Stroke Style Transfer

Sara Shaheen and Bernard Ghanem

King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia

Figure 1: *An overview of the proposed stroke style transfer technique. It deals with transforming the style of strokes in a query sketch to represent the style of strokes in a target sketch.*

Abstract

We propose a novel method to transfer sketch style at the stroke level from one free-hand line drawing to another, whereby these drawings can be from different artists. It aims to transfer the style of the input sketch at the stroke level to the style encountered in sketches by other artists. This is done by modifying all the parametric stroke segments in the input, so as to minimize a global stroke-level distance between the input and target styles. To do this, we exploit a recent work on stroke authorship recognition to define the stroke-level distance [SRG15], which is in turn minimized using conventional optimization tools. We showcase the quality of style transfer qualitatively by applying the proposed technique on several input-target combinations.

1. Introduction

The field of sketch style analysis and synthesis has attracted researchers for many years. This is due to its wide range of applications, such as cartoon making and professional art work production. In this paper, we propose an efficient technique for automatic sketch style transfer, which transforms one sketching style to another, regardless of the sketch content as depicted in Figure 1. This is accomplished by transforming the query sketch locally at the stroke level. It is built on insights uncovered by the discriminative SAR model, proposed in [SRG15]. In their authorship recognition work, the authors demonstrate that the subtleties of an artist's style can be recognized by analyzing the frequency of representative geometric stroke-level features. Inspired by their findings, we show in our work that it is feasible to transfer the sketching style of a line drawing to another by adopting a global representation of the sketch as a whole. Such representations are usually used for style recognition, as in [SRG15], so, to the best of our knowledge, this is the first time it is used for sketch style transformation.

In our style transfer, we first model stroke segments as rational (parametric) quadratic Bézier curves for both query and target line drawings. Based on the parametrization of the Bézier curves, the distribution of geometric features (e.g. stroke eccentricity) in the query sketch can be modeled and its SAR distance [SRG15] to the target sketch style can be minimized. In doing so, all strokes in the query are modified to closer resemble the target's stroke-level style.

Our technique is useful to apply subtle transformations on hand-drawn sketches. As demonstrated in our results, artists are enabled to use the stroke style transfer technique to get their sketches closer to a target style, which they are trying to mimic. This is essential when a new artist is assigned to draw a well-known cartoon character by following the same style as another artist. Artists no longer need to spend much time trying to copy every subtle detail of the original style. With our automated technique, they can focus on the global aspects of their sketches, while maintaining the local style features with good accuracy.

2. Related Work

In this section, we highlight previous work on sketch synthesis and style transfer. The techniques of [HLW93] is among the first stroke synthesis methods in the literature. Following this seminal work, several more approaches have been proposed. Freeman et al. [FTP03] apply artistic style transfer by matching the k-nearest artistic drawing styles in a database comprising hundreds of strokes annotated in all possible styles and rotations. A lot of work on style synthesis has focused on human portrait sketches. For example, the method of [BSM*13] used a Wacom tablet and a stylus pen to collect a database of face sketches, drawn by a number of artists using reference face photographs. Each stroke is parameterized as a directed curve along with pen parameters. These strokes are used to build a stroke library that represents the sketching style of an artist and is then used to synthesize a portrait sketch in different artistic styles. In comparison to this method, our focus is to transfer styles regardless of the sketch content. Moreover, we transfer sketches drawn by any medium, either digitally or via scanned versions of paper sketches. Moreover, the PortraitSketch system [XHLW14] al-

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lows auto-correction of strokes for face sketches by novice artists. It automatically adjusts the geometry and stroke parameters. Unlike our work, their corrections are based on features taken from the underlying source image, which the novice artist draws on top of it. HelpingHand [LYFD12] is a system for stroke synthesis based on filtered velocities and shape context from a library of 6D stylus trajectories.

