Journal of Zhejiang University SCIENCE
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Relighting multiple color textures*

DIAO Chang-yu (刁常宇)[1], LU Dong-ming (鲁东明)[1], LIU Gang (刘 刚)[2]

([1]*School of Computer Science, Zhejiang University, Hangzhou 310027, China*)

([2]*Conservation Institute, Dunhuang Academy, Dunhuang 736200, China*)

E-mail: Joyrain@zju.edu.cn; ldm@zju.edu.cn; Liugang@hotmail.com

Received Aug. 10, 2005; revision accepted Sept. 5, 2005

Abstract: With the development of digital library technology, library books made of paper can be digital released and read, and Endangered Cultural Heritages can be preserved. Traditional library's contents and functions can be greatly enhanced by digital technologies. For these new library objects, the primary key problem is precisely reconstructing their 3D models. When constructing complete 3D models, multiple color texture maps are often necessary. A commonly encountered problem uncounted during fusing of textures from multiple color images is color distortion. Each texture of a single 3D model may be obtained under possibly different lighting conditions and color response of the camera. To remove any visible seam and improve color consistency between the textures while avoiding color distortion, we propose a new efficient algorithm to relight all the texture images globally, spread residual light difference, and recolor each image by homogeneous transformation. A relative illumination model was adopted to obtain the relighting function. We choose $l\alpha\beta$ color space with minimal correlation between channels for many natural scenes, for calculating the relighting result. Looking into two overlapped images A and B, we can pairwise relight B into A's luminosity condition in two steps. We first scale B's l channel by the l_A/l_B ratio of the overlapped region. We can assume A and B are in a same color plane now. Then a homogeneous transformation is applied to B's α and β channels which moves B into A's hue and saturation condition. For multiple overlapped color textures, a patch based weighted global relighting method was proposed to minimize the total color difference. The pairwise relighting method was used between each two overlapped images, and the difference in every overlapped region after relighting was weighted and summed up to construct an energy value. We used Nelder-Mead method to find a minimal energy value and the relighting parameters for every image. After global relighting, textures become almost coherent. We simply blended the overlapped region along the texture border to remove small visual seams and get a final result. We illustrate our method by calibrating textures of a painted sculpture acquired with laser scanner. Experimental results were realistic and reliable and showed how this method can fuse multiple textures without color distortion.

Key words: Texture relighting, Digitization, Color correction, Texture blending
doi:10.1631/jzus.2005.A1284 **Document code:** A **CLC number:** TP391.72

INTRODUCTION

When constructing complete 3D models, multiple color texture maps are often necessary. Suppose that the object of interest is fixed and images of it are acquired by one or more cameras from different positions and directions. The viewpoints and the illumination may be different for each acquisition. The geometric model of the object may come from merging of several 3D models. The 2D-3D registration between the textures and the geometric model is done by a previous step by camera calibration method.

Taking images from different view angles and with different camera settings creates mismatching colors due to lighting and camera conditions. Even with careful lighting arrangement and use of a professional digital camera we can observe a significant discontinuity between images. This discontinuity often leads to an observable discrete hue boundary at the point where the selection of texture maps changed. This discrepancy probably arises because illumination conditions are slightly different and the camera

*Project supported by the National Basic Research Program (973) of China (No. 2002CB312106)

hue capture is non-linear (Bannai *et al*., 2004). The problem we address here is how to fuse these textures together. Additionally, when we digitize cultural heritages such as painted sculptures, the fusing process must not cause color distortion.

A common approach to the problem of texture fusing is to simply remove the seams near texture boundaries, while keeping texture slightly modified. By this method, the merged texture may have non-coherent colors, for example if one original texture may be redder or greener than the other overlapped one.

Rocchini *et al*.(1999) developed a four steps algorithm to bind multiple textures onto one 3D model. The algorithm includes vertex-to-image binding, patch growing, patch boundary smoothing (local registration) and texture-patches packing. The local registration step can achieve good texture stitching result, but the interpolation inside all frontier triangles using areal coordinates simply sums up overlapped pixel color, which cannot be used to calibrate the non-overlapped areas.

