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Brush stroke ordering techniques for painterly rendering

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Abstract

Painterly rendering algorithms often mimic classical hand-painting techniques to automatically generate stylized paintings from input images. These algorithms use a combination of techniques to express a variety of styles and artistic properties (e.g., contrast, mood), but often restrict the user from controlling the rendering order of overlapping brush strokes. This paper illustrates the importance of brush stroke ordering in creating stylistic effects and presents a layer-based painterly rendering algorithm that allows the user to specify a brush stroke ordering. Several of the presented orderings enable the renderer to reduce detail obstruction, simulate hand-painting techniques and enhance artistic styles.

Categories and Subject Descriptors (according to ACM CCS): I.3.4 [Computer Graphics]: Graphics Utilities—Paint systems

1. Introduction

Painterly rendering algorithms often transform images into stylized paintings by simulating the brush stroke techniques used by human artists to paint the canvas. Artists use these techniques to express desirable properties and convey the style of the painting. In *Olive Trees with the Alpilles in the Background* (1889), van Gogh used the technique of long, curved and coherent brush strokes to endow a sense of motion or flow, a property common to many styles. Similarly, the short horizontal strokes in *Starry Night Over the Rhone* (1888) enabled van Gogh to express the stillness of the lake and night sky.

The artist must order their brush strokes carefully to imbue the painting with these stylized properties. Many painterly rendering algorithms create curved brush strokes of various lengths but restrict the user from controlling the stroke order. For example, Hertzmann's algorithm combines curved brush strokes with several other techniques to generate artwork with impressionistic, expressionistic and pointillistic styling [Her98]. The algorithm generates the long and flowing strokes commonly found in expressionist works; however, the shorter strokes often overlap the longer ones, breaking them into fragments and cancelling their expressions of flow and motion.

This paper presents a stroke-based renderer based on Hertzmann's algorithm that supports customizable brush stroke ordering. Several of the discussed ordering techniques reduce occlusion around salient details and edges, improving the quality of artistic depictions. Also, these brush stroke orderings mimic classical hand-painting techniques, so they enhance control over stylistic properties including tone and mood.

2. Previous work

Stroke-based painterly rendering algorithms construct paintings by generating and accumulating individual brush strokes on the canvas image. Compared to global approaches that rely on filters and transforms, stroke-based algorithms usually simulate the physical techniques used by human artists to give the artwork a hand-painted appearance. This reliance on brush techniques also enhances the artist's control over the properties and style expressed by the painting.

The earliest of these algorithms use relatively simple brush strokes comprised of dots, lines and primitives with a single anchor point. Haeberli's algorithm uses the mouse as a metaphorical paintbrush to control the configuration of strokes [Hae90]. By automating the minutiae of creating individual strokes, the algorithm enables the artist to focus on higher level techniques such as stroke ordering and layering. However, this yields a one-to-many relationship be-

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tween mouse and brush strokes. This relative lack of control over the number and colour of strokes hinders the expression of colour-related properties such as tone and mood. The stroke ordering techniques in Sections 4.1 and 4.2 regain some of this lost control over colour.

The non-interactive algorithm by Litwinowicz places brush strokes on a grid using the image gradient to control stroke direction [Lit97]. While this automated, grid-based approach lends itself to temporally coherent video processing, it lacks the control afforded by a mouse-paintbrush metaphor. The algorithm balances utility with tradition: it places the strokes by grid and gradient, which does not reflect classical painting technique, but it preserves image details by clipping the brush strokes along salient edges. All of the ordering techniques in this paper assist in protecting these salient edges.

The rendition of salient edges plays such an important role in classical painting technique that two other stroke algorithms make it a fundamental part of their design. The algorithm of Hays and Essa uses a layering technique, refining the painting by placing fresh-layer strokes to reduce error in more detailed regions [HE04]. Collomosse's approach represents strokes as cones whose heights vary with the salience of the underlying image pixels [CH02]. When projected orthographically, these cones map shorter, salient strokes into the foreground. Both of these approaches preserve image salience but rely on short simple strokes to do so, limiting the expression of certain properties and artistic styles. Section 4.3 prescribes a brush stroke ordering capable of favouring longer foreground strokes.