The work of Hertzman et al. [HOCS02] is among the early methods of example-based sketch synthesis. They learn a statistical model of curves to synthesize new curves through a computationally intensive process. Moreover, in an attempt to investigate and define sketching styles, the work of Li et al. [LZW*13] transfers curve styles from examples of 2D curve shapes. Interestingly, it discriminates between style-revealing and content-revealing curves features. Their content-style separation analysis is based on a proposed feature-shape association matrix (FSM). Others used graph techniques for efficient stroke synthesis as in [KS10]. Moreoever, Lang et al. [LA15] proposes an autoregressive Markov model based on sampling over a series of learned feature distributions of curvature values. They explicitly have to handle non-pleasant scenarios, such as, overshoots and broken lines. More recently, ShipShape [FASS16] is developed as a general sketch beautification assistant based on preserving geometric relations between strokes. Their method is based on evaluating different geometric rules on a new sketched path using the previously drawn and resolved paths. Our technique applies sketch transfer considering features extracted from all strokes of the sketch and not each stroke independently, without the need for tracking paths during sketching. Clearly, each sketch synthesis and transfer approach starts by a unique definition of style and builds on this definition to perform transfer/synthesis. Our proposed work can be viewed as an addition to this literature.

3. Stroke-Style Transfer

In this section, we give a detailed description of our proposed technique. Our method is inspired by the work of [SRG15], which shows that the frequency in which an artist uses a set of basic strokes is unique to that artist and can be used for stroke authorship recognition (SAR). The authors developed a SAR distance (or loss) to measure the difference in style between two line drawings and then use this distance in sketch style transfer. Given the query line drawing $\mathbf{I}_q$ and a target stroke-style line drawing $\mathbf{I}_s$, we aim to transform the stroke segments of $\mathbf{I}_q$ such that the SAR distance between the transformed sketch $\mathbf{I}_{final}$ and that of $\mathbf{I}_s$ is minimized, as demonstrated in Figure 2.

3.1. Stroke-Based Sketch Representation

To formulate the SAR distance, drawings $\mathbf{I}_q$ and $\mathbf{I}_s$ are decomposed into strokes, which are further split into smaller segments, small enough to be modeled by conic sections. Each stroke segment is parameterized as a quadratic rational Bézier curve. Strokes are grouped together based on their eccentricity values (i.e. the deviation of a conic from a circle) to form a dictionary of stroke segments. Based on that, each sketch is represented as a histogram of stroke segments using a hierarchical bag-of-words (BoW) model [SZ03], which encodes some aspects of the artist's unique style. Further elaboration is provided in what follows.

Stroke Extraction and Segmentation. For this stage, sketches are first vectorized using Adobe Live Trace. It is an of-the-shelf digitization technique, which generates sketches that stay faithful to the original sketch [ADO10]. Following that, strokes are extracted from the vectorized sketches. However, extracted strokes are quite long and detailed so they need to be further split into smaller segments. To overcome this, we fit a b-spline curve to each stroke and locate break points at local maximum curvature locations in the b-spline. To avoid over-segmentation, linear strokes are handled by placing break points at its two ends. Each stroke segment is identified by the pixels between two consecutive break points.

Mathematical Characterization. After $\mathbf{I}_q$ and $\mathbf{I}_s$ are decomposed into stroke segments, each segment is parameterized using a quadratic rational Bézier curve model, as in Eq (1).

$$f(t) = \frac{\sum_{i=0}^{2} w_i \mathbf{p}_i B_i^2(t)}{\sum_{i=0}^{2} w_i B_i^2(t)}, \quad t \in [0,1], \tag{1}$$

where $\mathbf{p}_i$ is the i^{th} control point of the 2D curve, w_i is the corresponding weight, and $B_i^2(t)$ is the quadratic Bernstein polynomial (i.e. $(1-t)^2$, $2t(1-t)$, t^2). Following the standard form in [Wei91], we set $w_0 = 1, w_1 = w > 0$ and $w_2 = 1$. Bézier curves have been widely used in computer graphics to model smooth curves [Wei91, Far92]. By manipulating the control points of a Bézier curve, it can be intuitively deformed. Quadratic Bézier curves are enough to model conic sections and only three control points $\{\mathbf{p}_i\}_{i=0}^2$ are needed.

A fundamental parameter of a conic section is its eccentricity. Thus, eccentricity can be used not only to distinguish between different types of conics (as done in [SRG15]), but also to provide information of their overall shape. This feature is also invariant to rigid body deformations. In [SRG15], eccentricity is mainly used as a local feature to mathematically characterize stroke segments for sketch authorship discrimination. All of these stated motives among others listed in [SRG15] encourage us to choose eccentricity as the local feature to describe a stroke segment. The eccentricity e of a rational quadratic Bézier curve is computed as in Eq (2).

$$e(\mathbf{p}_0, \mathbf{p}_1, \mathbf{p}_2)^2 = \frac{2\sqrt{\triangle}}{\sqrt{\triangle} - b}, \tag{2}$$

where $\triangle = \left[k\|\mathbf{s}-\mathbf{t}\|^2 - 2(\|\mathbf{s}\|^2 + \|\mathbf{t}\|^2)\right]^2 + 4(k-1)(\|\mathbf{s}\|^2 - \|\mathbf{t}\|^2)^2$.

