Three-dimensional Surface Texture Synthesis

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Abstract

Texture synthesis has been extensively investigated by both computer vision and computer graphics communities during the past twenty years. However, the input and output are normally 2D intensity texture images. If the subjects are 3D surface textures (such as brick, woven or knitted textiles, embossed wallpapers etc.), these 2D synthesis techniques cannot provide the information required for rendering under other than the original illumination and viewpoint conditions. The aim of this thesis therefore is to develop inexpensive approaches for the synthesis of 3D surface textures. Few publications are available in this research area.

We first introduce an overall framework for the synthesis of 3D surface textures. The framework essentially combines surface representation methods with 2D texture synthesis algorithms to synthesise and relight new surface representations. Then we investigate five low-dimensional methods, namely the *3I*, *Gradient*, *PTM*, *Eigen3* and *Eigen6* methods, for extracting representations from a set of images of the 3D surface texture sample. The surface representations can be relit to generate new images under arbitrary lighting directions by linear combinations. These methods are quantitatively assessed by comparing the original and relit images. The results show that the *Eigen6* produces the best performance.

We select a 2D texture synthesis algorithm which is then extended into multi-dimensional space to use the five surface representations as input. In this way, we develop five approaches for the synthesis of 3D surface textures. The synthesised results are compatible with computer graphics systems and can be used in real-time rendering applications. The five synthesis approaches are qualitatively assessed by employing psychophysical experiments and non-parametric statistics. The results show that the two low-dimensional methods, the *Gradient* and *Eigen3*, on average offer as good a performance as of any of the other methods and incur low computational cost.

To my parents

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Principal Symbols

Symbol	**Meaning**	**Section first introduced**
$\mathbf{R}^{1}$	One-dimensional real space	3.2
$\mathbf{R}^{3}$	Three-dimensional real space	3.2
$\mathbf{R}^{6}$	Six-dimensional real space	4.5
$\mathbf{R}^{n}$	N-dimensional real space	3.2
(x, y)	Pixel location	3.2
(x_0, y_0)	Pixel location	3.2
(x_0', y_0')	Pixel location	3.2
$p(x, y)$	Surface derivative in x direction in spatial domain	3.2
$q(x, y)$	Surface derivative in y direction in spatial domain	3.2
$al(x, y)$	Albedo map	3.2
M	Matrix	4.4.1
U	Column-orthogonal matrix produced by decomposing a matrix **M** using SVD	4.4.2
W	Diagonal matrix containing singular values produced by decomposing a matrix **M** using SVD	4.4.2
$\mathbf{V}^{\mathbf{T}}$	Transpose of the orthogonal matrix produced by decomposing a matrix **M** using SVD	4.4.2
I	Image data matrix	4.4.1
$i_{11}, i_{12}, \ldots, i_{mn}$	Pixel intensity values in certain images.	4.4.1
$\mathbf{M_1}$	Surface representation matrix	4.4.1
$\mathbf{M_2}$	Known matrix for extracting surface representation matrix $\mathbf{M_1}$	4.4.1

$\mathbf{c}$	Coefficient vector for relighting	4.4.1
$i(x, y)$	Intensity of an image pixel at (x, y)	4.4.2
λ	Incident intensity to the surface	4.4.2
ρ	Albedo value of the Lambertian reflection	4.4.2
$\mathbf{l}$	Lighting vector	4.4.2
$\mathbf{n}$	Normalised surface normal	4.4.2
τ	Tilt angle of illumination	4.4.2
σ	Slant angle of illumination	4.4.2
$s(x, y)$	Surface height map in spatial domain	4.4.2
N	Surface normal matrix	4.4.2
A	Albedo matrix	4.4.2
$\mathbf{N_a}$	Scaled surface normal matrix	4.4.2
L	Lighting matrix	4.4.2
$\mathbf{L_{ptm}}$	Lighting matrix in the *PTM* method	4.4.3
$\mathbf{l_{ptm}}$	Lighting vector in the *PTM* method	4.4.3
$\mathbf{A_{ptm}}$	Polynomial Texture Map matrix	4.4.3
w_i	Singular value of the image data matrix $\mathbf{I}$, i=1,2,…	4.4.4
$\tilde{\mathbf{W}}_{\mathbf{I}}$	The approximation matrix of the diagonal matrix $\mathbf{W}$ containing the first few singular values	4.4.4
$\mathbf{i}_{(\tau_i,\sigma_j)}$	Image obtained under illumination tilt angle τ_i and slant angle σ_j .	4.4.4
η	Normalised *root mean-squared* errors	4.5.1
$\mathrm{P(u, v)}$	Denotation of $p(x, y)$ in frequency domain	4.5.3
$\mathrm{Q(u, v)}$	Denotation of $q(x, y)$ in frequency domain	4.5.3
$\mathrm{S(u, v)}$	Denotation of the spatial surface height map $s(x, y)$ in frequency domain	
(u,v)	2D frequency co-ordinate	4.5.3
L	The level of the lowest scale of an image pyramid	5.3.1
{X, (m,n)}	Pixel location at level *X* of the result pyramid	5.3.1
{X, (k, l)}	Pixel location at level *X* of the sample pyramid	5.3.1

$O(n)$	The computational complexity is the order of n	5.3.3
Ω_j	The overlapping area covered by block j in the sample image and the already synthesised pixels	5.4.3
(x_i, y_i)	The i^{th} pixel of the sample image covered by the overlapping area Ω_j	5.4.3
(x'_i, y'_i)	The i^{th} pixel of the result image covered by the overlapping area Ω_j	5.4.3
$\min\{\ldots\}$	Function to calculate the minimum value	5.4.3
$m_i(x, y)$	A pixel value at (x, y) in the i^{th} sample representation map	6.2.1
$m'_i(x', y')$	A pixel value at (x', y') in the i^{th} result representation map	6.2.1
α	Confidence level	6.3.1

Abbreviations

Abbreviations	**Meaning**	**Section first introduced**
SSD	Sum of Square Differences	2.1
BTF	Bidirectional Texture Functions	2.1
BRDF	Bidirectional Reflectance Distribution Function	2.3.1
SVD	Singular Value Decomposition	2.3.2
PCA	Principal Component Analysis	2.3.2
CUReT	Columbia-Utrecht Reflectance and Texture Database	2.3.2
3I	The method that uses three images of the sample as input for the synthesis and relighting	4.1
Gradient	The method that uses surface gradient and albedo maps as input for the synthesis and relighting	4.1
PTM	The method that uses Polynomial Texture Maps as input for the synthesis and relighting	4.1
Eigen3	The method that uses the first three eigen base images as input for the synthesis and relighting	4.1
Eigen6	The method that uses the first six eigen base images as input for the synthesis and relighting	4.1
rms	Root mean-squared errors	4.5
SAD	Sum of Absolute Differences	5.3
ANOVA	Friedman's nonparametric two-way Analysis of Variance	6.3.2