Manga Colorization

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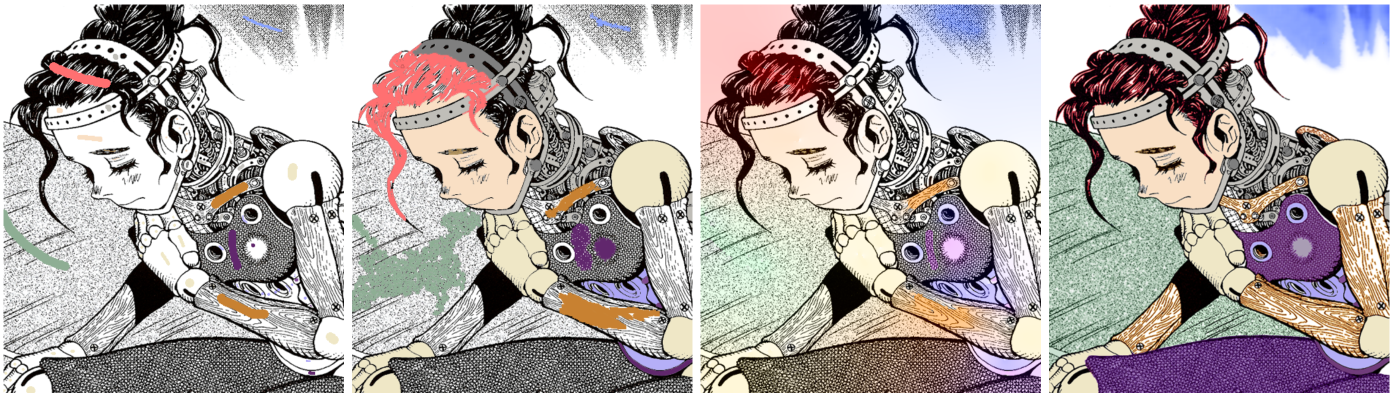

(a) Input (b) Flood-fill (c) Optimization (d) Our result

Figure 1: Colorization of pattern-continuous and intensity-continuous regions in manga. ©Yukito Kishiro / Shueisha

Abstract

This paper proposes a novel colorization technique that propagates color over regions exhibiting pattern-continuity as well as intensity-continuity. The proposed method works effectively on colorizing black-and-white manga which contains intensive amount of strokes, hatching, halftoning and screening. Such fine details and discontinuities in intensity introduce many difficulties to intensity-based colorization methods. Once the user scribbles on the drawing, a local, statistical based pattern feature obtained with Gabor wavelet filters is applied to measure the pattern-continuity. The boundary is then propagated by the level set method that monitors the pattern-continuity. Regions with open boundaries or multiple disjointed regions with similar patterns can be sensibly segmented by a single scribble. With the segmented regions, various colorization techniques can be applied to replace colors, colorize with stroke preservation, or even convert pattern to shading. Several results are shown to demonstrate the effectiveness and convenience of the proposed method.

Keywords: colorization, manga, segmentation

1 Introduction

The Japanese “manga”[1] (comic books in Japanese) is distinctive from traditional Western comic books in presenting fine details. The color manga can express even more semantics and artistic styles. However, mangas are seldom colored as coloring is time-consuming and labor-intensive. Most mangas only have a color cover and/or a few color pages inside to gain readers’ attention. Digital colorization techniques may provide a convenient way to colorize the mangas. Unfortunately, the intensive usage of strokes, hatching, halftoning and screening in mangas not just enriches the visual content and creates dramatic atmosphere, but also imposes many difficulties to digital colorization.

Existing colorization methods [Levin et al. 2004; Sykora et al. 2004] mainly rely on a “rough” continuity of gray levels to grow the affective regions, so as to segment the image into color regions. However, the black-and-white patterns in manga (Figure 1(a)) preserve no gray-level continuity to facilitate the segmentation, and hence existing methods may not work properly (Figures 1(b) & (c)). Instead, manga exhibits a rough *continuity of pattern*. In this paper, we propose a framework to conveniently colorize regions with a rough *pattern-continuity*, as well as intensity-continuous regions.

