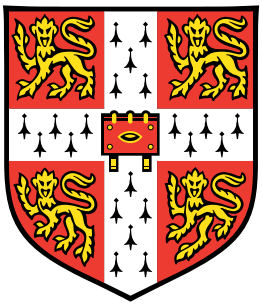
Color, Style and Composition in Image Processing



A thesis for the degree of
Doctor of Philosophy

Mark Grundland
Peterhouse College
Computer Laboratory
University of Cambridge
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Abstract

Ph.D. Thesis of Mark Grundland:
Color, Style and Composition in Image Processing

My work presents image processing techniques for facilitating artistic visual expression. Inspired by both visual art and visual perception, the aim of my research is to enhance the possibilities of visual communication by extending the repertoire of creative techniques available to digital artists. My work offers new ways to transform style, color, and composition in digital imaging. To improve control over stylized rendering, I propose a concise, multiresolution image representation that can simultaneously support both photorealistic reconstruction and non-photorealistic rendering. To improve control over color and contrast enhancement, I propose recoloring techniques to remap colors, find and replace colors, and convert colors to grayscale. To improve control over image compositing, I propose image blending operators designed to produce composites that preserve key visual characteristics of their components, including contrast, color, detail, and salience. Seeking mathematical models to express aesthetic and perceptual goals, I develop algorithmic image transformations that are shown to have a variety of practical applications across automated image rendering and interactive image editing.

Part I:

Transforming Style

Primary Contribution:

To improve control of image stylization, my work investigates the application of spatial partitions to image representation and rendering. I present a concise multiresolution image representation that can simultaneously support both photorealistic image reconstruction and non-photorealistic image rendering. In particular, I demonstrate a unified sampling and rendering framework, based on the Voronoi diagram, that can produce a wide range of non-photorealistic rendering styles amenable to a concise encoding. To validate the flexibility of this approach, I show how the user can interactively design original non-photorealistic rendering styles for use in this framework. To validate the applicability of this approach, I describe experiments in non-photorealistic rendering for progressive image compression.

Additional Contributions:

1. A qualitative evaluation of non-adaptive image sampling strategies for use in non-photorealistic image rendering, including a quantitative assessment of the accuracy of image sampling strategies in photorealistic image reconstruction.

2. An extension of the farthest point sampling algorithm that improves the reliability of automated adaptive sampling while allowing the user to exercise overall control over the sampling process by specifying an importance map.

3. A demonstration of how photorealistic scattered data interpolation methods, such as Gouraud shading and Shepard interpolation, can be modified and generalized to produce various non-photorealistic rendering effects.

4. An application of interactive evolution by aesthetic selection to the design of image rendering styles, made possible by encapsulating the definition of a rendering style in the formulation of a parametric procedural texture.

5. A discussion of the implications of applying non-photorealistic rendering to image compression, including a short survey of related research.

Publications and Presentations:

Generating Aperiodic Tilings Using Quasicrystals
Mark Grundland and Jiri Patera
Presented as a seminar at the Laboratoire de Physique Théorique de la Matière Condensée, Université Paris 7 Denis-Diderot (Paris, France, 23 May 2001).

Automated Artistic Image Rendering
Mark Grundland and Peter Robinson
Presented as a seminar at the School of Computer Science,
McGill University (Montreal, Canada, 29 August 2001).

Stylized Rendering For Multiresolution Image Representation
Mark Grundland, Chris Gibbs, and Neil A. Dodgson
Proceedings of SPIE, vol. 5666, pp. 280-292, SPIE. ISBN 0-8194-5639-X.
Presented as a talk at the Electronic Imaging Symposium,
Human Vision and Electronic Imaging X Conference (San Jose, USA, 17-20 January 2005).

Stylized Multiresolution Image Representation
Mark Grundland, Chris Gibbs, and Neil A. Dodgson
Journal of Electronic Imaging, to appear. ISSN 1017-9909.
Presented also as a talk at the EUROGRAPHICS Workshop on Computational Aesthetics in Graphics, Visualization and Imaging (Girona, Spain, 18-20 May 2005).

Collaborations and Supervisions:

Visualization of Quasicrystals [collaboration as a research assistant]
with J. Patera at the Centre de Recherches Mathématiques of the Université de Montréal, 2000-2001.

