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The Research of Terracotta Warriors Color Restoration Based on Color Transfer

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Abstract

This paper has made an analysis to color realistic restoration problem for Terracotta Warriors, and combining with graphic knowledge, two types of being solved key issues are extracted. Based on color transfer and aiming at the two key issues, the technology framework of color realistic restoration for faded Terracotta Warriors is put forward. Then, an improved Welsh algorithm is proposed to match color pixel, which using local eigenvalues and neighbor variance to form mixed distance measure function. The results of recolor experiments to natural scenery texture and gray texture of Terracotta Warriors show that, the improved color transfer algorithm of this paper is better in recolor gray texture than classical Welsh algorithm, especially for the painted texture which has hierarchical color structure.

Keywords: *color transfer, neighbor eigenvalues, neighbor variance, digital conservation, Terracotta Warriors*

1. Introduction

Terracotta Warriors is an historical treasure for Chinese nation, and its color texture of painted surface has hierarchical structure which made by raw lacquer and mineral pigments through painting [1] many times. However, due to burning, flooding, oxidizing and other reasons, the surface of unearthed painted Warriors becomes fading and shedding. Traditional skills in painting protection are facing three problems as following: (1) the breakthrough to printing and dyeing technology of ancient China. (2) The permanent preservation for painting. (3) The color restoration of large quantities of painted Warriors. In information age, it is an important research about how to use digital methods to achieve realistic recolor of color texture for faded Terracotta Warriors under virtual reality environment. The painted Terracotta Warriors model after recolor will has an important significance for the modern archaeological, innovative tourism and the inverse modeling of fade process for painting. In digital color restoration, ancient architecture color painting restoration and ancient painting restoration are typical, in which the former has its original painted pattern [2] as the restoration foundation, and the latter's problem focuses on image restoration algorithm [3]. But the research of color restoration for Terracotta Warriors has its own characteristics and problems.

Digital 3D model consists of two parts: geometry model and texture image. The latter reflects color information, and the texture image of faded Terracotta Warriors is gray. So the first problem for realistic color restoration of faded 3D solid is (1) the color restoration for gray texture, which is a process for Terracotta Warriors from gray texture to color texture, and relates to color image processing technology. Reference color texture image is selected from the partial residual recorded by digital tools from first scene and repaired painting works finished by hand painted expert according to historical data, as Figure 1

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[4] shown.

The residual painted recorded by digital tools

Painted Generals Warrior repaired by experts

Figure 1. Reference Color Texture Image

In terms of heritage, the key of color realistic restoration for 3D solid is the fitting to color texture and geometric model [5]. So the key problem of realistic color restoration for faded 3D solid is (2) the fitting to texture image after color restoration and the geometry model, which namely color texture mapping technology. Because the surface of Terracotta Warriors geometry is not a smooth flat, in order to reflect realistic, a reasonable perturbation is needed.

The work of this paper is to propose the technology framework of realistic color restoration for Terracotta Warriors based on problems of 3D model realistic color restoration which are color transfer of gray texture and bump mapping analyzed in before. And an improved algorithm based on color transfer is proposed to realize the color texture restoration for Terracotta Warriors in this paper.

2. Previous Works of Color Transfer

Color Transfer is an color transformation method based on statistics, which has been applied on ancient architecture color painting restoration [7], fading photo repair [8], medical image recolor [9, 10], video processing [11-14], *etc.* And its space foundation is $l\alpha\beta$ that proposed by Ruderman, *et al.*, [15] in 1998. Color transfer is a technology to realize the color transformation from color image to gray image by comparing the most similar pixel using operator between color image and gray image. Currently, the technology of color transfer is mainly summed up in three areas: the classic color transfer, statistical methods, and machine learning methods.

The classic color transfer is represented by Reinhard, *et al.*, [16] and Welsh, *et al.*, [17]. Reinhard, *et al.*, algorithm has achieved a good color transfer between color images, but in $l\alpha\beta$ color space, the α and the β have the same value for all pixels in gray image, of which the result is that the changed color information of reference image cannot be got by using it, so color transfer loses its significance. In Welsh algorithm, the color restoration of gray image is realized by searching match pixel, since only using the luminance value of pixel to match, there is match error among pixels which have the same luminance value but different color. This is also the point that will be improved in algorithm of this paper.