The proposed technique starts by scribbling the desired color on the interested regions. Our method then automatically propagates the color within the pattern-continuous regions. The propagation stops accurately at the boundary where the pattern exhibits abrupt change, even if there is no apparent outline. Figure 1(d) demonstrates our colorization result after faithfully segmenting the regions with similar patterns. These patterns can be as regular as the printed screening pattern (background and bed in Figure 1(a)) or as stochastic as hand-drawn hatching expressing textures and/or structures (hair and wooden arms).

The segmentation is achieved by applying a novel texture-based level set method which propagates boundary curves over regions with *similar but not necessarily homogeneous patterns*. The method can also propagate over disjoint regions containing a similar pattern. Note that although we only scribble on the girl’s left wooden arm in Figure 1(a), the segments of both arms are obtained

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[1] The Japanese word “manga” is used in this article in order to highlight the detail hatched and screened drawing that can be handled by the proposed method. We use the word to distinguish this kind of drawing from outline-based comic books for children.

(Figure 1(d)). We introduce a pattern-continuity speed function into the topological changing level set in order to achieve such segmentation goals.

Once the segmentation is done, we can colorize the regions using various methods. We demonstrate three ways to colorize them: 1) leak-proof colorization of intensity-continuous regions even when the boundaries are open or drawn casually (Figure 8), 2) colorization of pattern-continuous regions while preserving the original textures or structures of the patterns (wooden arms and hair in Figure 1(d)), and finally, 3) pattern-to-shading conversion for patterns expressing shading only (background in Figure 1(d)).

2 Previous Work

Colorization The early work in colorization was driven by the need to colorize classical black-and-white movies. However, the techniques used in these colorization systems are usually proprietary and seldom accessible. Some systems require manual outlining of regions in the key frames and automatically tracking them in the frames in between. However, the outlining is still labor-intensive and tedious [Burns ; Markle and Hunt 1987; Silberg 1998; NeuralTek 2003].

Several advanced and convenient colorization techniques for images and videos have been proposed in the past few years. Welsh et al. [2002] proposed an interactive colorization technique with minimal user intervention. It colorizes an image by matching the swatches in the grayscale image to those in the reference color image. Their approach was inspired by a method of color transfer between images [Reinhard et al. 2001]. The more generic image analogies framework is proposed by Hertzmann et al. [2001]. In their work, a general filter is learned from the relationship between two images A and A' using a simple multiscale autoregression, and then applied to an input image B to produce a new "analogous" image B'.

Irony et al. [2005] presented a novel method to colorize grayscale images by transferring color from a segmented example image. Instead of relying on a series of independent pixel-level decisions, they developed a new strategy that attempts to account for the higher-level context of each pixel. Target pixels are classified using LDA and image space voting with DCT coefficients as feature vectors. The colorized results exhibit nice spatial consistency.

Sykora et al. [2004] introduced a novel colorization framework for old black-and-white cartoon video. The dynamic part of the scene is represented by a set of outlined homogeneous regions which superimpose the static background. They combined unsupervised image segmentation, background reconstruction, and structural prediction to reduce manual intervention.

Levin et al. [2004] proposed a simple yet effective user-guided colorization method. The user can scribble desired colors in the interiors of various regions. They formulate the colorization as a constraint quadratic optimization problem. The basic assumption is that adjacent pixels having similar intensities should have similar colors. Their method works nicely for photographs and videos, in which intensity-continuity is generally maintained. However in our manga colorization application, the black-and-white hatching and screening preserve mainly pattern-continuity, not intensity-continuity. Figure 1(c) shows the result of applying Levin's method to manga. To colorize the drawing with hatching and screening, our method propagates the color over the pattern-continuous regions.

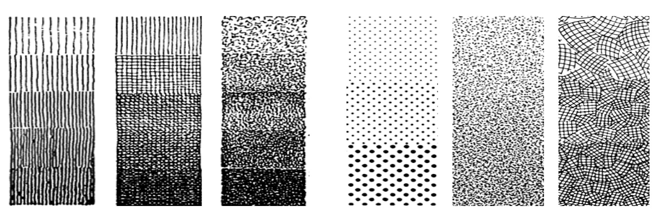
Texture-based Segmentation Our work is based on the texture-based segmentation that requires texture analysis and modeling. Textures are usually first analyzed by filtering techniques [Galun et al. 2003] and then represented by statistical models. The importance of texture properties such as size, aspect ratio, orientation, brightness, and density of repeated texture elements have long been awared in the classical perception studies by Julesz [1981]. The analysis has been significantly enhanced via the rich study in statistical representations including alternative Gabor filters [Weldon et al. 1996], filter bank responses [Varma and Zisserman 2003], random field models, and wavelet representations. These statistical features could then be utilized for texture classification, segmentation, or synthesis. For instance, the texture-based segmentation can be tackled by locating similar spatial-frequency content. The locating methods could be roughly classified into unsupervised segmentation [Hofmann et al. 1998], or boundary-based and region-based methods in supervised segmentation [Paragios and Deriche 1999]. In our application, we adopted the statistical representation based on Gabor wavelet.