In contrast to these simple stroke algorithms, approaches that render curved brush strokes tend to exhibit stylistic flexibility since they mimic a greater set of classical painting techniques. Gooch's algorithm partitions the image into similarly-coloured segments and then generates a cubic spline-based stroke along the center ridge of each segment [GCS02]. Park and Yoon take a similar approach, segmenting the input image, but then rendering a set of curved strokes in each segment [PY08]. Hertzmann builds up an output painting by generating layers of curved brush strokes, placing strokes along paths of maximum error between image and painting [Her98]. In a later paper, he repositions these strokes by adjusting control points to minimize an energy function encompassing salience, importance, and canvas coverage [Her01].

These curved stroke algorithms use intuitive techniques for creating and placing strokes, but they provide little control over strokes that overlap. For example, Hertzmann's algorithm randomizes the rendering order within each layer to avoid undesired regularity that may appear mechanical or repetitive [Her98]. These uncontrolled stroke orderings can obsure scene information by occluding salient edges with overlapping brush strokes (Figure 1). Also, overlapping brush strokes can divide a longer stroke into disjoint segments, resulting in a messy appearance. Similarly, image gradients may appear more textured than desired.

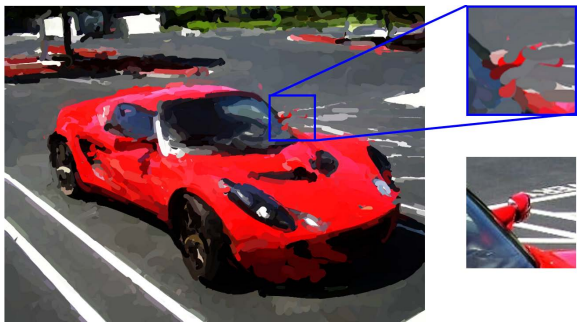

Figure 1: *Detail obstruction. Random stroke rendering order (left), close-up of obstructed mirror (top right), original image of mirror (bottom right).*

The algorithm parameters provide several mechanisms to reduce this brush stroke overlap. For Hertzmann's algorithm, decreasing the tolerance parameter and brush diameters reduces the obstruction frequency and magnitude, but also sacrifices the hand-painted quality of the output image (i.e., the results resemble the original image more than a painting). This corresponds to the artist choosing smaller brushes or painting fewer, shorter strokes, ultimately limiting their choice and control.

Standard artistic practice avoids these tradeoffs, preserves salient details and expresses stylistic properties by painting brush strokes in a specific order that usually sorts the strokes by luminance, colour, length or position [Mug69, Ric70]. In this paper we explore deterministic stroke orderings and their effect on aesthetics in painterly rendering. Section 3 augments Hertzmann's layer-based algorithm to support user-controlled brush stroke orderings, while Section 4 discusses how several of these orderings impact artistic control and painting style.

3. Ordered stroke algorithms

Hertzmann's original painterly rendering algorithm builds up a painting through layers of increasingly salient brush strokes [Her98]. Each layer increases the painting's level of detail by using smaller brush diameters and block sizes than the previous layer. The algorithm only paints strokes in blocks requiring more detail, more specifically, when the block's average colour difference exceeds a tolerance parameter. This approach implicitly and fundamentally orders brush strokes by grouping strokes of similar salience into layers.

The algorithm in Listing 1 generalizes Hertzmann's algorithm by generating layers of curved brush strokes and sorting each layer with a user-specified ordering at Line 4. Since this approach borrows the layering technique from

Hertzmann's algorithm, it implicitly orders the strokes into salience layers as well.