Interactively Evolving Artistic Styles [supervision of undergraduate project]
with C. Gibbs at the Computer Laboratory of the University of Cambridge, 2002-2003.

Height Interpolation from Geographical Data [supervision of undergraduate project]
with T. J. Minter at the Computer Laboratory of the University of Cambridge, 2002-2003.

Optimally Sampling for Image Reconstruction [supervision of undergraduate project]
with S. Mital at the Computer Laboratory of the University of Cambridge, 2002-2003.

Key References:

Amidror I. (2002). "Scattered Data Interpolation Methods for Electronic Imaging Systems: A Survey," *Journal of Electronic Imaging*, vol. 11, no. 2, pp. 157-176.

Darsa L. and Costa B. (1996). "Multiresolution Representation and Reconstruction of Adaptively Sampled Images," *Proceedings of SIBGRAPI*, Caxambu, Brazil, pp. 321–328.

Hertzmann A. (2003). "A Survey of Stroke-Based Rendering," *IEEE Computer Graphics and Applications*, vol. 23, no. 4, pp. 70-81.

Eldar Y., Lindenbaum M., Porat M., and Zeevi Y. Y. (1997). "The Farthest Point Strategy for Progressive Image Sampling," *IEEE Transactions on Image Processing*, vol. 6, no. 9, pp. 1305-1315.

Sims K. (1993). "Interactive Evolution of Equations for Procedural Models," *Visual Computer*, vol. 9, no. 8, pp. 466-476.

Part II:

Transforming Color

Primary Contribution:

To improve control over color and contrast enhancement, my work presents new techniques to construct global 1D, 3D, and 3D-to-1D color mapping functions:

1. I propose a novel 1D color histogram warping technique that applies a piecewise defined, continuously differentiable, monotonic, interpolating spline transformation to color histogram specification and modification tasks. In particular, this technique alters the color composition of an image to approximate a specified color distribution. To validate the flexibility of this approach, I demonstrate how its design enables the separate specification of contrast and color changes without causing undue image artifacts. To validate the applicability of this approach, I develop novel tools for color histogram equalization, color transfer, color emphasis, as well as interactive and automatic contrast enhancement.

2. I propose a novel 3D color space warping technique that applies a feature-based, continuous, volumetric transformation to interactive color image enhancement tasks. In particular, this technique alters the color composition of an image according to a specified mapping of color gradients. This approach extends the discrete substitution of colors in indexed color images to a continuous transformation of color gradients in continuous color images. To validate the flexibility of this approach, I show how common contrast adjustment and color correction operations can be expressed as affine color gradient transformations. To validate the applicability of this approach, I present examples of image recoloring, color transfer, and contrast enhancement.

3. I propose a novel 3D-to-1D color projection technique that applies a continuous, piecewise linear mapping of the color primaries and their saturation to perform automatic contrast enhancement for color to grayscale conversion. Compared with the standard color to grayscale conversion, this approach better preserves equiluminant chromatic contrasts in grayscale. Alternatively, compared with standard principal component color projection, this approach better preserves achromatic luminance contrasts in grayscale. Finally, compared with recent optimization methods for contrast enhancing color to grayscale conversion, this approach proves much more computationally efficient at producing visually similar results with stronger mathematical guarantees on its performance.

Additional Contributions:

1. The use of robust statistics, relying on quantile analysis as well as mode and valley detection, to characterize color distribution features in histogram specification and modification methods.

2. The use of a novel image dependent color space, featuring perceptually uniform color axes with statistically independent chromatic components, to reduce the color artifacts caused by applying histogram specification and modification methods that transform each color channel independently.

3. The design of novel user interfaces for interactive image enhancement tasks, relying on search and replace of color gradients to control color correction, direct manipulation by brush strokes to control contrast adjustment, and matching selections of image regions to control color transfer.

4. The representation of color gradients by a spherical parameterization to facilitate the specification of color editing operations, such as color shift, contrast adjustment, and color variation.

5. The development of a novel stochastic sampling technique, called sampling by Gaussian pairing, used to evaluate color differences belonging to image features of varying sizes by comparing each pixel to a nearby pixel randomly chosen according to a Gaussian displacement vector.