3 Algorithm

The whole process begins by a user scribbling on regions of interest. Our system processes the user input incrementally. This provides the user with full control of modification and refinement. In each incremental step, the user enters one or more scribbles to segment the desired regions. Our system provides two modes of propagations for segmentation, pattern-continuous (Section 3.3) and intensity-continuous (Section 3.4) propagations. It is up to the user to decide which mode of propagation should be employed in the current step. The pattern-continuous and intensity-continuous propagations are designed for hatched/screened region and intensity-continuous region with/without unclosed outlines, respectively. Once the regions are segmented, they can be colorized using the proposed stroke-preserving colorization, pattern-to-shading, and multi-color transition (Section 4), based on the user decision.

3.1 Hatching and Screening

In manga drawing, hatching and screening techniques are adopted to express various effects including shading, material reflectances, backgrounds, or even structures. While hatching mainly refers to hand-drawn strokes (Figure 2(a)), screening makes use of printed comic pattern papers (Figure 2(b)). A comic pattern paper is a transparent slide with a printed black pattern. The pattern can be produced digitally [Ostromoukhov and Hersh 1995] and may range from simple patterns of dots and lines to complex patterns of icons and line arts (Figure 2(b)). Artists may employ hundreds of patterns and their combinations to express artistic styles and create dramatic atmospheres.



(a) Hatching (b) Screening

Figure 2: The artist may employ intensity spectrums of strokes or screens to illustrate shading.

Both hand-drawn hatching and printed screening only use two colors, black and white. Hence the change in gray level is abrupt. This introduces difficulties to traditional color transfer techniques that mainly rely on the continuity or similarity of gray levels. However, hatching and screening do exhibit the continuity of patterns as evidenced in both Figures 2 and 3. This motivates us to exploit the color propagation based on *pattern-continuity*.

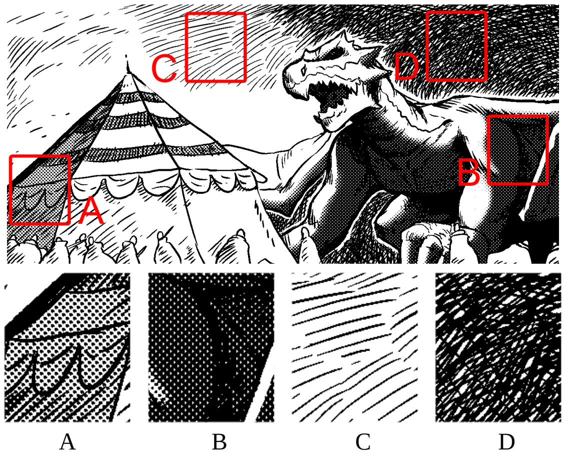


Figure 3: Screening and hatching are popular to create dramatic backgrounds.

3.2 Level Set

To do so, we employ the level set method due to its elegance in modeling multiple boundaries simultaneously. The geometric level set method, proposed by Osher and Sethian, is a zero surface method [Osher and Sethian 1988; Sethian 1996; Sethian 1999]. Its fundamental idea is to raise the modeling of boundaries from a two-dimensional planar curve into a three-dimensional curved surface, by embedding the propagating curves as the zero level set of a higher dimensional surface (Figure 5). This offers several advantages, including parameter-free representation, topological flexibility, and capability in dealing with local deformation.

The colorization over both pattern-continuous and intensity-continuous regions can be naturally formulated under the same mathematical framework. Besides the mathematical elegance, level set provides several conveniences. Its topological flexibility allows us to conveniently segment multiple disjointed regions with a single user scribble. Moreover, its capability in controlling local deformation allows us to conveniently leak-proof during colorization.