It may be possible to specify the stroke ordering in other painterly rendering algorithms, but the algorithms must buffer their brush strokes before rendering them and only reorder strokes of similar salience. Without this provision, ordering functions may blindly counteract other salience-preserving mechanisms. For example, Collomosse's algorithm explicitly calculates the salience of each brush stroke. Reordering the strokes (by changing their cone heights) without considering salience may succeed in expressing some property or style, but render smaller salient strokes underneath larger base layer strokes. This situation can be prevented by only reordering strokes of similar salience and then correcting the heights of neighbouring strokes to preserve their relative saliency.

Listing 1: *Layer based painterly rendering algorithm with brush stroke ordering*

```
1.  for each decreasing brush diameter
2.      prepare image
3.      generate the stroke set
4.      sort the stroke set
5.      paint the stroke set to canvas
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4. Brush stroke ordering techniques

The artist must balance many issues before painting brush strokes to canvas. Resource constraints, external requirements, personal motivation and experience, subject matter and paint medium (e.g., oils, acrylics) often factor into the chosen approach. After finding this balance, the artist selects a set of painting techniques to express the desired properties, styles and influences. These techniques usually specify or imply a brush stroke ordering.

Consider the example of an artist painting with oils. Traditionally, these artists use a canvas surface that must be stretched flat and coated with a gypsum-based medium [Mug69, Ric70, May70]. This white coating can be tinted or re-coated with a base layer to create a consistent background only visible between brush strokes. For example, black and ultramarine blue backgrounds tend to support night scenes better than white backgrounds. Oil paints, made of powdered pigment, linseed oil and turpentine, often have colour-specific drying times, so placing fast-dry colours over slow-dry colours can cause cracking. Even before considering style, the artist may select an ordering or layering that addresses these details.

Any combination or weighting of artistic techniques discussed in this section can be used to implement a brush stroke ordering function. Compared to a random stroke-ordering, the implemented orderings enhance the artistic style and reduce the detail obstruction of the resulting paintings. Except where otherwise noted, the stock images were painted with the recommended Hertzmann algorithm parameters (brush diameters = $(40, 20, 10)$ pixels, stroke lengths $\in [20, 50]$ pixels, tolerance = 0.226, grid size = 1 pixel, blur = 1) [Her98].

4.1. Tone and luminance

Artists often create tone, the range of luminance or apparent brightness of a painting, by ordering brush strokes according to their luminance, painting from dark-to-light or vice versa [Mug69, Ric70]. Tonal structure often contrasts light and shadow, as in Botticelli's *Venus and Mars* (1493) which balances equal parts darkness and brightness. Rembrandt's *Der Mann mit dem Goldhelm* (1650) favours darker tones to produce a dramatic scene while Monet's *Seerosen* (1920) draws out lighter tones to yield a softer image.