Color transfer technology using statistical methods is a histogram method [18, 19] and an adaptive color transfer [20]. First, in paper 18, local texture is described by statistical histogram. Second, there is a linear transformation for luminance channel of two images

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in the uncorrelated opposition color space. Then, pixel matching between images is completed by neighbor texture characteristics of pixels which are described by statistical histogram. This method has an advantage of small computation, while improving the accuracy of the matching pixels. However, there also has the problem of high consistency requirements about corresponding to the luminance and the color. The adaptive color transfer synthesis technology is based on statistics and proposed by Hu et al in paper 20. Its difference with the classic color transfer algorithm is the conversion for color space. It uses PCA theory to adaptively give color space transformation matrix rather than the original color space conversion using a fixed transition matrix, as while as taking advantage of the local statistics comparing to complete the transfer for local luminance and color texture.

In recent years, machine learning methods such as particle swarm optimization and genetic algorithms have been applied in many areas of digital image processing. In paper 9, many search algorithms of machine learning are applied on color transfer for medical images, in which the consistency and naturalness of recolor medical organs and tissues are achieved by constructing the fitness function of luminance and texture features for block source image and target image block. But there is a drawback of parameter-dependent.

3. The Solution of Color Restoration based on Color Transfer

On the ground of analysis to color realistic restoration in introduction, and combining with color transfer technology, the technology framework of color realistic restoration for Terracotta Warriors is proposed. As well as mixed color distance measure function is put forward based on neighbor eigenvalues to improve Welsh color transfer algorithm for matching error among pixels that have the same luminance value but different color.

3.1. The Technology Framework of Color Realistic Restoration for Terracotta Warriors

Starting from the faded gray Terracotta Warriors texture image, in this section, and the achievement of color restoration for texture image as intermediate process to restoration painting Terracotta Warriors, at last the specific methods of unresolved issues are elicited according to the two key existent problems in color realistic restoration of 3D Terracotta Warriors solid. The technology framework combining with the current mainstream technologies is shown in Figure 2.

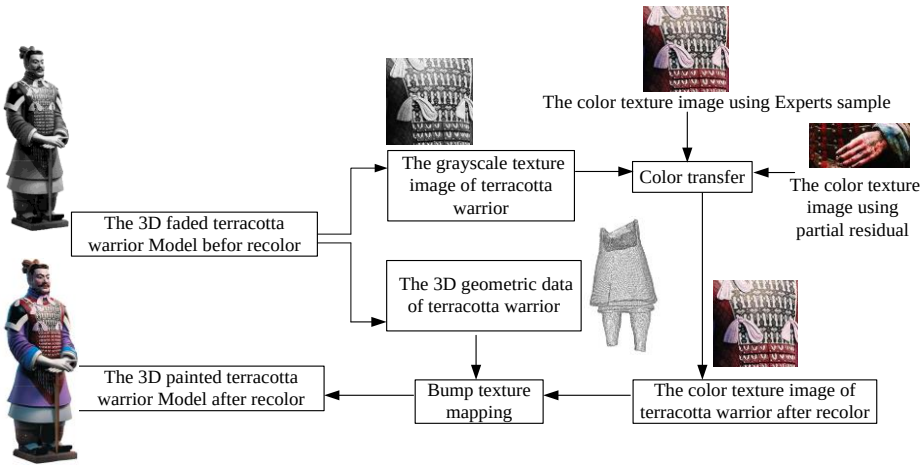

Figure 2. The Technology Framework of Color Realistic Restoration for Terracotta Warriors

In Figure 2, faded Terracotta model to be color restored is composed by geometric model and gray texture images. The first step in color realistic restoration is how to achieve gray texture repainting, that is gray image recolor problem. Color transfer that is a new technology in image processing can achieve color deliver between two images, and gray image recolor is an important content of it.

The color reference image from two sources: (1) the partial residual of color texture image recorded by digital tools in first scene, as shown in Figure 2. (2) A small amount of color texture of painted Warriors repaired by hand painted expert according to historical data, as shown in Figure 2. The color restoration of gray texture image for Terracotta Warriors is achieved by searching the most similar point using a suitable color distance operator in the color reference image for gray texture and by transferring color in the next.

Welsh algorithm is a typical algorithm in color transfer, in which faded gray image G is helped to learn and succeed color from color reference image C. The process of algorithm as follows:

Step1 Converting G and C from RGB space to $l\alpha\beta$ space (component l to save luminance information, component α and β to save color information);

Step2 Searching for the best match points by comparing the gray, and calculated as follows:

$$match_j = \min \left| G_{l_i} - C_l \right| \quad (1)$$

In the formula (1), the best match points of pixel i in G is be searched among C. Through subtracting respectively between G_{l_i} and each C_l, the best match points are pixels j in C corresponding with the minimum in subtracting.