We start by describing the problem formulation of propagating color over pattern-continuous regions (such as in Figure 4(b)), followed by propagation over intensity-continuous regions (such as in Figure 4(a)). The level set method embeds the propagating curve

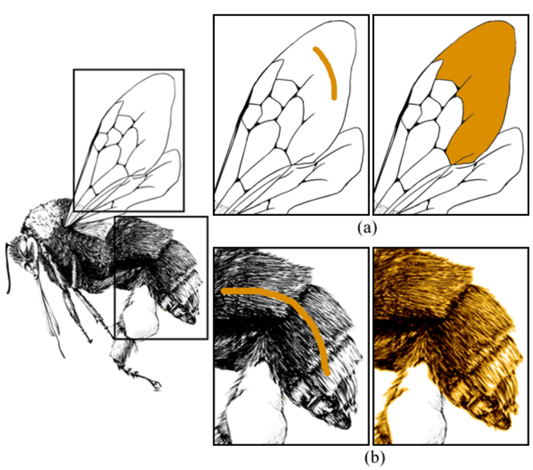


Figure 4: Colorization of (a) intensity-continuous and (b) pattern-continuous regions.

Γ as the zero level set of an implicit function Φ (i.e. the curve of $\Phi = 0$), which is defined over the entire image domain. As illustrated in Figure 5, the dimensionality of the level set function Φ is one dimension higher than the evolving curve. In our case, Φ is a 3D surface. The level set method tracks the evolution of a front that is moving normal to the boundary with a speed $F(x,y)$. The speed function may be dependent on the local or global properties of the evolving boundary or driven by the external forces. Function Φ is initialized based on a signed distance measured from the user scribble. The evolution of the boundary is defined by the partial differential equation on the zero level set of Φ:

$$\frac{\partial \Phi}{\partial t} = -F|\nabla \Phi| \tag{1}$$

where t is the time of evolution. The speed function F governs the actual behavior of the evolving boundary, including its movement and the stopping criteria.

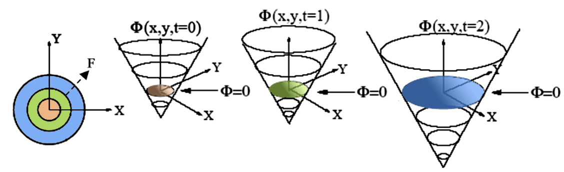


Figure 5: Level set transforms the front propagation into an initial value problem into a space of one higher dimension.

For segmentation problems, the influence of the speed function F can be split into two major parts, F_A and F_G (Equation 2). F_A is the positive advection term causing the front to uniformly expand. F_G depends on the geometry of the propagating front, such as local curvature. It controls the smoothness of the propagating front. Mathematically,

$$\frac{\partial \Phi}{\partial t} = h \cdot (F_A + F_G)|\nabla \Phi| \tag{2}$$

where F_A is normally a constant; $F_G = -\varepsilon\kappa$ such that κ is the local curvature of the evolving curve Γ and ε is a constant; h is a filter or halting component, to terminate the curve evolution.

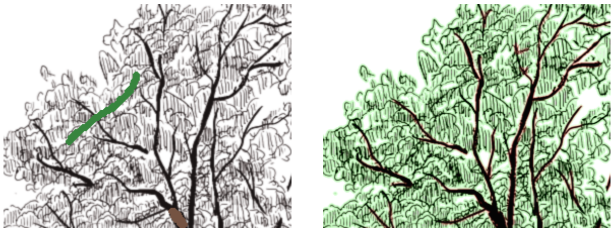
The level set propagation starts by initializing Φ. In our application, we initialize Φ as the signed distance from the user scribble. With Φ, the evolving curve Γ is naturally obtained ($\Phi = 0$). A narrow band is constructed as the region surrounding Γ with a specified width. For each pixel within the narrow band, Φ is updated according to Equation 2. With this updated Φ, a new Γ can be computed. The iteration continues until convergence.

