Statistical Sketching for Non-Photorealistic Rendering Models and Animations

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Abstract

This paper further investigates the use of a statistical sketching model previously introduced in [Mignotte (2003)]. In this Bayesian framework, the localization and deformation of each pencil stroke of the sketch to be synthesized is viewed as the search of its Maximum A Posteriori (MAP) estimate. First, we improve this model by bringing a pencil stroke rendering procedure combined with a local rendering example-based process to significantly enhance its application for automatic synthesis of artistic depiction styles. Second, we show how this sketch synthesis procedure is suitable to easily synthesize a continuous gamut of sketch styles. Finally, we show how this model can also be exploited for several other interesting NPR applications. Among them, we describe a metamorphosis process between two sketches over times. We illustrate the interest and potential of these unsupervised techniques with images simulating automatic synthesis of various illustration styles and animated sequences with NPR effects.

Keywords: Non-photo-realistic Rendering (NPR), Sketch rendering model, NPR animation, Bayesian statistical model.

1. Introduction

In the past few years, there has been a great deal of research work in creating artistic styles by computer. This field of research is known as Non-Photorealistic Rendering (NPR). This field of research refer to any image processing techniques which can transform an image into a specific artistic styles (or more precisely that suggest a depiction style) such as ink painting, pointillist style, engraving, stylized halftoning, charcoal drawing, etching, etc., or, more generally, in a style other than realism (see [Reynolds (2003)] for a excellent review of existing NPR techniques).

Among these depiction styles, freehand sketch remains especially appealing. It can be used for illustrative purposes or artistic effects, but this representation style is also interesting due to its ability to abstract away detail, to clarify or simplify shapes (e.g., for content-based image retrieval application [Kato et al. (2002)]) and to focus the viewer's attention on relevant features [Salisbury et al. (1997)]. In addition, this stylized depiction allows to efficiently convey a great deal of information with very few pencil strokes. Let us add that an initial and preparatory sketch is sometimes the first essential step in some artistic drawings. It is the case of ink painting, graphite or charcoal pencil style, etc. or more generally, in all artistic styles where pencil strokes are used as primitives. In these cases, the initial sketch can then be refined, in a second step, with techniques specific to

each illustration style (such as smudging¹, mass shading, etc.), allowing to suggest volume, depth, shadows and details of the different shapes contained in the scene.

There are many commercial softwares [design Painter (2003); Photoshop (2003)] or previous works [Durand et al. (2001); Salisbury et al. (1997, 1994)] which propose (widely) supervised systems in which the user has to place each individual stroke manually to create the sketch (by using or not an input real image) and, in a second step, that controls over the tone, the smudging and amount of details or systems that use a 3D polygonal mesh information [Markosian et al. (1997)]. These systems are rather flexible tools that help the user to produce, interactively, computer-generated drawings for some traditional styles. To our knowledge, none considered an unsupervised system, which could be applied directly from an input grey-level real image, for both pencil stroke placement (creating a sketch) and for a final automatic rendering that will be specific to a particular depiction style (example-based). Let us add that the methods proposed by the computer graphics community are generally specifically tailored to a particular rendering style and/or are purely deterministic algorithmic (excepted [Szirányi and Tóth (2001, 2000)] and/or not expressed in a statistical/mathematical framework.

Nevertheless, one of them is expressed in the context of machine learning and is general enough to be used for different depiction styles. It is the case of the framework for processing images by example called image analogies recently proposed by Hertzmann *et al.*. Their model allows to learn an image transformation from one pair of *before* and *after* images (which can be respectively a blurred and non-blurred version of a sample with a given artistic style) them applying the transformation to a blurred real input photograph to produce an output image with an analogous style of the one in the first initial image sample pair [Hertzmann et al. (2001)]. Nevertheless, their method does not succeed to capture larger-scale features such as pencil strokes and only some local aspects of an illustration style may be captured.

Among the existing unsupervised systems, tailored to a particular rendering style, we can cite the stochastic image rendering method recently proposed in [Szirányi and Tóth (2001, 2000)] to simulate the painting process where the paintbrush-like image transformation is based on a random searching to insert (brush-)strokes into a generated image at decreasing scale of brush size. This work is formulated in the framework of global energy-based model (using scale-space theory and mathematical morphology) and basically minimizes a distortion measure computed on the original input image and the currents painting composed of all generated brush strokes. Let us also mention the work of DeCarlo and Santella (2002) describing an approach to stylizing and abstracting photographs and transforming images into a line-drawing style using bold edges and large regions of constant color.

In the context of unsupervised sketch mathematical estimation, from an input image, we can also cite the model proposed in [Guo et al. (2003)] that integrates three components: a descriptive texture model (Julesz ensemble), a generative model with image primitives (textons) and a gestalt field for application in image interpretation (in order to automatically separate the input image into "sketchable" or structures and "non-sketchable" or textures), image and video compression or edge detection (incorporating structural information).