Lensch *et al*.(2001) used a silhouette-based algorithm for texture registration and stitching, and developed an automated texture registration and stitching method for real world models. A smooth transition is achieved by blending between the textures across the border triangles. Their technique has high efficiency, but the non-overlapped areas were still uncalibratable.

The Digital Michelangelo Project did a great job on 3D scanning of large statue. Leroy *et al*.(2000) proposed a color processing pipeline. They first mapped color onto the mesh, then computed diffuse reflectance of each vertex, and finally blended multiple observations. When blending multiple textures, the following factors were considered: obliquity of the surface with respect to the light, projected area of the surface with respect to the camera, proximity to the mirror direction, suppression of highlights, proximity to a silhouette edge with respect to the camera, proximity to a silhouette edge with respect to the light and proximity to the edge of the color image. Their pipeline successfully processed over 7000 images for the Michelangelo 3D model. The color system was calibrated before digitization, but only geometric distortion, 3D coordinates and spatial radiometric effects were considered. There was no global color correction in their work.

Beauchesne and Roy (2003) did texture fusing through relative illumination estimation and extrapolation. Their approach modifies not only the overlapped region but also the rest of the textures in order to get a realistic texture. It is much more realistic than weighted averaging, but color differences could not be global minimized.

Agathos and Fisher (2003) first developed a method for correcting the color of the images acquired from two different views, with two stages: (1) A global correction that does a color transform estimated from the two different colors observed at pixels in the overlap region; (2) A local correction to smooth out small color variation boundaries that are left out. After that, they introduce a new approach to remove color discrepancies between multiple overlapped images (Bannai *et al*., 2004). The solution is to choose a patch X with a good appearance, and then find transformations $T_{Y\rightarrow X}$ ($Y\neq X$) that minimize the total color error over all overlapped pixels. After global color correction, all the images will have continuous illumination condition, but color distortion may be produced when overlapped textures have different hue.

In our approach, a three-step algorithm is used for relighting multiple color textures without accompanying color distortion: (1) A global patch based luminosity correction transforms all textures into the same illumination condition; (2) A global patch based color correction transforms overlapped textures into continuous hue condition; (3) A local correction to blend small color variation boundaries.

The major advantages of our method are that it gives realistic results, and cause little color distortion. It does not require calibration of the color system before digitization, and is very easy to use. The main constraint is that our method suggests points with similar normals were under similar lighting conditions.

GLOBAL PATCH BASED LUMINOSITY CORRECTION

When someone takes two different images of an object, the illumination and color are usually different. Without taking into account the non-linear camera hue affect, we can find a luminosity transformation that can correct the different illumination.

Method

We use the Beauchesne and Roy (2003)'s model which based on the following hypotheses:

(1) Parallel rays. Suppose that all the light sources are punctual and infinitely far away, thereby making all the rays coming from a source parallel near the object of interest.

(2) Smoothness. Consider objects having no normal discontinuity, except at the edge of the mesh.

(3) View factor. For each point on the surface of the object, define the view factor as the fraction of the illumination sphere that is visible from the infinitesimal surface patch around this point. Assuming that a surface patch can only receive light from the hemisphere centered on its normal, the view factor should be at most 1/2.

(4) Convexity. Only consider objects which are convex or almost convex. Combined with the previous hypotheses, it implies that all the points with similar normals have similar illumination.

(5) BRDF (Bidirectional Reflectance Distribution Function). It is isotropic and similar for the points having similar normals.

(6) Orthographic projection. Suppose that each image is taken from far enough so that all the rays are approximately parallel.

(7) Reliable normals. Assume that we can rely on the geometries to deduce the normals.

(8) Texture overlap. Assume that, in each pair of textures we want to adjust, there is an overlapped region between them.