3.3 Pattern-Continuous Regions

In order to evolve the boundary over pattern-continuous regions as in Figure 4(b), the key is to measure the change of pattern instead of the ordinary change of intensity. We model a pattern-based halting term $h_P(x,y)$ as

$$h_P(x,y) = \frac{1}{1 + |D(T_{\text{user}}, T_{\text{front}}(x,y))|}. \tag{3}$$

where T_{user} is the pattern feature on the user scribbles, and $T_{\text{front}}(x,y)$ is that on the propagating front. Function D is a distance function measuring the difference between features at the propagating front and that at the user scribble. Here we simply use the sum of square difference as the distance measure.



(a) (b)

Figure 6: (a) Careless scribble (green) crossing mainly over the leave areas but slightly over a small amount of trunk area. (b) Our method can still faithfully separate the leaves from the trunk.

Pattern Feature A useful choice of pattern feature is the statistical feature in Gabor wavelet domain [Manjunath and Ma 1996]. Given an image $I(x,y)$, its Gabor wavelet transform is given as

$$W_{m,n}(u,v) = \int_{\Omega} I(x,y) g^{*}_{m,n}(u-x, v-y)\,dxdy, \tag{4}$$

where $g_{m,n}$ is the self-similar filter dictionary defined in the Appendix; superscript * denotes the complex conjugate; and subscripts m and n index the scale and orientation, respectively. We then compute the mean $\mu_{m,n}$ and the standard deviation $\sigma_{m,n}$ of the magnitude of the transform coefficients:

$$\mu_{m,n} = \int\int |W_{m,n}(x,y)|\,dxdy, \tag{5}$$

$$\sigma_{m,n} = \sqrt{\int\int (|W_{m,n}(x,y)| - \mu_{m,n})^2\,dxdy}. \tag{6}$$

The feature vector we defined is composed of $\mu_{m,n}$ and $\sigma_{m,n}$ of multiple scales and orientations. They represent the local structures in multiple scales and orientations. In all of our experiments, we use four scales $M = 4$ and six orientations $N = 6$ inside a $w \times w$ window, where w is normally 16. Our feature vector formed is

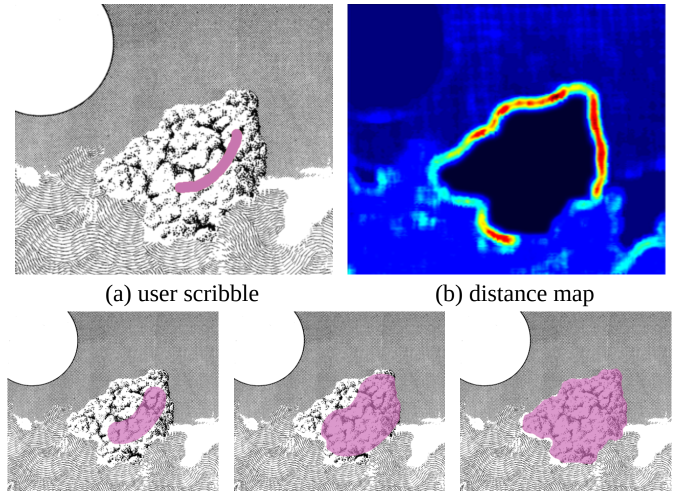
$$T = [\mu_{0,0}\ \sigma_{0,0}\ \mu_{0,1}\ \ldots\ \mu_{3,5}\ \sigma_{3,5}]. \tag{7}$$

Given the user scribble, we compute the pattern features at k points sampled uniformly on the scribble. We then perform clustering on these feature patterns, identify the major cluster, and compute the average of this cluster. This average is regarded as the representative feature pattern, T_{user}. With this approach, our method can still identify a sensible pattern feature even if the user has carelessly scribbled over a small amount of undesired region as shown in Figure 6.

Propagation Within the pattern-continuous regions, $h_P(x,y)$ is close to unity because $D(T_{\text{user}}, T_{\text{front}})$ is small. Therefore, the positive advection component F_A pushes the front outwards, while the curvature component F_G maintains the smoothness of the propagating front. On the other hand, speed function F drops to zero when the front approaching the boundaries, where there is abrupt change in pattern. The propagation starts from the user scribble and then grows outwards and stops at the boundary where F is reduced to zero.

Figure 7(b) shows the distance map computed with respect to the representative pattern feature on scribble (Figure 7(a)). Red color indicates large distance values while the black color indicates small distance values. With this distance map, the propagating front can successfully halt at places where patterns are substantially different from that at the scribble. Figures 7(c)-(e) show the intermediate steps during propagation.