In mass shading, the artist renders every visible tone in the subject as literally as possible by merging component pencil lines Sousa and Buchanan (1999) Guptill (1977). Stippling consists in drawing small dots or very short lines. Hatching consists in drawing lines with one definite and continuous movement, parallel to each other, and very near together to produce an even tone. Cross-hatching is the rendering of tone values by superimposing one series of parallel lines diagonally across another series of parallel lines Salwey (1925)

The unsupervised drawing system, we propose, is viewed as a two step (coarse-to-fine) process, generally followed by most of the drawers; namely a sketch rendering technique completed by a rendering technique specific to a given depiction style. This allows us to produce drawings in a variety of traditional styles.

More precisely, starting from an input grey-scale image, an initial sketch is first generated. This step tends to create, with simulated pencil strokes, a realistic and preparatory sketch drawing. This sketch renderer allows to outline and clarify the silhouette while abstracting aways details and highlighting relevant features in the shape of scene objects contained in the input image. Each individual stroke need not be drawn precisely in order to create a more natural and hand-drawn sketch. To this end, we propose a Bayesian formulation for this sketch rendering issue [Mignotte (2003)]. As likelihood model of this inference, we exploit the recent statistical model of the gradient vector field distribution proposed by Destrempes and Mignotte for contour detection [Destrempes and Mignotte (2002a)] and shape localization [Destrempes and Mignotte (2002b)]. A global prior deformation model for each pencil stroke is also considered. In this Bayesian framework, the placement of each stroke is viewed as the search of the Maximum A Posteriori (MAP) estimation of its deformations. We use a stochastic optimization algorithm in order to find these optimal deformations for each pencil stroke. We improve this model by bringing a pencil stroke rendering procedure combined along with a local rendering example-based process to significantly enhance its application for the automatic synthesis of artistic depiction styles. We also show how this sketch synthesis scheme, involving a parametric model for each localized pencil stroke, is both suitable to easily synthesize a continuous gamut of sketch styles and to create some artistic NPR animated effects and animations. Among them, we present a metamorphosis process between two sketches over times.

A part of this work should be seen is in the context of NPR animation, which is quite recent in the computer graphic community [Curtis (1999)]. To the best of our knowledge there is no other NPR methods that was interested in sketch morphing for NPR applications. Shape contour Morphing was nevertheless successfully applied for other applications. Among them a metamorphosis technique between two shapes has already been proposed, in the pattern recognition field, for the on-line handwriting recognition problem [Pavlidis et al. (1998)]. A segmentation process is first defined to model a cursive word or a hand-drawn line figure by pieces of wire. Shape metamorphosis occurs through stretching and bending of the artificial wire. The amount of energy spent in morphing one shape to another is then used as a dissimilarity measure. In other words the degree of morphing is exploited as primary matching criterion. In the same spirit, Arvo and Novins present a similar approach to recognize individual handwritten character and gradually transformed them. via a metamorphosis and energy-based correspondence algorithm, into clean typography [Arvo and Novins (2000.)]. In the same idea, but in the computer interface field, [Arvo and Novins (2000)] propose a new sketching interface in which shape recognition and morphing are also tightly coupled. Raw input strokes are continuously morphed into ideal geometric shapes, even before the pen is lifted. By means of smooth and continual shape transformations the user is apprised of recognition progress and the appearance of the final shape. [Wenyina et al. (2001)] extends the idea of on-line graphics recognition system that can predict user's intention, to input more complex shapes. In [Jin et al. (2001)], a stroke morphing concept is presented in computer graphics. This flow and shape-oriented morphing technique is used to generate automatically artificial strokes creating in this way more natural-looking pen-and-ink illustration with fewer user strokes.

Secondly, the initial preparatory sketch is then refined with an example-based local rendering model, used to transfer the textural tone value of a given artistic depiction style [Mignotte (2002)]. This allows to render the texture of each pencil stroke, previously localized and allows to reveal the shape (i.e., to suggest volume and depth), details, and shadows of the different objects contained in the image. In our application, this last procedure also tends to simulate the tonal adjustment technique classically used by the artist (e.g., smudging, mass shading, stippling, hatching or crosshatching 1 (see Fig. 1)). To this end, we have stated this problem in the multiresolution energy minimization framework and exploited the multiscale non parametric model already proposed in [Mignotte (2002)] and derived from the non-parametric sampling technique introduced by Wei et al. for texture synthesis [Wei and Levoy (2000)]. This model appears to be interesting to also capture some local characteristics of a rendering style from an artistic illustration example. The Wei's example-based sampling algorithm has also inspired some recent research works in sketch or curve synthesis. We can cite the work of Chen et al. on facial caricature synthesis [Chen et al. (2001)], or the work of Hertzmann et al. [Hertzmann et al. (2002)] or Jodoin et al. [Jodoin et al. (2002)] that efficiently exploits this deterministic sampling technique to generate (after learning from examples) hand-drawn styles of curves for non-Photorealistic rendering and automatic synthesis of freehand sketch drawings with a particular style.