To provide some control over the representation as in [XKF10], we set $k = \frac{1}{w^2}$, $\mathbf{s} = \mathbf{p}_0 - \mathbf{p}_1$, $\mathbf{t} = \mathbf{p}_2 - \mathbf{p}_1$ and $b = -k\|\mathbf{s}-\mathbf{t}\|^2 - 4(\mathbf{s} \cdot \mathbf{t})$. For derivation, proof and further discussion on eccentricity of rational Bézier curves refer to [XKF10].

Eccentricity Distribution. Given each stroke segment s_i characterized by an eccentricity value e_i, where $i \in \{1, ..., M\}$ and M is the number of stroke segments in $\mathbf{I}_q$, we now represent this sketch as a distribution of eccentricity values. Following the framework in [SRG15], we build a stroke segment dictionary of K elements using hierarchical k-means clustering on the stroke segments of the free style dataset. We choose $K = 20$ for our experiments. Using the K elements of this dictionary as high dimensional quantized bins and following the traditional BoW technique, we can represent a

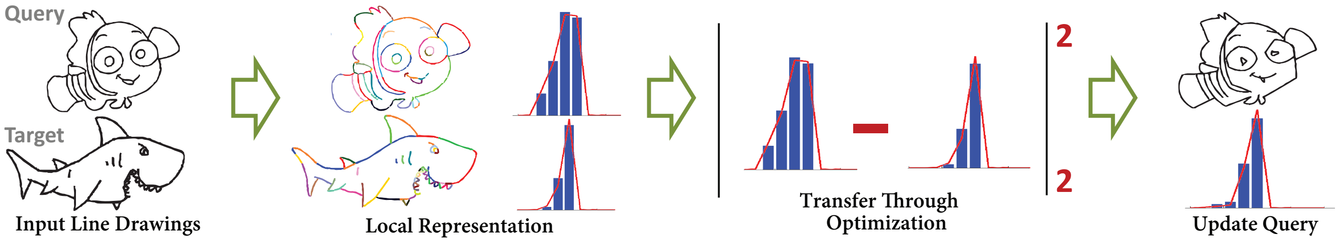

Figure 2: *The work flow towards stroke style transfer: (1) given a query and a target line drawings ;(2) apply techniques for stroke extraction and segmentation and characterize each stroke segment mathematically upon which each sketch is represented as a distribution of feature frequency; (3) solve an optimization to approximate the query distribution to the target's; (4) update the query sketch accordingly.*

sketch as a histogram of these stroke segments using their eccentricity information. In other words, a sketch (either query $\mathbf{I}_q$ or target $\mathbf{I}_s$) can be represented using a K dimensional histogram, which quantifies the frequency in which each stroke segment is used.

To modify the strokes in $\mathbf{I}_q$, we need to parameterize its BoW histogram, so as to generate a smooth functional form that can be varied to minimize a particular objective. We use kernel density estimation (KDE) for this purpose. We estimate the probability of each bin ($\mathbf{b}_k\ \forall k \in 1,\cdots,K$), in the histogram using Gaussian kernel density estimation as shown below:

$$f(\mathbf{b}_k) = \frac{1}{M\sqrt{2\pi}h}\sum_{i=1}^{M}\exp\left(\frac{-\left[e_i(\mathbf{p}_0^i,\mathbf{p}_1^i,\mathbf{p}_2^i)-\mathbf{b}_k\right]^2}{2h^2}\right),$$

where h is the bandwidth value ($h = 0.1$ for our experiments), e_i is the eccentricity in Eq (2) of the i^{th} stroke segment. By concatenating the probabilities of all K bins, we obtain the desired sketch representation histogram $\mathbf{h}_q$ for $\mathbf{I}_q$. Note that this histogram is parameterized by the control points of all M stroke segments $\{\mathbf{p}_0^i,\mathbf{p}_1^i,\mathbf{p}_2^i\}_{i=1}^M$.