Let: $I_i(p): S \rightarrow \mathbb{R}^+$ be the observed image intensity for texture I at a given point p; $d_i \in G$ be the orientation of the orthographic projection of image i. It turns out that there is an equation like this:

$$I_i'(p, d_i) = C_i I_i(p, d_i) \quad (1)$$

where I_i' are the re-rendered texture, C_i is the relative illumination. For a given pair of textures 1 and 2, a linear combination interpolated value can be obtained as:

$$C_i = \frac{k_1 I_i(p, d_i) + k_2 I_{3-i}(p, d_{3-i})}{I_i(p, d_i)} \quad (2)$$

When interpolating within multiple textures, we use a technique like Bannai *et al.*(2004) used to correct luminosity globally. For simplicity, we start with 3 images A, B and C. The theory below applies for any arbitrary topology of overlapped regions. Suppose A&B, B&C and C&A overlap and A has a good color appearance. Then, A's luminosity will be the target and B's and C's luminosity should be transformed to A's luminosity. We can estimate the luminosity transformations $T_{B\rightarrow A}$ from B to A and $T_{C\rightarrow A}$ from C to A by using corresponding pixel values in the overlapped region. To guarantee that there is no luminosity difference between B and C, we propose finding transformations $T_{X\rightarrow A}$ that minimizes the total luminosity error E over all overlapped pixels. The equation is as follows:

$$E = \sum_{i,j,m(i\neq m)} \left(T_{i\rightarrow A} L_{\overline{ji}} - T_{m\rightarrow A} L_{\overline{jm}}\right)^2 \phi(i,m,j) \quad (3)$$

where A is the target luminosity, $L_{\overline{ji}}$ is the luminosity value of pixel j in image i, $L_{\overline{jm}}$ is the luminosity value of pixel j in image m, $\phi(i,m,j)$=1 if pixel j is seen in both image j and image m and 0 otherwise. From Eqs.(1) and (2), define $k_i = T_{i\rightarrow A} (k_i \in \mathbb{R}^+)$, so we can find the global linear combination interpolation value for each texture. But simply replace $T_{i\rightarrow A}$ with k_i will cause k_i=0 for every texture. We change E to the following equation so we can avoid that:

$$E_{\mathrm{L}} = \sum_{i,j,m(i\neq m)} \left(k_i L_{\overline{ji}} - k_k L_{\overline{jm}}\right)^2 \phi(i,m,j) + w\sum_j \left|(1-k_A) L_{\overline{jA}}\right| \quad (4)$$

where w is the weight of image A. Now we can transform all textures' luminosity to be the same as that of A. To estimate luminosity transformations that minimize the total luminosity error E_{L} over all overlapped pixels, MATLAB minimization function *fminsearch* was used. To reduce calculations, only 2%~5% of pixels in the overlapped region were chosen and the best solution was estimated by calculating the total luminosity error E_{L} from the sub samples.

Color space

When we adjust the luminosity of textures, the color of the textures should not be affected. Otherwise, the hue condition may be changed due to the correlationship between RGB values. We choose the *lαβ* color space for our processing, which was developed by Ruderman *et al*.(1998). The *lαβ* color space minimizes correlation between channels for many natural scenes. Reinhard *et al*.(2001) proposed a method for copying color from one image to another, which is similar to our texture relighting work.

The little correlation between the axes in *lαβ* space enables our application of different operations in different color channels with some confidence that undesirable cross channel artifacts will not occur. Additionally, this color space is logarithmic, which means to a first approximation that uniform changes in channel intensity tend to be equally detectable (Laming, 1986).

To convert RGB images into *lαβ* color space, we firstly need to convert the image to LMS space, and then transform LMS space into *lαβ* space. Reinhard *et al*.(2001) derived the following equation between RGB and LMS space:

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.3811 & 0.5783 & 0.0402 \\ 0.1967 & 0.7244 & 0.0782 \\ 0.0241 & 0.1288 & 0.8444 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{5}$$

Eq.(6) is used to convert the data to logarithmic space:

$$\begin{aligned} L' &= \log L \\ M' &= \log M \\ S' &= \log S \end{aligned} \tag{6}$$

The equation between *L′M′S′* and *lαβ* space is as follows:

$$\begin{bmatrix} l \\ \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{6}} & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & -2 \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} \tag{7}$$

If we think of the *L* channel as red, the *M* as green, and the *S* as blue, we can see that this is a variant of many opponent-color models (Wyszecki and Stiles, 1982). Thus the *l* axis represents an achromatic channel, while the *α* and *β* channels are chromatic yellow-blue and red-green opponent channels. Flanagan *et al*.(1990) mentioned this color space earlier because, in this color space, the achromatic axis is orthogonal to the equiluminant plane. We use *l* to present luminosity of textures, so the transform of luminosity will not affect hue condition.