With the implicit representation of propagation curves, level set can naturally handle topological changes, such as boundary splitting and merging. In other words, disjoint regions can be selected by a single user scribble (wooden arms and hairs in Figure 1(d)).



(a) user scribble (b) distance map

(c) step 100 (d) step 300 (e) result

Figure 7: (a) The original drawing with complex patterns and the initial scribble. (b) The distance map with respective to the representative pattern feature on the scribble. (c)-(e): The front propagation steps.

3.4 Intensity-Continuous Regions

The color propagation over ordinary intensity-continuous regions can also be treated under the same framework. In order to achieve this, we need to define another halting term h_I that measures the change of intensity gradient. With the h_I in Equation 8, the color propagating front can naturally stop at the outline edge as in Figure 4(a).

$$h_I(x,y) = \frac{1}{1 + |\nabla(G_\sigma \otimes I(x,y))|} \tag{8}$$

where $G_\sigma \otimes I(x,y)$ denotes convolution of the image I with a Gaussian smoothing filter G_σ with a characteristic width of σ. The expression $|\nabla(G_\sigma \otimes I(x,y))|$ is essentially zero except at the place where the image gradient changes abruptly (e.g. at the outline edge).

Leak-Proofing Using simple flood-fill available in commercial software, there will be leaking (Figure 8(a)) due to the unclosed and stylish boundaries commonly found in manga. In order to leak-proof the segmented regions, we introduce one more component, F_I, into the speed function F and rewrite $F = h_I(F_A + F_I + F_G)$, and F_I is defined as

$$F_I(x,y) = -F_A R\left(\frac{|\nabla G_\sigma \otimes I(x,y)| - M_2}{M_1 - M_2 - \delta}\right), \tag{9}$$

where M_1 and M_2 are the maximum and minimum values of the magnitude of image gradient $|\nabla G_\sigma \cdot I(x,y)|$; parameter $\delta \in [0, M_1 - M_2]$ is the *relaxation factor*; function R clamps the input value to [0,1]. With this relaxation factor, when the front propagates to the place where the gradient is close to, but may not be equal to, M_1 (the maximum), the speed function F drops to zero. Hence it prevents the propagation front to leak through the gaps. Note how the propagation halts reasonably at the blown-up areas in Figures 8(c) & (d).

Unlike the propagation in pattern-continuous regions, disjoint-region propagation is prohibited in intensity-continuous region, because the semantics-bearing pattern (such as the wood and hair pat-

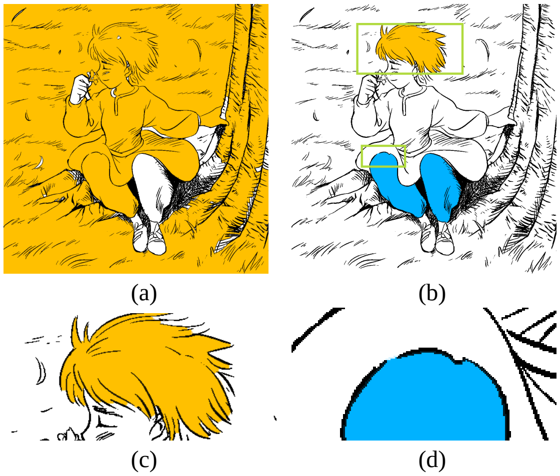


Figure 8: (a) Severe leaking is common during flood-filling. (b) shows our result after introducing the relaxation factor into the speed function. (c) & (d): Blow-ups of the gaps.

terns in Figure 1) is usually absent in the intensity-continuous regions.

4 Colorization and Results

Once the segmented regions are obtained, we can colorize them using various methods. This paper demonstrates three ways to colorize these segmented areas.

Color Replacement For the intensity-continuous region, filling color can be trivially done by replacing the black or white color by the user color on the scribble. Both Figures 8(b) and 12(d) demonstrate the colorization results with leak-proofing.