Figure 1: Examples of real drawings using a soft graphite pencil. (a) Freehand preparatory sketch drawing made by the French artist J.-C. Mezieres extracted from the European comic magazine "Valerian and Laureline". (b) Drawings from L. da Vinci combining the sketch and outline information with the tonal modeling created respectively by a smudging and mass shading process, and an hatching and cross-hatching technique. (c) A manga drawing and (d) Sketch of Juliette Recamier using a soft graphite pencil.

This paper is organized as follows. Section 2 recalls the statistical localization strategy of each pencil stroke of the sketch drawing to be created. Section 3 describes the rendering procedures used for each pencil stroke and the finished rendering result used to transfer the textural tone value of a given artistic depiction style. Section 4 describes the morphing strategy. Finally, obtained results and applications of the sketching method and Morphing animation exploiting this sketching model are presented in Section 5. Then we conclude in Section 6 with some perspectives.

2. Bayesian Sketching Model

2.1 Prior Model

In this model, a pencil stroke is represented by a set of τ labeled points $\gamma = (x_1, y_1, \dots, x_{\tau}, y_{\tau})$ equally sampled which approximate the outline of a straight line and linked by a cubic B-spline (Fig. 2). In order to take into account the variability of the stroke deformations, a set of admissible global non-affine and affine deformations is introduced.

Non-Affine Deformations In this deformation model (first proposed by [Jain et al. (1996)] for the localization of shapes), the template image is considered to be mapped on a deformable unit square $S = [0,1]^2$. The deformation is then represented by $(x,y) \mapsto (x,y) + \mathcal{D}(x,y)$, a smooth mapping of the unit square onto itself in which $\mathcal{D}(x,y)$ is the following displacement function,

$$\mathcal{D}_{\xi}(x,y) = \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{\xi_{m,n}^{x} e_{m,n}^{x}(x,y) + \xi_{m,n}^{y} e_{m,n}^{y}(x,y)}{\lambda_{m,n}},$$

with, $e_{m,n}^{x}(x,y) = (2\sin(\pi nx)\cos(\pi my), 0),$
 $e_{m,n}^{y}(x,y) = (0, 2\cos(\pi nx)\sin(\pi my)).$

For m, n = 1, 2, ... Low values of m and / or n correspond to lower frequency components of the deformation in the x and y directions, respectively. $\lambda_{m,n} = \pi^2(n^2 + m^2)$ are the normalizing constants. The parameter vectors ξ are the projections of the displacement function on the orthogonal basis defined by e^x and e^y . In order to allow a sufficiently wide range of possible deformations, while keeping the number of parameters reasonable, we use M = N = 2. Fig. 2 illustrates the series of deformations of an initial template using higher order terms and different values of M and N. The deformation becoming more complex as higher frequency components are added to the displacement function \mathcal{D} (see [Mignotte (2003)]).

Affine Deformations Finally, we introduce a set of admissible rigid deformations involving translation (τ_x, τ_y) , scaling *s*, and rotation ψ applied point-wise to the template.

Let now γ_{θ} be a deformed version of the original template γ_0 according to the aforementioned deformations with parameter vector θ , composed of 4 affine + 4 non affine deformation parameters, i.e., $(\xi_{1,2}^x, \xi_{2,2}^x, \xi_{1,0}^y, \xi_{2,1}^y)$ (due to the symmetry of the non-deformed original template associated to the stroke). Let Θ be the random variable corresponding to the vector of deformations. We model the distribution of Θ (global prior model) by (see [Jain et al. (1996)]),

$$P_{\Theta}(\theta) \propto \mathscr{U}(\tau_x, \tau_y, s, \psi) \exp\left(-\rho \underbrace{\sum_{\xi_i \in \xi} \left((\xi_i^x)^2 + (\xi_i^y)^2\right)}_{U_p(\xi)}\right),$$



Figure 2: Global non-affine deformations, (a) $\xi_{1,2}^x = -4, \xi_{2,2}^x = -1, \xi_{1,0}^y = 4$. (b) by adding $\xi_{2,2}^y = -4$.

where \mathscr{U} designates the uniform distribution and where the parameter ρ allows to control the "rigidity" of the pencil stroke.

2.2 Likelihood Model

The likelihood of deformations is based on the statistical distribution of the gradient vector field (norm and angle) of the gray levels on and off edges [Destrempes and Mignotte (2002a)]. This model can define, with a true statistical meaning, the likelihood of a deformation θ (or equivalently a pencil stroke template γ_{θ} with deformation parameters θ) by the following Gibbs distribution, $P_{Y/\Theta}(y/\theta) = Z_y^{-1} \exp(-U_l(\theta, y, \gamma))$, where *Y* represents the set of random variable couples associated to the gradient vector of each pixel of the input image. Z_y is a normalizing constant and γ designates the parameter vector of this likelihood distribution which is preliminarily estimated [Destrempes and Mignotte (2002a)].