Our implementation modifies step 4 of Listing 1. The ordering function maps the stroke colour to a luminance in the interval $[0, 1]$ (as in [Her98]) and then renders each layer's strokes in luminance order: decreasing for dark-to-light, increasing for light-to-dark.

The luminance-based ordering (Figure 2) renders more well-defined edges and smoother gradients compared to a random stroke ordering. In particular, note the sharply rendered edges in the support columns of the luminance-ordered paintings. Also, note the gradient uniformity as the support column fades into the shadowy background. The luminance-based ordering sorts the brush strokes into bands of similar luminance, naturally preserving high contrast edges and smooth gradients. As well, this bias reduces stroke occlusion and segmentation between strokes of vastly different luminance by rendering similarly illuminated strokes to the foreground.

Figure 2 also demonstrates enriched tonal structure: the dark-over-light ordering darkens the image, while the light-over-dark ordering brightens it. The luminance banding introduced by the dark-over-light ordering tends to hide lighter strokes, deepening the shadow and causing it to creep outward. The reverse is true for light-over-dark ordering: the banding hides darker strokes, chasing back the lightened shadows.

The light-over-dark ordering sometimes creates a milky or watery appearance reminiscent of watercolour paintings (Figure 3). The gradient-banding of luminance ordering reduces the textured stroke appearance and hides finer details. While this enhances some styles, it may be undesirable for others. Modifying the colour jitter, brush diameter and tolerance may help recover some lost texture and detail.

4.2. Colour and mood

The colours in Picasso's pre-cubist works exhibit a breadth of moods and atmospheres [O'B94]. Dull blues and greens

Figure 2: *Luminance stroke ordering. Original image (top left), random (top right), light-over-dark (bottom left), dark-over-light (bottom right). Parameters: stroke lengths* $\in [20, 50]$ *pixels.*

with a somber appearance characterize his "blue period" works. The "rose period" works, represented by oranges, reds and pinks, appear vibrant and cheerful.

Mood can be expressed by adjusting the brush stroke colours (e.g., increasing the redness) [SBC06], but a more subtle approach pulls out naturally occuring colours in the scene or painting. The implemented ordering function measures the colour difference between the stroke and a parameter colour (i.e., by summing the RGB component differences in quadrature) and then renders the least different strokes last, in the foreground.

Colour-based stroke ordered paintings share many traits with their luminance-ordered counterparts. Both orderings tend to preserve edges and produce smoother gradients, and both may lose detail and texture in finely detailed images. These similarities arise because their ordering functions tend to sort strokes into bands of similar colour.

