 5	0.2	0.2	0.1	1.5	1.0	55
Fig. 8a	1.0	1.0	0.5	1.0	1.0	364
Fig. 9a	1.0	1.0	0.5	1.0	1.0	106
Fig. 9b	0.1	1.0	0.5	1.0	1.0	99
Fig. 9c	1.0	0.1	0.5	1.0	1.0	111
Fig.9d	1.0	1.0	0.5	1.0	1.0	230
Fig. 9e	0.1	1.0	0.5	1.0	1.0	203
Fig. 9f	1.0	0.1	0.5	1.0	1.0	210
Fig. 10a	0.25	1.0	0.5	1.0	1.0	235
Fig. 10b	1.0	1.0	0.5	1.0	1.0	256
Fig. 10c	0.3	1.0	0.5	1.0	1.0	347



(a)



(b)

Fig. 7 The comparison of the filling results between our method and the methods in [13]: the *left column* is the initialization, the *middle column* shows the result generated using the methods in [13] after a time interval, and the *right column* is the result generated using our method after the same time interval

in Fig. 9a and d is the plain weave, the diffusion of the dyes id uniform. However, the structures of the cloth in the Fig. 9b, e, c and f are respectively the twill weave and the satin weave, which affect the diffusion of the dyes on the cloth. The dyes on the twill weave diffuse along the horizontal direction, and the dyes on the satin weave diffuse along the vertical direction. Besides, the results in the Fig. 9a, b and c are initialized by only one stroke, and the

(a) (b)

Fig. 8 The comparison between (**a**) our simulation result, and (**b**) a real photo of hand-painted printing patterns

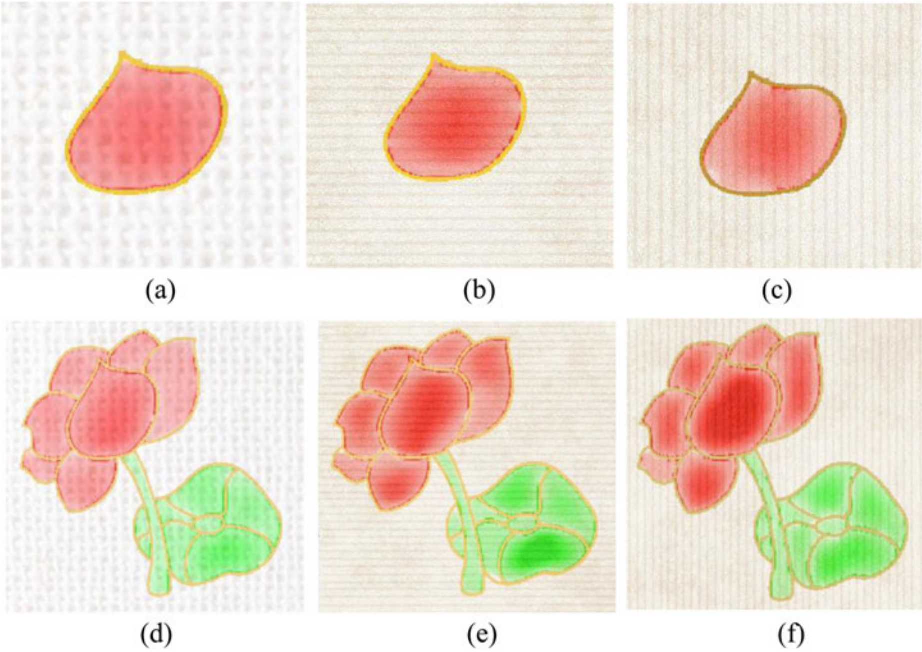


Fig. 9 The simulation results of hand-painted printing patterns on cloth of different structures: (**a**) the plain weave, (**b**) the twill weave, and (**c**) the satin weave, (**d**) the plain weave, (**e**) the twill weave, and (**f**) the satin weave