2.3 MAP Stroke Deformation

From the likelihood and prior distributions and Bayesian inference, the posterior $P_{\Theta/Y}(\theta/y) \propto \exp[-(U_l(\theta, y, \gamma) + \rho U_p(\xi))]$ of a deformed pencil stroke is defined Mignotte (2003). We can then view the localization of each pencil stroke, in a sketch drawing, as finding its deformation θ that maximizes $P_{\Theta/Y}(\theta/y)$ or equivalently as a the search of the MAP estimation of θ , i.e., $\hat{\theta}_{MAP} \in \arg\min_{\theta} U = U_l + \rho U_p$. The assumption is that the global *minima* for U corresponds to a good deformation of a pencil stroke. In order to efficiently optimize the complex energy function U, we resort to a stochastic optimization algorithm [François (1998)] and in order to speed up the convergence rate, we proceed as described in Algorithms 1. and 2.

3. Style Rendering Model

3.1 Stroke Rendering

• The first enhancement is to simulate a given texture for each pencil stroke (e.g., charcoal, graphite pencil, chalk, soft pastel, etc.). In our application, the texture of a stroke is generated from a precomputed texture image. This later texture is created from a real drawing sample with a specific

Sketch EstimationIInput image to be sketched of Size N_I U(.)Gibbs energy with stroke deformation parameters $\theta = (\tau_x, \tau_y, s, \psi, \xi)$
location, scale, orientation, gradient angle at s, non-linear deformations1. InitializationSet of potential location \leftarrow Canny detector on I
 $k \leftarrow 0$ 2. Pencil Stroke Localizationfor each $N_w \times N_w$ non-overlapping sliding window W over I do
for each potential location s with coordinate (τ_x, τ_y) within W do $\hat{\theta} \leftarrow$ E/S minimization François (1998) of $U(\theta)$ with: $\frac{N_I}{13} \leq s \leq \frac{N_I}{3}$,
 $\psi(\tau_x, \tau_y) - \frac{\pi}{4} \leq \psi \leq \psi(\tau_x, \tau_y) + \frac{\pi}{4}$,
 $-5 \leq \xi_{m,n} \leq 5$, $\forall m, n$. $\theta_k \leftarrow$ arg min $_{s \in W} U(\hat{\theta})$ and record stroke with parameter θ_k & energy $U(\theta_k)$
 $k \leftarrow k+1$

Algorithm 1: Sketch estimation of a pencil stroke with deformation parameters θ and MAP energy $U(\theta)$.

E/S Algorithm		
U(.)	A real-valued <i>l</i> -variable function,	
$\mathcal{N}(a)$	defined on <i>E</i> , to be minimized The neighborhood of an element $a \in E$ defined by	
D	{ $b \in E$: for some $1 \le j \le l$, $ b_j - a_j \le r(M_j - m_j)$, $b_i = a_i, i \ne j$ } (= l/r) The diameter of the exploration graph E (endowed with the system of neighborhoods $\int \mathcal{N}(a)$ = r)	
x	$x = (x_1, \dots, x_n)$, an element of E^n , called a population	
x	$\hat{x} \in E, \hat{x} = \arg\min_{x_i \in (x_1, \dots, x_n)} U(x_i),$ i.e., the minimal point in <i>x</i> with the lowest label	
р	The probability of exploration	
k	The iteration step	
E	A finite discrete subset of the Cartesian product $\prod_{j=1}^{l} [m_j, M_j]$ of <i>l</i> compact intervals	
n	The size of the population (greater than D)	
r	A real number $\in [0,1]$ called the radius of exploration (with r	
	greater than the ε -machine)	
1. Initial Random $k \leftarrow 2$	ization initialization of $x = (x_1,, x_n) \in E^n$	
2. Explor	ration/Selection	
while <i>a</i> s	topping criterion is not met do	
1.	Compute \hat{x} ; $\hat{x} \leftarrow \arg \min_{x_i \in x} U(x_i)$	
2.	Draw <i>m</i> according to the binomial law $b(n, p)$	
	• For $i \leq m$, replace x_i by $y_i \in \mathcal{N}(x_i) \setminus \{\hat{x}\}$	
	according to the uniform distribution (Exploration Step)	
	 For <i>i</i> > <i>m</i>, replace <i>x_i</i> by <i>x̂</i> (Selection Step) 	
3.	$k \leftarrow k+1$ and $p \leftarrow k^{-1/D}$	
L		

Algorithm 2: E/S optimization algorithm

depiction style and thanks to a non-parametric procedure of texture synthesis, such as the one proposed by [Efros and Leung (1999)] or its multiscale (and faster) version proposed by [Wei and Levoy (2000)]. Once a texture has been created for a specific depiction style, it can be archived and exploited for another sketch rendering use (see Fig. 3).