$$\mathbf{h}_q(\{\mathbf{p}_0^i,\mathbf{p}_1^i,\mathbf{p}_2^i\}_{i=1}^M) = [f(\mathbf{b}_1)\ \cdots\ f(\mathbf{b}_k)]^\top \qquad (3)$$

3.2. Transferring Stroke-Style from $\mathbf{I}_s$ to $\mathbf{I}_q$

In this section, we show that stroke-style transfer is realized by solving a properly formulated optimization problem. It is based on the assumption that sketches drawn by the same artist have more similar representative feature distributions (KDEs) than sketches drawn by different artists, while remaining independent of sketch content. This assumption is validated in [SRG15]. We aim to transfer the style of $\mathbf{I}_s$ (represented by $\mathbf{h}_s$) to that of $\mathbf{I}_q$ (represented by $\mathbf{h}_q$). This can be done by minimizing the objective in Eq (4).

$$\{\triangle\mathbf{x}_i^*\}_i^M = \underset{\{\triangle\mathbf{x}_i\}_i^M}{\operatorname{argmin}} \left\|\mathbf{h}_q\left(\{\triangle\mathbf{x}_i\}_i^M\right)-\mathbf{h}_s\right\|_2^2 + \lambda\sum_{i=1}^{M}\|\triangle\mathbf{x_i}\|_2^2, \quad (4)$$

where $\mathbf{h}_q$ is the KDE of eccentricities $(e_i,...e_M)$ from sketch $\mathbf{I}_q$, and $\mathbf{h}_s$ is the same KDE for sketch $\mathbf{I}_s$. The set of optimization variables in this optimization is $\{\triangle\mathbf{x}_i\}_i^M$, where $\triangle\mathbf{x}_i = [\triangle\mathbf{x}_i{}^0;\ \triangle\mathbf{x}_i{}^1;\ \triangle\mathbf{x}_i{}^2] \in \mathbf{R}^6$ is the concatenation of the three offset vectors for the 2D control points $\mathbf{p}_0^i$, $\mathbf{p}_1^i$ and $\mathbf{p}_2^i$ of the i^{th} segment s_i of $\mathbf{I}_q$. In other words, $\mathbf{I}_q$ will be transformed into $\mathbf{I}_{final}$ by transforming each segment s_i in $\mathbf{I}_q$ into another segment $\hat{s}_i$ with the following three control points: $\hat{\mathbf{p}}_j^i = \mathbf{p}_j^i + \triangle\mathbf{x}_i{}^{*j}$ for $j \in \{0,1,2\}$.

As in many inverse problems, we breakdown the cost function into two complementary parts: a data term and a regularizer. The data term $\left\|\mathbf{h}_q\left(\{\triangle\mathbf{x}_i\}_i^M\right)-\mathbf{h}_s\right\|_2^2$ encourages that the SAR distance between the query and target eccentricity histograms be minimum, i.e. the query style gets closer to the target style. The regularizer term $\sum_{i=1}^M \|\triangle\mathbf{x_i}\|_2^2$ penalizes a degenerate transfer that simply copies the target. In our work, we set the tradeoff coefficient $\lambda = 0.5$, as upon experiment is found to balance between transferring the style and preserving the content of the sketch.

Implementation Details. Each stroke segment curve passes through $\mathbf{p}_0$ and $\mathbf{p}_2$, the initial and last points of the Bézier curve. To preserve connectivity in our transferred sketch, we enforce $\triangle\mathbf{x}_i{}^0 = \triangle\mathbf{x}_{i-1}^2$ (or equivalently, $\hat{\mathbf{p}}_0^i = \hat{\mathbf{p}}_2^{i-1}$) in the optimization, whenever the $(i-1)^{\text{th}}$ and i^{th} curves are connected in $\mathbf{I}_q$. In addition to connectivity, we should maintain similar coherence between consecutive and connected stroke segments in the transformed sketch as in the query sketch (refer to Figure 3 for an example). In other words, tangent values between connected curves should be preserved in $\mathbf{I}_{inter}$. Since we are only interested in finding the tangent at the beginning and end of the curve segment (at $t \in \{0,1\}$), we produce an analytical form of the tangent at both ends of each curve segment and force tangent values at the end of one segment and the beginning of the connected segment to be equal. We add this equality to the objective function of our optimization.

After obtaining the $\{\triangle\mathbf{x}_i^*\}_i^M$ solution from the optimization, we generate the control points of $\mathbf{I}_{final}$ and use these control points to sample the underlying Bézier curves using the de Casteljau algorithm [DC85] to render the transferred sketch.