6. The development of a novel dimensionality reduction technique, called predominant component analysis, used to find a color axis that best represents the colors of image features by maximizing the covariance of the projected color differences and their prescribed importance weights.

Publications and Presentations:

Interactive Contrast Enhancement by Histogram Warping
Mark Grundland and Neil A. Dodgson
Computational Imaging and Vision, vol. 32, pp. 832-838, Springer. ISBN 1-4020-4178-0.
Presented as a talk at the International Conference on
Computer Vision and Graphics (Warsaw, Poland, 22-24 September 2004).

Automatic Contrast Enhancement by Histogram Warping
Mark Grundland and Neil A. Dodgson
Computational Imaging and Vision, vol. 32, pp. 293-300, Springer. ISBN 1-4020-4178-0.
Presented as a talk at the International Conference on
Computer Vision and Graphics (Warsaw, Poland, 22-24 September 2004).

Color Histogram Specification by Histogram Warping
Mark Grundland and Neil A. Dodgson
Proceedings of SPIE, vol. 5667, pp. 610-621, SPIE. ISBN 0-8194-5640-3.
Presented as a poster at the Electronic Imaging Symposium,
Color Imaging X: Processing, Hardcopy, and Applications (San Jose, USA, 17-20 January 2005).

Color Search and Replace
Mark Grundland and Neil A. Dodgson
Computational Aesthetics 2005, pp. 101-109, EUROGRAPHICS. ISBN 3-905673-27-4.
Presented as a talk at the EUROGRAPHICS Workshop on Computational Aesthetics in
Graphics, Visualization and Imaging (Girona, Spain, 18-20 May 2005).

Decolorize: Fast, Contrast Enhancing, Color to Grayscale Conversion
Mark Grundland and Neil A. Dodgson
Pattern Recognition, vol. 40, no. 11, pp. 2891-2896. ISSN 0031-3203.
Presented also as a poster at the International Symposium on
Non-Photorealistic Animation and Rendering (Annecy, France, 5-7 June 2006).

Collaborations and Supervisions:

Interactive Contrast Enhancement [supervision of undergraduate project]
with R. Vohra at the Computer Laboratory of the University of Cambridge, 2004-2005.

Contrast Brushes [collaboration on an unpublished manuscript]
with R. Vohra at the Computer Laboratory of the University of Cambridge, 2005.

Color Correction [supervision of undergraduate project]
with A. Phillips at the Computer Laboratory of the University of Cambridge, 2005-2006.

Adaptive Smoothing and Noise Reduction [supervision of undergraduate project]
with T. Craig at the Computer Laboratory of the University of Cambridge, 2005-2006.

Key References:

Gooch A. A., Olsen S. C., Tumblin J., and Gooch B. (2005). "Color2Gray: Salience-Preserving Color Removal," *Proceedings of SIGGRAPH*, Los Angeles, USA, pp. 634-639.

Hardeberg J. Y., Farup I., Kolas O., and Stjernvang G. (2002). "Color Management for Digital Video: Color Correction in the Editing Phase," *International IARIGAI Research Conference*, Lake of Lucerne, Switzerland.

Rasche K., Geist R., and Westall J. (2005). "Re-Coloring Images for Gamuts of Lower Dimension," *Proceedings of EUROGRAPHICS*, Dublin, Ireland, pp. 423-432.

Reinhard E., Adhikhmin M., Gooch B., and Shirley P. (2001). "Color Transfer between Images," *IEEE Computer Graphics and Applications*, vol. 21, no. 5, pp. 34-41.

Strickland R. N., Kim C. S., and McDonnell W. F. (1987). "Digital Color Image Enhancement Based on the Saturation Component," *Optical Engineering*, vol. 26, no. 7, pp. 609-616.

Weeks A. R., Sartor L. J., and Myler H. R. (1999). "Histogram Specification of 24-Bit Color Images in the Color Difference (C-Y) Color Space," *Nonlinear Image Processing X*, San Jose, USA. Proceedings of SPIE, vol. 3646, pp. 319-329.

Zamperoni P. (1995). "Image Enhancement," *Advances in Imaging and Electron Physics*, vol. 92, pp. 1-77.