corresponding timings in Table 2 are the rendering time actually. The results in Fig. 9d, e and f are initialized by some strokes dynamically, and the corresponding timings in Table 2 are the total time including the painting process and the rendering time. The simulated time is approximately 100 s with simple printing patterns in the Fig. 9a–c, and the simulated time is only approximately 210 s in the Fig. 9a–c, while the printing patterns in Fig. 9d–f is more complicated than the printing patterns Fig. 9a–c. This may be due to the fact that we add only one stroke of dyes on the cloth in Fig. 9a–c, however we added some strokes of dyes on the cloth in the Fig. 9d–f. So, if we paint more dyes in the painting patterns in the painting process, the time of the simulated hand-painted printing patterns on cloth would be reduced with the complicated printing patterns. More results are shown in Fig. 10.

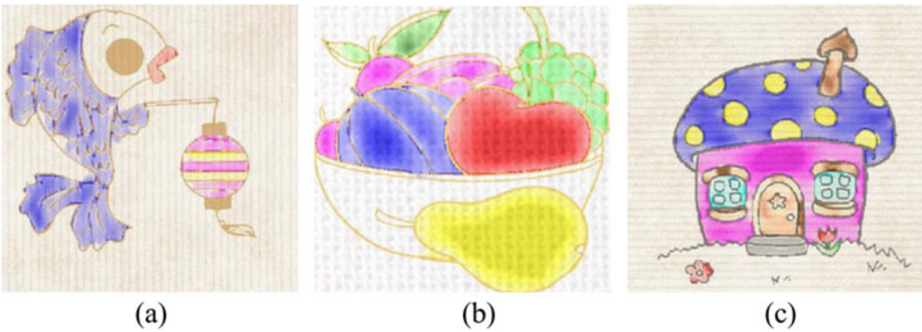


Fig. 10 More simulation results of hand-painted printing patterns on cloth generated using our method

4 Conclusions and future work

Simulation of hand-painted printing patterns on cloth is a rarely studied topic, posing a great challenge to researchers such as generating the complex contours and modeling the interactions between dyes and cloth according to the real process of this traditional handicraft. To our best knowledge, this is the first attempt to develop computational algorithms for such simulation. We constructed the interwoven structure of cloth using the cloth grid model, and generated the contour grid by inputting the contour image or the color image, which can be adopted to determine the interaction areas between dyes and cloth. A computational model, called MDGADM, was developed to simulate the diffusion of dyes in cloth. Since our method took full account of the procedures of hand-painted printing patterns on cloth, it succeeded in simulating various hand-painted printing patterns on cloth with rich textures and colorful designs. In addition to hand-painted printing patterns on cloth, our method also has the potential to be employed for simulation of other similar image patterns.

However, our method has the following limitations. We currently rendered the two-dimensional printing patterns in the plane, and the cloth model was simulated as the two-dimensional grid as well. We have not considered the rendering of the real cloth and the influence of the illumination. Additionally, our method did not solve the mixing among different dyes, i.e., a local region of the printing patterns is filled with two or more types of dyes; blending the density of different dyes is a simple way to handle this issue, which could be further improved by exploring the advanced techniques of mixing fluids [10].

The printing patterns are not only painted on cloth, but also widely exist on the surface of other artifacts such as the ceramics. In the future, by incorporating the simulation model of other materials, we will further extend our approach to more types of interesting hand-painted printing patterns. Our future work also includes improving the current method to simulate dynamic hand-painted printing patterns on 3D curved cloth, for example, animating colorful printing patterns on the surface of clothes in a more lively way. To improve the efficiency of the method by maximizing the ability of GPU and the parallel computation of multi-core techniques, might also be worth studying, which could greatly benefit the 3D simulation.

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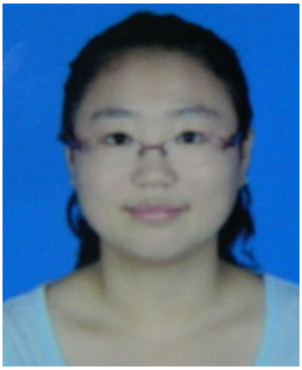

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