In Figure 4, the colour-based stroke ordering draws out powerful moods in the paintings by rendering certain coloured strokes in the foreground. Note that the original image contains little red. The ordering creates a warmer painting by placing the reddest brush strokes in the foreground, resulting in a painting that contains more red than the original image. However, when the ordering places the reddest strokes in the background, the red disappears from the painting altogether, emphasizing a cold, dark mood with blues and greens.

4.3. Stroke length

Artists use lines to define detail by depicting edges and creating tone (e.g., by hatching lines to create shadow) [Mug69]. The brush diameter and stroke length determine the appearance of these lines, contributing to the style of the painting. Expressionist works tend to use longer strokes (compared to many other styles), creating flowing lines and exaggerated curves such as those in Munch's *The Scream* (1893)

Figure 3: *Luminance ordered strokes. Original image (left), light-over-dark (center), dark-over-light (right). Parameters: stroke lengths* $\in [20, 50]$ *pixels.*

[Her98, Mug69, Ric70]. Other painting styles such as pointillism and impressionism use shorter strokes, yielding a dappled appearance similar to Seurat's *Sunday Afternoon on the Island of La Grande Jatte* (1884).

Ordering brush strokes by length (long-over-short) pulls line-related details to the foreground, enhancing the style while also reducing stroke obstruction and segmentation. These styles can be simulated just by changing Hertzmann's algorithm parameters (e.g., maximum and minimum stroke length), but using length-based stroke ordering provides greater control over the quality of these longer strokes.

The two stroke length orderings focus on different goals, so they produce dramatically different results. In Figure 5, the long-over-short ordering preserves the soft ripples on the water using long, uninterrupted strokes. These horizontal strokes emphasize the stillness of the water, stressing an expressionistic style. While the short-over-long ordering produces a choppier water appearance, it depicts a smoother sky gradient with impressionistic undertones. These effects can be moderated by adjusting the tolerance and stroke length bounds.

4.4. Location

To emphasize certain scene details, the artist may place them in the foreground by painting towards the center of the canvas or some focal point. One ordering function that simulates this spatial layout technique sorts brush strokes by their average absolute distance from the selected focal point.

The near-over-far location-based ordering preserves details nearest the focal point while producing smooth gradients. This mechanism can be used to ensure spatially-oriented details render in the foreground, avoiding occlusion and segmentation. While these focal details render more accurately, the region near the focal point tends to grow into the surrounding scene. This side effect can be controlled by choosing a non-linear distance function (e.g., assign random distances to strokes outside a radius parameter). Figure 6 demonstrates the details preserved by placing a focal point near the peacock head.