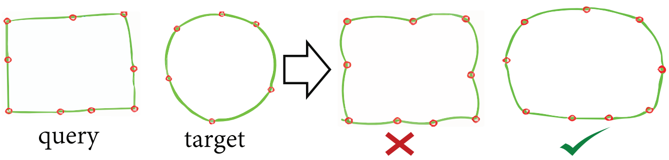

Figure 3: *A comparison of transfer results when a rectangle sketch is used as the query and a circle as the target. The synthesis result on the left uses our optimization without maintaining local coherence in tangent, which leads to poor non-smooth (cloudy like) transfer. The transfer on the right, however, enforces this coherence leading to a more visually appealing result.*

4. Results

In this section, we provide an assessment of the visual results obtained using our stroke style transfer approach. We test our algorithm on different sketches from the vectorized free-style sketch data set of [SRG15]. As shown in Figure 4, transferring a sketch of a shark drawn by an artist using a gold fish sketch drawn by another artist leads to the replacement of those edgy strokes of the shark sketch with rounder ones of the golden fish. It is also obvious that the content is still preserved and that the transferred sketch still represents a shark but a fatter one. Moreover, comparing the histograms of the eccentricity feature of the query, target, and transfer result shows that the transferred sketch distribution is closer to the target sketch than it is to the query, which has the same content. This validates our choice of minimizing the SAR distance in our stroke-style transfer optimization in Eq (4). Another example is demonstrated in Figure 5, where we transfer the stroke style of one sketch into multiple styles using different target sketches. We choose our targets to represent the same content (a star), but with varying stroke characteristics (frequencies of eccentricity). Interestingly, the transfer results reflect the influence of the target sketch; the sharper the target is, the sharper the transferred results are and vice versa. This is quantitatively evident when we visualize the eccentricity histograms of the transferred sketches. This clearly shows how our transfer technique enables artists to create endless variations of their sketches based on the target style they choose along with preserving their sketch content.

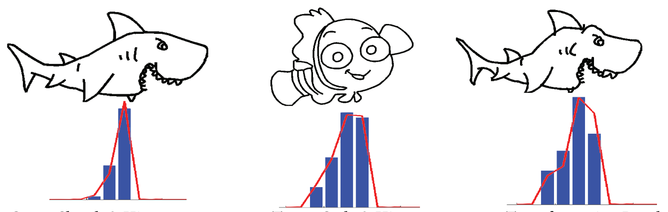

Figure 4: *An example of stroke style transfer. The transferred shark sketch is rounder and less edgy in comparison to the prior transfer sketch (query). Moreover, the feature frequency distribution of the transferred sketch is closer to the distribution of the target golden fish sketch than it is to the query.*

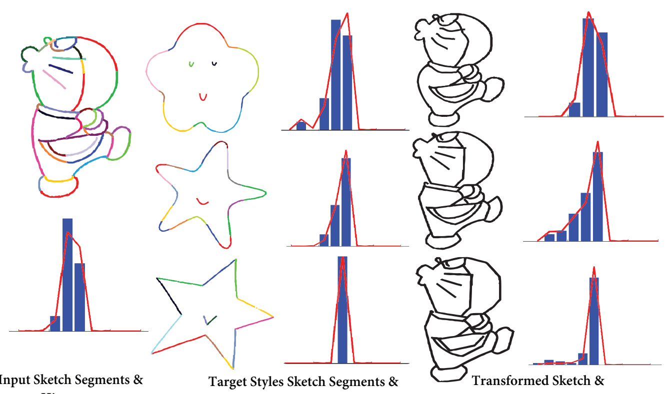

Figure 5: *An example of stroke-style transfer of a line drawing using various target sketches. Different transferring results are obtained reflecting the roundness and sharpness properties of target.*

5. Conclusion

This paper, targets the transfer of sketching at the stroke level through modifying the parameters of stroke segments of a sketch. To do so, a global sketch distance between both query and target sketches is minimized. Our sketch style transfer technique can be used to transfer a sketching style independent of the sketched content and for sketches drawn either digitally or by hand.

Limitations Our proposed method is just the start towards achieving a comprehensive sketch style transfer. It only modifies existing strokes with no elimination or addition of strokes. Although this helps in applying changes where the difference between styles is minor, there is a great potential of improvement in progressive research work which enables major transformations.

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