Part III:

Transforming Composition

Primary Contribution:

To improve control over image compositing, my work proposes four new image blending techniques for producing composite images that can preserve the key visual characteristics of the component images used to create them. Linear interpolation is the standard method of image blending used in image compositing. However, as linear interpolation acts to reduce variation, its output may not maintain the visual quality of its input, requiring compositing artists to manually compensate for faded contrast, dull colors, lost details, or lack of emphasis. To address these longstanding shortcomings of image blending, I examine different ways to redefine the basic equation of linear interpolation. I show how to reformulate its results, its operators, its linearity, and its weights in order to better account for contrast, color, detail, and salience. My contrast preserving technique applies statistical analysis in order to recover the contrast lost due to linear interpolation. My color preserving technique applies vector algebra in order to implement a novel color mixing model that favors vivid colors over neutral tones. My detail preserving technique applies generalized means in order to emphasize variation over uniformity when combining image features at various scales. Finally, my salience preserving technique applies information theory in order to retain the most informative regions of the input images. To validate the flexibility of these techniques, I demonstrate that they can simultaneously blend multiple, independent, multiresolution images with variable degrees of transparency. To validate the applicability of these techniques, I describe applications to cross dissolve, image fusion, image morphing, image smoothing, and mipmapping.

Additional Contributions:

1. A discussion of the aesthetic problems associated with image blending by linear interpolation, including an explanation of their statistical causes and their perceptual effects.

2. An extension of grayscale isomorphic image processing and color homomorphic image processing to color isomorphic image processing, which establishes an isomorphism between the image colors and the real numbers, allowing any mathematical operation defined on real numbers to be applied to colors without losing its algebraic properties or mapping colors out of gamut.

3. An examination of the roles of opacity and salience in image compositing and their impact on the dominance and coverage properties of the cross dissolve visual effect.

Publications and Presentations:

Cross Dissolve Without Cross Fade:
Preserving Contrast, Color and Salience in Image Compositing
Mark Grundland, Rahul Vohra, Gareth P. Williams and Neil A. Dodgson
Computer Graphics Forum, vol. 25, no. 3, pp. 577-586. ISSN 0167-7055.
Presented as a talk at the EUROGRAPHICS Annual Conference
(Vienna, Austria, 4-8 September 2006).

Nonlinear Multiresolution Image Blending
Mark Grundland, Rahul Vohra, Gareth P. Williams and Neil A. Dodgson
Machine Graphics and Vision, to appear. ISSN 1230-0535.
Presented as a talk at the International Conference on
Computer Vision and Graphics (Warsaw, Poland, 25-27 September 2006).

Improving Image Quality in Image Compositing
Mark Grundland, Rahul Vohra, Gareth P. Williams and Neil A. Dodgson
Presented as a seminar at the Department of Electronics, Computer Engineering and Automatics,
University of Girona (Girona, Spain, 22 May 2007).

Collaborations and Supervisions:

Cross Dissolve Without Cross Fade [collaboration on a published paper]
with R. Vohra and G. Williams at the Computer Laboratory of the University of Cambridge, 2006.

Nonlinear Multiresolution Image Blending [collaboration on a published paper]
with R. Vohra and G. Williams at the Computer Laboratory of the University of Cambridge, 2006.

Low Cost Information Theoretic Salience [collaboration on an unpublished manuscript]
with N. Dodgson at the Computer Laboratory of the University of Cambridge, 2006.

Key References:

Burt P. J. and Adelson E. H. (1983). “A Multiresolution Spline with Application to Image Mosaics,” *ACM Transactions on Graphics*, vol. 2, no. 4, pp. 217-236.

Burt P. J. (1984). “The Pyramid as Structure for Efficient Computation,” *Multiresolution Image Processing and Analysis*, edited by A. Rosenfeld, Springer-Verlag, pp. 6-35.

Perez P., Gangnet M., and Blake A. (2003). “Poisson Image Editing,” *Proceedings of SIGGRAPH*, San Diego, USA, pp. 313-318.

Porter T. and Duff T. (1984). “Compositing Digital Images,” *Proceedings of SIGGRAPH*, Minneapolis, USA, pp. 253-259.

Shvaytser H. and Peleg S. (1983). “Pictures as Elements in a Vector Space,” *Proceedings of the Conference on Computer Vision and Pattern Recognition*, Washington, USA, pp. 442-446.