4.5. Comparisons

Figure 7 compares all of the stroke ordering techniques presented in this paper using a common source image. These paintings were generated from a single layer of strokes with the same brush diameter, so each painting sorts and renders the same set of strokes. As a result, the stroke orderings alone induce the stylistic properties portrayed by these paintings.

5. Conclusions

This paper describes an abstraction of a stroke-based painterly rendering algorithm that enhances artistic stylization by enabling the user to specify a brush stroke ordering. Several of these ordering techniques augment other painting techniques while addressing the quality issues commonly attributed to random stroke ordering.

In particular, the brush stroke ordering techniques in Section 4 improve aspects of certain artistic styles while also reducing detail obstruction. The luminance and colour based orderings stand out in these respects, especially since they reflect traditional hand-painting techniques common to many artistic styles.

The long-over-short length-based ordering technique pre-

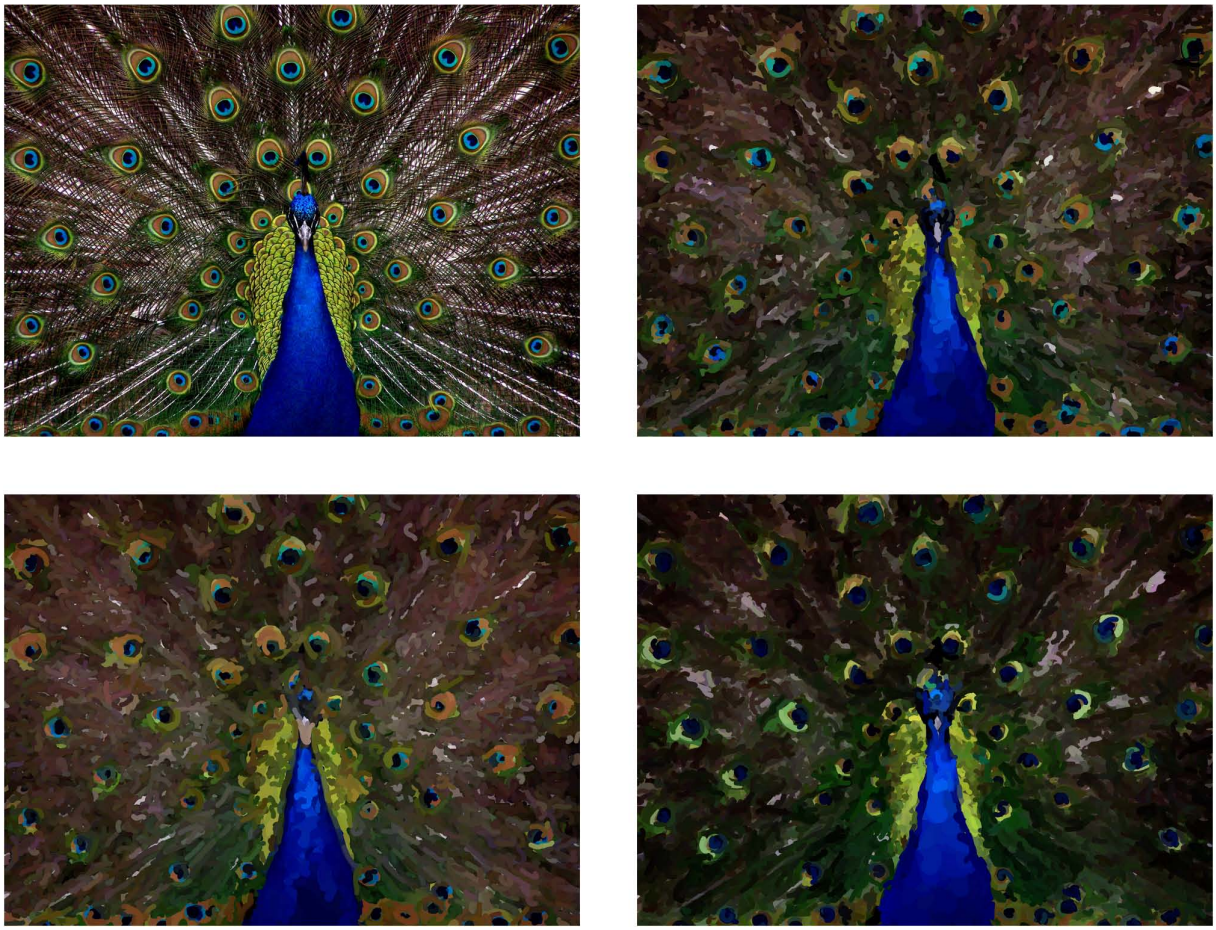

Figure 4: *Colour ordered strokes. Original image (top left), random (top right), reds in foreground (bottom left), reds in background (bottom right). Parameters: stroke lengths* $\in [20,50]$ *pixels, key colour = red* $(1,0,0)$.

serves longer expressionistic strokes, while the short-over-long technique renders smooth gradients with shorter impressionistic strokes. While these long, flowing strokes can be used to express many artistic properties, they pollute smooth gradients with an abundance of texture, hindering realistic or impressionistic depictions. This incompatibility may be resolved in the future by a hybrid stroke ordering function that renders long-over-short strokes in some image segments, but short-over-long in others [SSS05]. The long-over-short ordering technique may also be used with gradient fields to produce the coherent brush stroke flows that symbolize motion in van Gogh's expressionist works [OM04].

These deterministic brush stroke orderings also reduce the randomness caused by overlapping brush stroke rendering, so they may improve temporal coherence between painted frames or serve as a basis for painterly animation.

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Figure 5: *Stroke length ordering. Original image (top left), random (top right), longer strokes in foreground (bottom left), short strokes in foreground (bottom right). Parameters: brush diameters* $= (40, 30, 20)$ *pixels, stroke lengths* $\in [1, 800]$ *pixels.*

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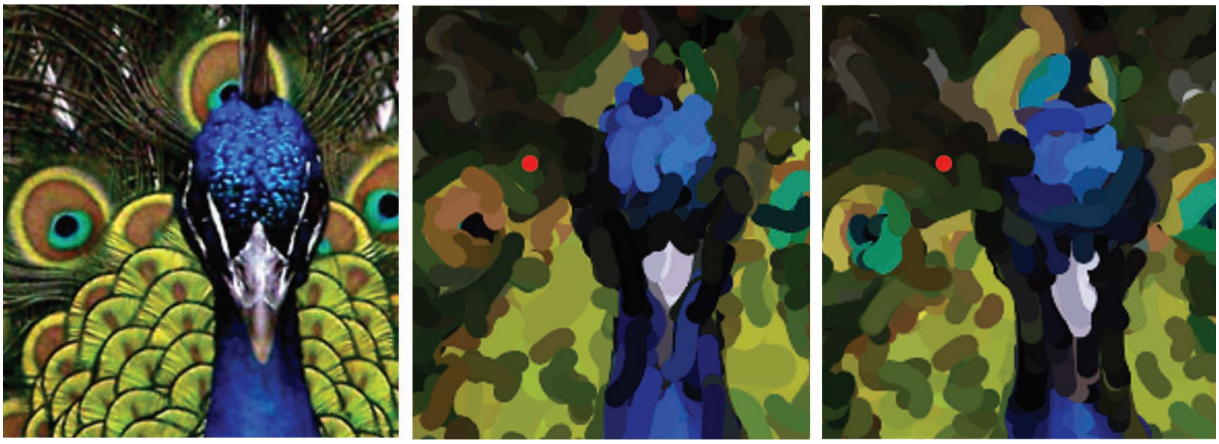

Figure 6: *Location ordering. Original image (left), random (middle), strokes nearest the marked focal point in foreground (right).*

Figure 7: *Single-layered painting with different stroke orderings. Original image (top left), random (top middle), light-over-dark (top right), red hues in foreground (bottom left), short-over-long (bottom middle), near-over-far (bottom right).*