Step3 Color Transferring from the best match points C_j to G_i.

$$\begin{cases} G_{\alpha_i} = C_{\alpha_j} \\ G_{\beta_i} = C_{\beta_j} \\ G_{l_i} = G_{l_i} \end{cases} . \quad (2)$$

Component α and β of C_j are transferred respectively to G_i through the formula (2), and the value of component l are kept.

Step4 Converting back to RGB space.

The second step is how to fit recolor texture image and 3D geometry model. Considering unsmooth characteristics of the geometry model surface, bump texture mapping is adept to achieve fit in technical framework. In bump texture mapping, through using Phong illumination model [21] what determined by reflected light to alter normal vector (also called luminance) of the geometrical model surface, visual bump is caused to show the true roughness sense of surface. Because the randomness of normal direction of Terracotta Warriors surface, there is a random in reflected light direction, and another fact is that luminance of the geometry surface is a function of normal vector. In 1978, Blinn [22] first proposed bump texture mapping technology, in which perturbation in surface normal is to generate rough surface for object. Its parametric equation is expressed as follows:

$$S'(u,v) = S(u,v) + R(u,v)N \quad (3)$$

The formula (3) includes mathematical functions about perturbative surface for geometric model of Terracotta Warriors, in which S means smooth surface, R means perturbation function, N is normal vectors of S, S' is surface after perturbation. Through perturbation normal vectors are:

$$N' = (S_u + R_u N) \times (S_v + R_v N) \quad (4)$$

S_u and S_v are partial derivatives of S along the direction of u and v respectively, the same time R_u and R_v are partial derivatives of R along the direction of u and

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v respectively, and here $R(u,v)$ is any derivative function. Based on the principle of Blinn, there are a variety of bump technology followed. For example emboss bump mapping, dot-product bump mapping and parallex bump mapping.

The key problems of color realistic restoration to be solved for terracotta model are recovered as follows:

(1)Color transfer based on partial residual and expert sample;

(2)Bump texture mapping of color realistic restoration.

3.2. Mixed Distance Measure Function based on Neighbor Eigenvalues

In Welsh algorithm, pixels are matched by using luminance value to achieve recolor for gray image, but in gray image, the case is that there are often a large number of pixels have the same luminance value which may correspond to the same color or different color. When the latter case, error matching will be occur in Welsh algorithm. For improving the error matching of different color pixels which have the same luminance value, the similarity of neighbor matrix, the deviation degree to pixels in neighbor matrix and luminance value are used together in this paper to decide matching. The similarity of neighbor matrix and the deviation degree to pixels in neighbor matrix are described respectively using eigenvalues and variance of matrix, and mathematical expression of eigenvalues as follow:

$$\left|\lambda E - A\right| = 0 \tag{5}$$

neighbor matrix of 5×5 is selected and denoted by A. The formula (5) represents the characteristic equation of neighbor matrix，λ means neighbor eigenvalue, E means identity matrix. The characteristic equation is a solving problem of polynomial of n, and its roots λ are all eigenvalues of n order matrix A. Commonly used numerical methods for solving eigenvalue are [23]: power method, inverse power method, and Jacobi method. In this paper, eigenvalue is calculated by Matlab function.

The mathematical expression of neighbor variance is shown in equation (6).

$$\mathrm{var} = \frac{1}{n^2}\sum_{q=1}^{n^2}(a_q - \frac{1}{n^2}\sum_{q=1}^{n^2} a_q)^2 \tag{6}$$

In which, n take 5，n^2 means the number elements in 5×5 neighbor matrix，var means the variance of pixel a in 5×5 neighbor matrix, and $\frac{1}{n^2}\sum_{q=1}^{n^2} a_q$ is the average of neighborhood. Neighbor variance can reflect the dispersion of all elements in neighbor matrix, and also is the measure of dispersion degree for average of elements in neighbor matrix. The bigger value, means the larger differences between the luminance value and its neighbor average, also means the bigger color change and the higher gap between elements in neighborhood. The smaller value, means the closer of luminance value to its neighbor average, also means the smaller color change and the lower gap between elements in neighborhood. So, neighbor variance can reflect the related degree for a point and its neighbor color change.