Figure 3: *Example of texture of pencil stroke created from a real drawing sample with a specific depiction style and thanks to a non-parametric texture synthesis technique.*

• The second enhancement we propose is to render each pencil stroke with variable width and pressure. In our model, the stroke thickness and pressure first depends on the considered depiction style and is also modeled as being linearly inversely proportional to the Gibbs energy U associated to its (more or less likely) localization (see Sect. 2.3); A less probable stroke (in the MAP sense) is drawn with a low thickness and pressure and inversely. An energy map visualizing the likeliness of each stroke for an example of sketch estimation is given in Fig. 4c. The pressure applied to the pencil stroke is herein simulated by a contrast reduction of the luminance Y (extracted from the YIQ color space) of the pre-computed texture image.

• In order to further improve the realism of the rendering effect, the local tone value (at site *s*) of the texture generated by each pencil stroke is also darkened (log-linearly) proportionally to the number of pencil stroke passing at a specific location. This requires a pre-computed accumulation map specifying the number of strokes accumulated at each site *s* of the sketch image (more precisely we compute locally the logarithm(NUMBER OF STROKES PASSING AT SITE *s*) +1). An example of such stroke accumulation map (thus without textural rendering for each stroke) is given in Fig. 4d.

• Finally, another way to improve the rendering result is to add random perturbation (or small "wiggles") to each control points of the stroke template in order to simulate a real hand-drawn appearance and to contribute to naturalness (allowing to make strokes more *lively*).

We use these rendering enhancements (see Sect. 5) and the whole rendering procedure of each detected pencil stroke is described more precisely in pseudo-code in Algorithm 3.



Figure 4: (a) Real Image. (b) Set of strokes given by the Stroke localization procedure. (c) Example of sketch drawing visualizing the likeliness of each pencil stroke (energy map displayed with the following convention; white: low probable, dark: highly probable localization of the stroke). (d) Example of Sketch drawing visualizing the number of pencil stroke passing at a specific location (accumulation map displayed with the following convention; white: low accumulation, dark: high accumulation of strokes).

3.2 Final Rendering

This unsupervised sketch procedure can be easily combined with an example-based Bayesian local rendering model [Mignotte (2002)], used to transfer the tonal adjustment (or the texture created by the smudging effect in regions where there is no detected contours and thus no pencil stroke placement) of a given artistic rendering depiction style. In this context, the proposed scheme allows to simulate automatic synthesis of various artistic illustration styles (see Section 5).

	Rendering Procedure of a Pencil Stroke
$egin{array}{c} T \ A \ U_{ m min} \ U_{ m max} \end{array}$	Texture image (pre-computed) (cf. Fig. 3) Accumulation map (cf. Fig. 4d) Minimal energy of the stroke set Maximal energy of the stroke set
$egin{array}{ll} w_{ m min} \ w_{ m max} \ au_U \ au_U \ au_A \end{array}$	Minimal width of a stroke Maximal width of a stroke Energy weighting parameter Accumulation weighting parameter
1. Initialization $T \leftarrow \text{YIQ conversion of } T$	
2. Pen •	cil Stroke Rendering $\theta \leftarrow$ Perturbation of θ width of the stoke; $w \leftarrow (U(\theta) - U_{\min}) \frac{(w_{\max} - w_{\min})}{(U_{\max} - U_{\min})} + w_{\min}$
• For each site <i>s</i> located under the brush stroke, the luminance <i>Y</i> of <i>T</i> at <i>s</i> ($\hat{Y}_T(s)$) is defined as;	
	$\hat{Y}_T(s) \leftarrow Y_T(s) \left[1 - \tau_A A(s) - \tau_U U(\theta) \right]$
Draw	antialised stroke with deformation parameter θ ,

width w and textural rendering generated under the strokes given by T (with the $\hat{Y}IQ$ color space)

Algorithm 3: Rendering procedure of a pencil stroke with deformation parameters θ and MAP energy $U(\theta)$.

4. Sketch Morphing Model

The parametric model of localization of each stroke adopted in the proposed unsupervised sketch rendering method is particularly well suited for transforming one sketch into another, allowing, in this way, to create a very broad range of artistic and animated NPR visual effects. To this end, our strategy consists in the following three steps;

• Firstly, a method is required to get the same number of stroke in the source and destination sketch. To this end, we simply duplicate homogeneously the stroke of the estimated sketch with the lowest number of pencil strokes.

• Secondly, a technique is required to get a look-up table indicating the correspondence of each stroke of the source sketch with a stroke belonging to the destination sketch. To this end, we simply search the closest stroke belonging to the destination sketch (a stroke which has not been previously selected) of each stroke of the source sketch. For this distance, we use a L_2 norm between the two centers of the two candidate strokes. The sum of these different L_2 distances give us a global energy of correspondence. We repeat this procedure for different starting strokes stemming from the source sketch and we retain the look-up table associated to the lowest global energy of correspondence.