Stroke-Preserving Colorization As mentioned before, the artist may use hatching/screening to express material reflectances, textures, or even shapes, it is sometimes necessary to preserve the original pattern during colorization. Instead of naïvely replacing the whole region with a single color, it is colorized by bleeding colors out of the strokes/patterns. The user color is multiplied with the halting term h_I in the YUV space.

$$Y_{\text{new}}(x,y) = Y_{\text{user}} \otimes |1 - h_I(x,y)|^2,$$
$$(U,V)_{\text{new}} = (U,V)_{\text{user}} \qquad (10)$$

where Y is the luminance channel; subscripts $_{\text{new}}$ and $_{\text{user}}$ correspond to the output and the user colors respectively; $\otimes$ is the convolution operator; and h_I is defined in Equation 8. Hence the user color shows up wherever $h_I \to 0$. Figures 4(b), 11 and 13 show the results colorized by the mentioned method. Note that the complex strokes in Figure 11 express both the textures on tree trunk and the shapes of leaves.

Besides the color-bleeding method, we also allow the user to simply replace the pair of black and white colors by a user-specified color pair. In Figure 13, two sets of colors are used to explicitly highlight two hidden meanings: (b) a turquoise eye, and (c) the Big Bang.

Pattern to Shading The artists commonly use the change of density in hatching and screening to recreate shading. Such a technique is usually found at the background of the drawing. As color can readily reproduce such shading effect, we can convert the pattern to smooth color shading. In order to achieve this, we first calculate the local intensity within the pixel neighborhood,

$$s = f \otimes Y_{\text{image}}. \qquad (11)$$

where Y_{image} is the pixel gray value in the original image and f is a box filter. Note that $s \in [0,1]$. Then the Y channel is linearly mapped by

$$Y_{\text{new}} = sY_{\text{user}},$$
$$(U,V)_{\text{new}} = (U,V)_{\text{user}} \qquad (12)$$

Figures 1(d) and 14 show two results colorized with this pattern-to-shading method. The original screening in Figure 14(a) is replaced by a smoothly changing dark blue sky. Note that some of the stars can be segmented and preserved, as the side product of segmenting the sky.

Multi-color Transition Sometimes it may be required to colorize the same region with two or more colors to achieve certain effects. To incorporate the smooth color transition among multiple scribbles with different colors, the $(Y,U,V)_{\text{user}}$ can be simply computed by blending the user colors on the scribbles with the weights proportional to the distances from the corresponding scribbles. Figure 9 demonstrates such smooth color transition in the sunset sky.

Limitation The proposed method has a limitation when two patterns overlap each other as demonstrated in Figure 10. The purple scribbles are intended to segment the wave pattern while the green scribbles are used to segment the halftone screen expressing shading (Figure 10(a)). However, the system fails to segment the region where both patterns overlap at the sleeve of the kimono (Figure 10(b)). The reason is that the system regards the overlapped pattern as a distinct pattern.

5 Conclusions

In this paper, a new technique for colorizing mangas is proposed. It propagates colors over pattern-continuous regions containing hand-drawn hatching and printed screening patterns. The user is free from manually segmenting the patterned regions. Both pattern-continuous and intensity-continuous regions can be segmented under the same mathematical framework. We have demonstrated, via several examples, that the proposed method is robust enough to propagate colors over various complex patterns exhibiting similarity.

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Appendix

Given a 2D Gabor function $g(x,y)$ and its Fourier transform $G(u,v)$,

$$g(x,y) = \left(\frac{1}{2\pi\sigma_x\sigma_y}\right)\exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}\right)+2\pi jWx\right], \quad (13)$$

$$G(u,v) = \exp\left\{-\frac{1}{2}\left[\frac{(u-W)^2}{\sigma_u^2}+\frac{v^2}{\sigma_v^2}\right]\right\}, \quad (14)$$

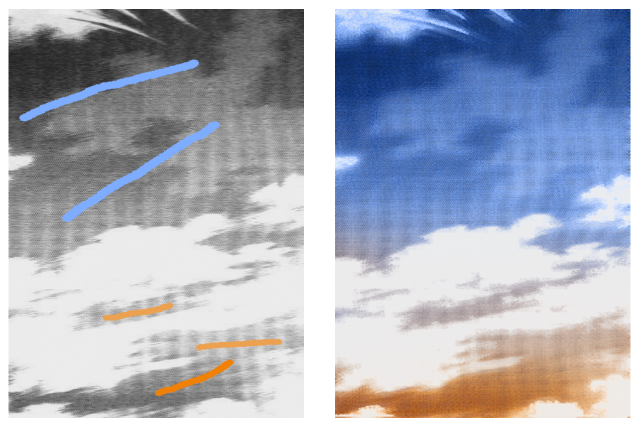
where $\sigma_u = 1/2\pi\sigma_x$ and $\sigma_v = 1/2\pi\sigma_y$, a class of self-similar filter dictionary $g_{m,n}$, can be obtained by dilating and rotating the wavelet coefficients $g(x,y)$ by,

$$g_{m,n}(x,y) = a^{-m}G(x',y')$$

where $a > 1$, m and n are integers.