GLOBAL PATCH BASED COLOR CORRECTION

Like what we have done to luminosity of the textures, we can do global patch based color correction. But, if we use the same linear transform interpolation separately to *α* and *β* channels, the resulting texture color may be depigmented or distorted. So we let $\boldsymbol{T}_{X\to A}$ transform *α* and *β* channels together by homogeneous transformation, as the follows:

$$\begin{bmatrix} \alpha_i' \\ \beta_i' \\ 1 \end{bmatrix} = \boldsymbol{T}_{i\to A} \begin{bmatrix} \alpha_i \\ \beta_i \\ 1 \end{bmatrix}, \left(\boldsymbol{T}_{i\to A} = \begin{bmatrix} \cos\theta_i & \sin\theta_i & t_{i1} \\ -\sin\gamma_i & \cos\gamma_i & t_{i2} \\ 0 & 0 & 1 \end{bmatrix} \right) \tag{8}$$

Eq.(8) is similar to Reinhard *et al*.(2001)'s color transform method:

$$\alpha' = k(\alpha - \langle a \rangle) + \langle a \rangle \tag{9}$$

The orthogonal matrix consisting of *θ* and *γ* can prevent color transformation from distortion. We propose finding transformations $\boldsymbol{T}_{X\to A}$ that minimize the total color error E_C over all overlapped pixels. E_C is defined as follows:

$$E_C = \sum_{i,j,m(i\neq m)} \left\| \boldsymbol{T}_{i\to A} \begin{bmatrix} \alpha_{\overline{ji}} \\ \beta_{\overline{ji}} \end{bmatrix} - \boldsymbol{T}_{m\to A} \begin{bmatrix} \alpha_{\overline{jm}} \\ \beta_{\overline{jm}} \end{bmatrix} \right\|^2 \phi(i,m,j) + \sum_j \left\| \begin{bmatrix} \alpha_{\overline{jA}} \\ \beta_{\overline{jA}} \end{bmatrix} - \boldsymbol{T}_{A\to A} \begin{bmatrix} \alpha_{\overline{jm}} \\ \beta_{\overline{jm}} \end{bmatrix} \right\|^2 \tag{10}$$

The MATLAB minimization function *fminsearch* was used again to estimate color transformations that minimize the total color error E_C.

LOCAL CORRECTION

After the global luminosity correction and color correction, the color discrepancies between texture images were minimized, but in practice the remainder error can still cause visual edges on texture boundaries. These dissimilarities can be further reduced by local corrections.

Burt and Adelson (1983) developed a multi-resolution image mosaics method, which can be used for blending texture perfectly, even under serious adverse condition. In practice, after global correction, textures become almost coherent. So we choose a simple but easy-to-implement way to blend all textures together, similar to the method of Rocchini *et al*.(1999).

RESULTS AND DISCUSSION

We have applied this method to digitize No. 158 Mogao Cave of Dunhuang of China. There are three sculptures in this cave. The length of the biggest is 15.70 m, and that of the other two is about 5 m. The 3D models of the cave and sculptures were scanned by a 3rd Tech Deltasphere 3000 laser range scanner. The texture images were acquired by a KODAK DCS 660C camera. A 14 mm, a 35 mm and a 60 mm lens were used.

Some original acquired images of a painted sculpture's head and the corrected results are presented in Fig.1.

Fig.1 The upper row presents original texture images. We can see the last one was overexposed. Overexposure of that image caused abnormal high red value. The lower row presents the corrected texture images, all of which were under the similar lighting and hue conditions

The digitization results of those three sculptures are shown in Fig.2. The lying down sculpture had a gray color appearance, so we rendered this model with lighter illumination to achieve good visual result.

Fig.2 Digitization results of those three sculptures. Each of them consists of about 1 million triangles and over 80 pieces of textures

By successful digitization of the No. 158 Cave, our algorithm was validated to be practical. With the help of this algorithm, we can build realistic 3D model with precise multiple color textures. Constructing precise textures is very important for digitization of cultural heritage and real world figure. Our algorithm provides an effective way to do it.