In order to get a pleasant sketch morphing result, we have noticed that this step was crucial and better morphing results was found if we finally select, for each association of stroke, the minimal distance between the one given by a closeness distance, as explained above (step 1.) rescaled by a *coherence* factor β ($\beta > 0$) and a kind of *coherence* distance computed as follows (step 2.),

- First, we search, among the set of (not previously selected) strokes stemming from the destination sketch, the closest stroke of the previously selected stroke. Let *S*₁ be this stroke.
- We compute the L_2 norm between S_1 and the stroke stemming from the closeness distance d_{clos} and the source sketch. We obtain a *coherence* distance d_{cohe} .
- We choose S_1 if $d_{\text{cohe}} \leq \beta d_{\text{clos}}$ else we return the stroke of the destination sketch given by step 1.

This strategy is close to the one followed by [Hertzmann et al. (2001)] in the context of learning filters and [Ashikhmin (2001)] in the context of texture synthesis. In our application, the larger the value of β , the less the line are broken, during the morphing process, leading to a visually more pleasant metamorphosis from one sketch to another. This strategy allows to give a less chaotic metamorphosis process and to maintain similar parts between the initial and the target sketch.

• Finally, we linearly interpolate each stroke stemming from the source sketch with deformation parameters Θ and MAP energy $U(\theta)$ to its associated destination stroke with parameters (Θ' , $U'(\theta')$). This interpolation is discretely timed to give a series of intermediate sketch.

The whole strategy of Sketch Morphing is algorithmically summarized in Algorithm 4.

5. Experimental Results

The prototype template of a pencil stroke is a B-spline connected 12-points model. The gradient vector field probability map and its parameters are given by [Destrempes and Mignotte (2002a)]. For the Canny edge detector, the lower and upper thresholds are given by the estimation technique proposed in [citecs1]. This estimation relies on a single threshold determining the percentage of edges to be found. This last threshold and the size of the non-overlapping sliding window N_w determine the number of strokes of the sketch drawing ($N_w = 11 \times 11$ pixels in all the examples shown in this paper). The weighting factor ρ penalizing the prior term U_p with respect to the likelihood term U_l is set to 0.1. The Diameter of the exploration graph of the E/S algorithm are set equal to D = 32 and the size of the population is n = 20. These two control parameters are classically used and are independent of the energy function to be minimized [François (1998)].



Algorithm 4: Sketch morphing procedure.

We recall that, for each stroke, the restricted domain *E* on which is minimized the function is given in Section 2.3. We consider 1000 iterations of the *E/S* optimization procedure for each local optimization procedure. In total, the procedure takes 20 minutes for a sketch drawing on a 1.2 GHz PC workstation running Linux. For the rendering procedure of each stroke, the width of each pencil stroke is considered to be within the interval $[w_{\min} = 1, w_{\max} = 6]$. τ_U and τ_A is set to 0.1.

5.1 Sketching Model Results

Fig. 5 show a few available sketch styles easily obtained by varying parameters of the pencil stroke model. More precisely,

• Fig. 5b is the plausibility map of each stroke of the estimated sketch (energy map displayed with the following convention; white: low probable, dark: highly probable localization of the stroke).

• Fig. 5c is obtained by adding wiggling perturbations for each pencil stroke.

• Fig. 5d is obtained by dividing all the estimated global non-affine deformation parameters by a factor of four and by lightening the number of pencil strokes by a factor of 1.5. To this end, the pencil strokes are selected of the following manner; Until we obtain the desired number of strokes, we do 1. we select the most probable stroke (in the MAP sens) contained in a window with a given size sz. 2. if the number of stroke is higher (respectively lower) than the desired number, we increase (respectively decrease) the size sz of the window.)

• By amplifying all the estimated non-affine deformation parameters (by a factor of 2 and 3.5 in the presented example), we obtain Fig. 5e and Fig. 5f. (with a lightening factor of 1.5).

• By adding more or less random perturbations (according to a uniform distribution) to the affine deformation parameters, we obtain the sketch style shown in Figs. 5g and 5h.

• By adding random perturbation to the point of the initial template of each pencil stroke, we obtain the depiction style shown in Fig. 5i.

• By lightening the number of strokes with a factor of 1.5, and drawing each one with a thickness proportional to its length, we obtain the style shown in Fig. 5j.

• By using the previous style with a spread filter, we obtain Fig. 5k.

5.2 Style Rendering Model Results

By texturing each pencil stroke with an example-based rendering procedure, we obtain the sketches given in Figures 6,7 and 8.

By combining this sketch result with an example-based local rendering model, such as the one proposed in Mignotte (2002), we obtain the images shown in Figures 9, 10 11 and 12 with the following depiction style; black ink, graphite pencil, sanguine, charcoal style (red chalk), black and fat charcoal, etching, brown and dry charcoal, ink and water painting, etching and a style combining the white and black chalks.

5.3 Sketch Morphing Model Results

Figures 13-15 show several example of sketch morphing and NPR animation. The first row of images show how this morphing procedure can be used to gradually convert a sketch into another one or any contour into a portrait sketch.