In color transfer, gray texture image is called source image, and reference image is called target image. Mixed color distance is got by combining luminance value, neighbor eigenvalue and variance as equation (7).

$$m\_d = \frac{(a_{ij} - a'_{i'j'}) + (\lambda_{ij} - \lambda_{i'j'}') + (\mathrm{var}\_a_{ij} - \mathrm{var}\_a'_{i'j'})}{3} \tag{7}$$

In which $1 \le i \le M, 1 \le j \le N$ ， means the scope of source image and target image. a_{ij}, λ_{ij} and var_a_{ij} are luminance value, neighbor eigenvalue and variance of source image a_{ij} respectively. $a'_{i'j'}, \lambda_{i'j'}'$ and $\mathrm{var}\_a'_{i'j'}$ are luminance value, neighbor eigenvalue and

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variance of target image $a'_{i'j'}$ respectively. The average of difference of them is took as color distance, the smaller the value, the closer color distance for two pixels, and more color matching. Equation (5), (6) are brought to equation (7) and the result can be simplified. The mixed color distance measure function as equation (8):

$$H_{m\_d} = \min \frac{n^2(a_{ij} - a'_{i'j'}) + n^2(\lambda_{ij} - \lambda_{i'j'}') + \sum_{q=1}^{n^2}(a_q - \frac{1}{n^2}\sum_{q=1}^{n^2} a_q)^2}{3n^2}, 1 \le i \le M, 1 \le j \le N. \quad (8)$$

4. Experiments

Expert repaired color method in addition to three issues having been analyzed in introduction, another issue is that there is mottled phenomenon in repaired image, shown in Figure 3.

Figure 3. The Mottled Color Image Repaired by Experts

so it cannot meet the requirements of visual virtual display. For verification the performance of the improved Welsh algorithm to restoration gray texture image for faded Terracotta Warriors under the technology framework of realistic color restoration, there is a comparison between classic Welsh algorithm and the mixed color distance measure function in experimental part.

4.1 Experiments Results

Under the technology framework of color realistic restoration for Terracotta Warrior and based on color transfer technology, faded texture images are achieved restoration in experiment. Here faded images are called source image, while reference color images are called target image. First, $l\alpha\beta$ color space is used to color transferring. Then the color matching relationships between source image and target image are determined by the mixed color distance measure function. Last, color transferring is completed between matching pixels. Classic Welsh algorithm and improved algorithm of the mixed color distance measure function are used respectively for natural scenery texture, faded texture of arm armor based on expert repaired image, and faded texture of face based on residual color. The results are shown in Figure 4-6.

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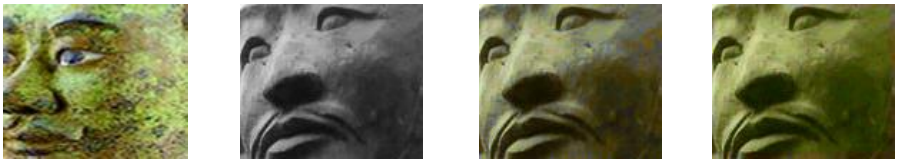
Target image 1-color | Source image1-gray | color transfer effect of welsh algorithm | color transfer effect of the paper’s method

Figure 4. Color Restoration for Natural Scenery Texture

Target image 2-color | Source image2-gray | color transfer effect of welsh algorithm | color transfer effect of the paper’s method

Figure 5. Color Restoration for Faded Texture of Arm Armor based on Expert Repaired Image



Target image 3-color | Source image3-gray | color transfer effect of welsh algorithm | color transfer effect of the paper’s method

Figure 6. Color Restoration for Faded Texture of Face based on Residual Color

4.2. Discussion

Seen from the effect of color restoration for three pieces of grey texture image, the method of this paper is better to achieve color transfer than classical Welsh algorithm. In which, Welsh algorithm has obvious color distortion in grassland part of Figure 4, while the method of this paper has a realistic restoration grass. To the painting of Figure 5 which has hierarchical structure, the blue of the Welsh algorithm after color transfer is far from the purple in target image, while the method of this paper is close to color of the target image. About restoration for faded texture of face in Figure 6, the method of this paper is obviously better than the Welsh algorithm in realizing green face.

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5. Conclusion and Future Work

In this paper, under the specific application of color texture restoration for faded Terracotta Warrior, the technology framework of color realistic restoration for Terracotta Warriors is proposed combining technology of color transfer and bump texture mapping from the graphic point of view. And two key problems of color restoration for faded 3D model are summarized. Then an improvement is proposed for color transfer technology which is the first problem in the technology framework. In experimental part, there is a comparison for restoration effect between classical Welsh algorithm and the improved method, and the results show that the improved method can good achieve faded texture restoration for painted color which has hierarchical structure. But a relatively satisfactory restoration effect is the increased cost of computational. How to ensure the restoration effect and save computing cost is a question for further study. At the same time, gray texture after restoration needs to be fitted with geometry model in color realistic restoration of 3D model that is the second key problem-bump texture mapping.

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