There are two main weaknesses in our algorithm. (1) Global estimation computing slows down when the texture amount increases. We can split the textures into several groups to optimize computation. (2) The overlapped regions of textures must contain enough kind of color. Otherwise, the global correction result may be invalid.

References

Agathos, A., Fisher, R.B., 2003. Colour Texture Fusion of Multiple Range Images. Proc. 4th Int. Conf. on 3-D Digital Imaging and Modeling, Banff, p.139-146.

Bannai, N., Agathos, A., Fisher, R.B., 2004. Fusing Multiple

Color Images for Texturing Models, Proc. 2nd Int. Symp. on 3D Data Processing, Visualization, and Transmission (3DPVT), Thessaloniki, p.558-565.

Beauchesne, E., Roy, S., 2003. Automatic relighting of overlapping textures of a 3D model. *CVPR*, (2):166-176.

Burt, P.J., Adelson, E.H., 1983. A multiresolution spline with application to image mosaics. *ACM Transactions on Graphics*, **2**(4):217-236.

Flanagan, P., Cavanagh, P., Favreau, O.E., 1990. Independent orientation-selective mechanism for the cardinal directions of colour space. *Vision Research*, **30**(5):769-778.

Lensch, H.P.A., Heidrich, W., Seidel, H.P., 2001. A silhouette-based algorithm for texture registration and stitching. *Graphical Models*, **63**(4):245-262.

Levoy, M., Pulli, K., Curless, B., Rusinkiewicz, S., Koller, D., Pereira, L., Ginzton, M., Anderson, S., Davis, J., Ginsberg, J., Shade, J., Fulk, D., 2000. The Digital Michelangelo Project: 3-D scanning of large statues. Proc. SIGGRAPH, p.131-144.

Laming, D.R.J., 1986. Sensory Analysis. Academic Press, London.

Rocchini, C., Cignomi, P., Montani, C., Scopigno, R., 1999. Multiple Textures Stitching and Blending on 3D Objects. Proc. of Eurographics Rendering Workshop, p.173-180.

Ruderman, D.L., Cronin, T.W., Chiao, C.C., 1998. Statistics of cone responses to natural images: Implications for visual coding. *J. Optical Soc. of America*, **15**(8):2036-2045.

Reinhard, E., Ashikhmin, M., Gooch, B., Shirley, P., 2001. Color transfer between images. *IEEE CG&A Special Issue on Applied Perception*, **21**(5):34-41.

Wyszecki, G., Stiles, W.S., 1982. Color Science: Concepts and Methods, Quantitative Data and Formulae, 2nd Ed. John Wiley & Sons, New York.

Welcome contributions from all over the world

http://www.zju.edu.cn/jzus

- ♦ The Journal aims to present the latest development and achievement in scientific research in China and overseas to the world's scientific community;
- ♦ JZUS is edited by an international board of distinguished foreign and Chinese scientists. And an internationalized standard peer review system is an essential tool for this Journal's development;
- ♦ JZUS has been accepted by CA, Ei Compendex, SA, AJ, ZM, CABI, BIOSIS (ZR), IM/MEDLINE, CSA (ASF/CE/CIS/Corr/EC/EM/ESPM/MD/MTE/O/SSS*/WR) for abstracting and indexing respectively, since started in 2000;
- ♦ JZUS will feature **Science & Engineering** subjects in Vol. A, 12 issues/year, and **Life Science & Biotechnology** subjects in Vol. B, 12 issues/year;
- ♦ JZUS has launched this new column "**Science Letters**" and warmly welcome scientists all over the world to publish their latest research notes in less than 3–4 pages. And assure them these Letters to be published in about 30 days;
- ♦ JZUS has linked its website (http://www.zju.edu.cn/jzus) to **CrossRef**: http://www.crossref.org (doi:10.1631/jzus.2005.*xxxx*); **MEDLINE**: http://www.ncbi.nlm.nih.gov/PubMed; **HighWire**: http://highwire.stanford.edu/top/journals.dtl; **Princeton University Library**: http://libweb5.princeton.edu/ejournals/.