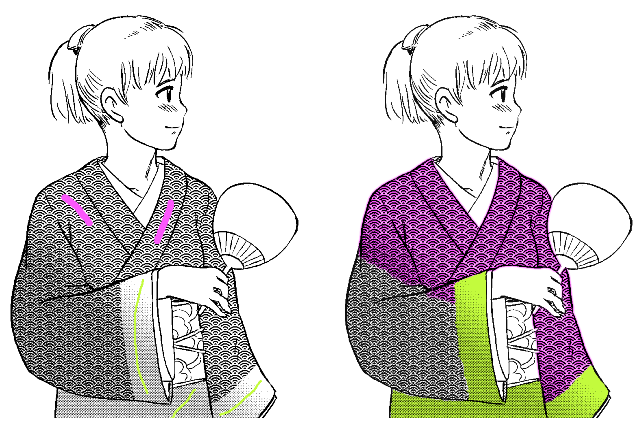
$$x' = a^{-m}(x\cos\theta + y\sin\theta), \quad (15)$$
$$y' = a^{-m}(-x\sin\theta + y\cos\theta), \quad (16)$$

where $\theta = n\pi/N$ and N specifies the total number of orientations. The scale factor a^{-m} ensures that the energy is independent of m.



(a) (b)

Figure 9: Smooth color transition within the same segmented region.

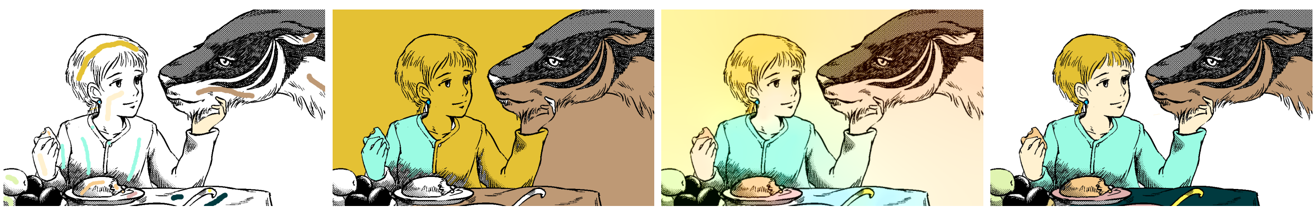


(a) (b)

Figure 10: Level set propagation fails to identify the overlapped pattern.

(a) (b) (c)

Figure 11: Stroke-preserving colorization. Even the user carelessly scribbles the colors, the leave region can still be sensibly separated from tree branches. A color-bleeding approach is used in this example.



(a) (b) (c) (d)

Figure 12: Leak-proof colorization over intensity-continuous regions with unclosed boundaries. (a) Input drawing with user scribbles. (b) Severe leaking resulted using flood-filling. (c) Result from optimization-based colorization. (d) Our result.

(a)
(b)
(c)

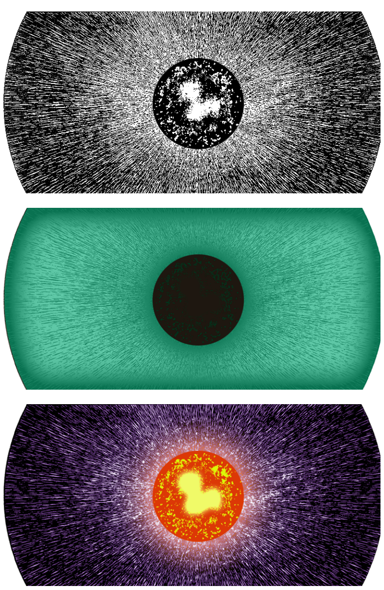


Figure 13: Two sets of colors are used to explicitly highlight the two hidden meanings.

(a) (b)

Figure 14: Pattern-to-shading.