Figure 5: From left to right and top to bottom; Real Image, Plausibility map of each pencil stroke, Different other sketch styles obtained by varying parameters of the pencil stroke model (see text for more explanation).



Figure 6: Sketch with a local rendering procedure for texturing each pencil stroke.



Figure 7: Sketch with a local rendering procedure for texturing each pencil stroke.



Figure 8: Sketch with a local rendering procedure for texturing each pencil stroke.



Figure 9: Sketch drawing combined with a local rendering procedure to transfer the textural tone value of a given depiction style.



Figure 10: *Sketch drawing combined with a local rendering procedure to transfer the textural tone value of a given depiction style.*



Figure 11: Examples of sketch drawing combined with the (example-based) local rendering model. From left to right, real drawing sample used to train the local rendering model with respectively (from top to bottom), the black and fat charcoal and the etching style, sketch drawing with the textural tone value generated by each local rendering model with the pre-mentioned style.

We can create slightly different sketch drawings by adding a random perturbation. These slightly different sketches and the stroke morphing procedure allow to create a kind of vibration allowing to make liver the sketch and interesting animated NPR effects (see the animation result).

6. Conclusion & Discussion

In this paper, we have extended the sketching model previously introduced in [Mignotte (2003)] in which the estimated sketch is viewed as a set of pencil strokes detected in the MAP sens, with a rendering procedure for each stroke using the recent techniques of non-parametric texture synthesis. In addition to create automatic and realistic hand-sketch drawing for illustrative purposes or artistic effects, this statistical sketch procedure can be used for several other interesting NPR applications. By tweaking adding more or less random or parametrically-controlled perturbations to each control points of the stroke template, a continuous gamut of sketch styles can be generated ranging from a tightly controlled technical drawing to a loose and gestural sketch. Combined with an example-based local rendering model, used to transfer the textural tone value of a given depiction style, this method can considerably enhance a non-parametric model of automatic synthesis of illustration style from examples.

This Bayesian sketch model is also suitable for an example-based deformation model from a sample of pencil strokes extracted from a real freehand sketch drawing. This can be done in a training step by using a Probabilistic Principal Component Analysis or a mixture of PPCA [Tipping and Bishop (1999)] allowing to learn the principal non-linear deformations (and the prior distribution associated to these deformations) of the stroke shapes preferentially used by the artist in a given



Figure 12: Examples of sketch drawing combined with the (example-based) local rendering model. From top to bottom and From left to right; Real drawing sample used to train the local rendering model with respectively the brown and dry charcoal style and the ink and water painting style, and Real photograph and sketch drawing with the textural tone value generated by each local rendering model with the pre-mentioned style.



Figure 13: *Example of sketch morphings* ($\beta = 0.7$).

freehand drawing. Nevertheless, reliable detection of individual strokes in a freehand drawing, necessary to constitute the learning set, is not an easy task and can only be done with supervision.

Finally, we have shown how this model is also suitable to create an some artistic animated effects and NPR animations.

References

- James Arvo and Kevin Novins. Smart text: A synthesis of recognition and morphing. In AAAI Smart Graphics Symposium, Stanford, CA, USA, March 2000.
- James Arvo and Kevin Novins. Fluid sketches: Continuous recognition and morphing of simple hand-drawn shapes. In Proceedings of the 13th Annual ACM Symposium on User Interface Software and Technlogy, pages 73–80, San Diego, California, USA, November 2000.
- M. Ashikhmin. Synthesizing natural textures. In *proceeding of ACM Symposium on Interactive 3D Graphics*, pages 217–226, Research Triangle Park, NorthCarolina, March 2001.



Figure 14: *Example of sketch morphings* ($\beta = 0.7$).



Figure 15: *Example of sketch morphings* ($\beta = 0.7$).

- H. Chen, Y. Q. Xu, H. Y. Shum, S. C. Zhu, and N. N. Zhen. Example-based facial sketch generation with non-parametric sampling. In *International Conference on Computer Vision*, (*ICCV'01*), pages 433–438, Vancouver, Canada, July 2001.
- C. Curtis. Non photorealistic rendering, section: "non-photorealistic animation". In *Proceedings of SIGGRAPH 1999, Course 17*, Los Angeles, CA, USA, August 1999.
- Doug DeCarlo and Anthony Santella. Stylization and abstraction of photographs. In *Proceedings* of SIGGRAPH 2002, pages 769–776, San Antonio, Texas, USA, July 2002.

Fractal design Painter. Fractal design corporation, 2003.

- F. Destrempes and M. Mignotte. Unsupervised detection and semi-automatic extraction of contours using a statistical model and dynamic programming. In *4th IASTED International Conference on Signal and Image Processing, ICSIP'02*, pages 66–71, August 2002a.
- F. Destrempes and M. Mignotte. Unsupervised localization of shapes using statistical models. In *4th IASTED International Conference on Signal and Image Processing, ICSIP'02*, pages 60–65, August 2002b.
- F. Durand, V. Ostromoukhov, M. Miller, F. Duranleau, and J. Dorsey. Decoupling strokes and high-level attributes for interactive traditional drawing. In *Proceedings of the 12th Eurographics Workshop on Rendering*, pages 71–82, August 2001.
- A. A. Efros and T. K. Leung. Texture synthesis by non-parametric sampling. In 7th International Conference on Computer Vision, ICCV'99, pages 1033–1038, Kerkyra, Grece, September 1999.
- O. François. An evolutionary strategy for global minimization and its Markov chain analysis. *IEEE Trans. on Evolutionary Computation*, 2(3):77–90, 1998.
- C. Guo, S-C. Zhu, and Y.N. Wu. A mathematical theory of primal sketch and sketchability. In *International Conference on Computer Vision 2003 (ICCV'03)*, Nice, France, October 2003.
- A.L. Guptill. Rendering in Pencil. The Pencil Points Press, Inc., New-York, 1977.
- A. Hertzmann, C. E. Jacobs, N. Olivier, B. Curless, and D. H. Salesin. Image analogies. In Proceedings of SIGGRAPH'2001, pages 327–340, California, USA, July 2001.
- A. Hertzmann, N. Oliver, B. Curless, and S. M. Seitz. Curve analogies. In *Eurographics Workshop* on Rendering, pages 233–245, Pisa, Italy, June 2002.
- A.K. Jain, Y. Zhong, and S. Lakshmanan. Object matching using deformable templates. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 18(3):267–278, 1996.
- Hee-Jeong Jin, Young-Jung Yu, and Hwan-Gue Cho. Creating pen-and-ink illustration using stroke morphing method. In *Computer Graphics International 2001 (CGI'01)*, pages 113–122, Hong Kong, China, July 2001.
- P.M. Jodoin, E. Epstein, M. Granger-Piché, and V. Ostromoukhov. Hatching by example: a statistical approach. In *Non-Photorealistic Animation and Rendering 2002*, (*NPAR'02*), Annecy, France, June 2002.
- Z. Kato, X. Ji, T. Szirányi, Z. Tóth, and L. Czúni. Content-based image retrieval using stochastic paintbrush transformation. In 9th IEEE International Conference on Image Processing, ICIP'02, Rochester, USA, September 2002.
- L. Markosian, M. A. Kowalski, S. J. Trychin, L.D. Bourdev, D. Goldstein, and J.F. Hughes. Realtime nonphotorealistic rendering. In *Proceedings of SIGGRAPH*'97, pages 415–420, September 1997.
- M. Mignotte. Bayesian rendering with non-parametric multiscale prior model. In 16th IEEE International Conference on Pattern Recognition, ICPR'02, volume 1, pages 247–250, Québec, Canada, August 2002.

- M. Mignotte. Unsupervised statistical sketching for non-photorealistic rendering models. In 10th IEEE International Conference on Image Processing, ICIP'03, September 2003.
- Ioannis Pavlidis, Rahul Singh, and Nikolaos P. Papanikolopoulos. On-line handwriting recognition using physics-based shape metamorphosis. *Pattern Recognition*, 31(11):1589–1600, 1998.
- Photoshop. Adobe systems. 2003, 2003.
- C. Reynolds. Stylized depiction in computer graphics, NPR (non photo-realistic rendering), painterly and toon rendering. http://www.red3d.com/cwr/npr/, 2003.
- M.P. Salisbury, S.E. Anderson, R. Barzel, and D.H. Salesin. Interactive pen-and-ink illustration. In *Proceedings of SIGGRAPH'94*, pages 101–108, July 1994.
- M.P. Salisbury, M.T. Wong, J.F. Hughes, and D.H. Salesin. Orientable textures for image-based pen-and-ink illustration. In *Proceedings of SIGGRAPH*'97, pages 401–406, August 1997.
- J. Salwey. The Art of Drawing in Lead Pencil. B.T. Batsford, Ltd., 1925.
- M Sousa and J. Buchanan. Computer-generated pencil drawing. In *Tenth Western Computer Graphics Symposium*, March 1999.
- T. Szirányi and Z. Tóth. Optimization of paintbrush rendering of images by dynamic mcmc methods. In *Lecture Notes on Computer Science*, volume 2134, pages 201–215, 2001.
- T. Szirányi and Z. Tóth. Random paintbrush transformation. In *15th ICPR'00*, volume 3, pages 155–158, 2000.
- M. E. Tipping and C. M. Bishop. Mixtures of probabilistic principal component analyzeers. *Neural Computation*, 11(2):443–482, 1999.
- L.-Y. Wei and M. Levoy. Fast texture synthesis using tree-structured vector quantization. In *Proceedings of SIGGRAPH'2000*, pages 479–488, California, USA, July 2000.
- Liu Wenyina, Wenjie Qian, and Rong Xiao. Smart sketchpadałan on-line graphics recognition system. In *International Conference on Document Analysis and Recognition (ICDAR'01)*, Seattle, WA, USA, September 2001.