DUNHUANG ART CAVE VIRTUAL REBUILDING AND NAVIGATION

Applying multimedia, intelligence and design technologies in Dunhuang arts

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Abstract. Dunhuang Art Cave is confronted with the serious influence of natural forces. Integrating Multimedia, Artificial intelligence and CAD, we can virtually preserve and reproduce the original cave architecture, painting sculptures and murals. This paper first introduce the main ideas of Dunhuang cave virtual rebuilding, cave virtual navigating, mural color restoring as well as Dunhuang-style pattern designing, and then analyzes in detail their technical issues and show results of prototype systems. In the end, we give a brief summary.

Introduction

Dunhuang Art Cave (DAC), which is located near Dunhuang, Gansu province, northwest of China, includes three cave sites: Mogao Grotto, Yulin Grotto as well as West-thousand-Buddha Grotto. Presently, there exist more than five hundred caves ranging from the Northern and Southern Dynasties to the Yuan Dynasty, which comprise about fifty thousand square meter murals and about three thousand painting sculptures. It is one of most famous cultural heritage sites in the world, and has provided plentiful material for researching into Chinese ancient art, history, culture and so on. Three most important components of DAC are architecture, mural and painting sculptures, which possess not only great artistic value but also profound cultural significance. Therefore, DAC was established as a national key culture relic by the State Council of P. R. China in 1961, and was also named as World History and Culture Heritage by UESCO in 1987.

As located inside the desert area, DAC is confronted with the serious influence of natural efflorescence and disaster. How to preserve, investigate and exploit the cultural heritage is a very important subject. Presently, the experts of Dunhuang Academy have already carried out a lot of projects, which investigate cultural relic preservation, restoration, reinforcement, achievement as well as management. These projects involve environment measurement and analysis, mural pigment analysis and pigment fading test, material for restoration and reinforcement. In particular, computers come to be used to restore and manage the digital mural images with a high resolution.

However, how to fundamentally solve the preservation problems of DAC and speed up the investigation and exploitation of the cultural relics is still a very complicated and significant engineering task.

Fortunately，the rapid development of information technologies continue to invent new methods for preserving, investigating and exploiting DAC. The purpose of our project is just to provide new tools for DAC through synthesizing CG, VR, CV, MM, AI and Network technologies. In the following section, we will discuss Cave Virtual Rebuilding, Cave Virtual Navigating, Mural Color Restoring and Dunhuang-Style Pattern Designing respectively.

2. Cave Virtual Rebuilding

Virtual Rebuilding System (VRS) is developed to provide various effective facilities for digital preservation and investigation. VRS will be a good assistant of researchers, and will greatly improve their work efficiency and quality. Cave modeling is the basis of virtual rebuilding. Presently, there exist many commercial modeling tools, such as 3Designer (Alias/Wavefront), Designer, SoftImage and Cosmo Creator. Besides, the VRML is also a perfect modeling protocol of virtual reality on Internet.

As most objects have ample details and complex architecture in real applications, it is a very complicated task to modeling objects in detail. People begin to develop new methods to help complex modeling. Now, there are two main approaches: rebuilding based on 3D scanning (using 3D-scanners) and rebuilding based on depth images (depth images taken from many different viewpoints)(Brian C, 1996). These methods can not only reduce the workload of modeling, but also make modeling easier.

In the following, we will introduce the pivotal problems in our research.

2.1. THE DEFINITION OF DAC MODEL

According to the different architectural designs, we can divide caves into five main types: Nirvana Cave, Central Pole Cave, Big Buddha Cave, Back Screen

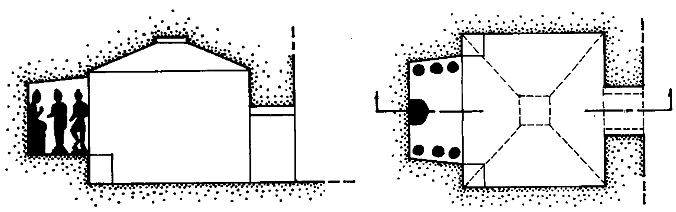


Figure 2.1 the platform and side view of a sample cave

Cave and so on.

As shown in the left figure, we can see that these cave designs are quite similar: all are composed of front room, back room, corridor, pole/alcove, roof, painting sculptures and so on. Their architectural designs are regular, except for some complex Buddha niche and painting sculptures, so the modeling of cave designs is relatively easy.

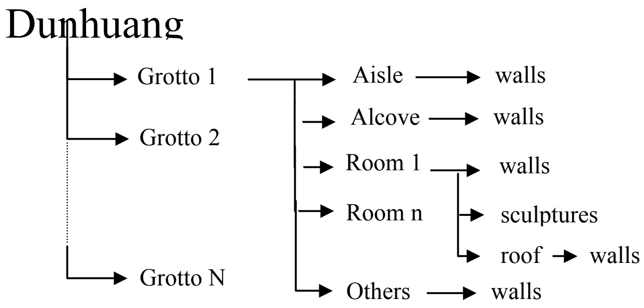


Figure 2.2 cave

We modeled the caves using VRML protocol, because it is easy for browsing on the net. 3DMAX, HomeBuilder, VRCreator and SuperSpace on PC can help us model. We used 3DMAX modeling together with mural textures to represent the cave designs.

2.2. MOSAIC OF MURAL IMAGES

The Dunhuang Mural is an important part of DAC. In order to obtain good impression, the murals on each wall are composed of more than 50 overlapped photo images. Therefore we need to solve the problem of mosaic.

For the planar mosaic, the images from one same plane are merged via a 3x3-transform matrix. We have two methods to get the matrix: one is manual and the other is automatic. With the manual method, we need to set up corresponding relationship of four point pairs between the two images. From the four point pairs, we can get eight linear equations, and then get eight projection matrix parameters. This method can get very good results, but it depends on the user's skill. Besides, if we have lots of images, then finding the corresponding points will be a complicated task. So we use the automatic method—Graig method (Craig G,1996). Computers can get the matrix automatically. Its basic principle is to compute the square sum of the pixel intensity differences between the two images, then choose the least one. The formula is as follows:

$$E = \sum_i [I'(x_i', y_i') - I(x_i, y_i)]^2 = \sum_i e_i^2$$

Due to the diversification of illumination, image distance and overlapping areas, some images have gradient distortion and magnitude differences. In our experiments, we divided the photo images into three groups according to their different conditions (see Fig. A.1 in the appendix A). We found that if the images had more overlapping areas, we could get better effect. Furthermore, the changes of image distortion, rotation and chromatism have great influence on the effect of mosaicking.

From experiments, we think there are two main causes for the effect of mosaicking. First, the method has some limitations, because it merges the images through matrix, which is correlated with the difference of intensity. There will be some abnormal matrix, which makes the square sum of the pixel intensity differences smaller (maybe smallest), but it is not the correct mosaic matrix, especially for images with less color contrast. And fewer overlapping areas will also raise the more possibility of errors. Secondly, because of the long history, Dunhuang murals often have the fading problems, which makes the color of murals flatter and the contrast of murals less. So the mosaic of images is very difficult.

If we make the overlapping area between images bigger, the error will be smaller. So in our practice, we use 'local mosaic' strategy. Here is the basic principle. Suppose the shadow of image A is the overlapping area between image A and image B. First we intercept part of A as C. Suppose the position of C in A is (x, y), then we compute the transform matrix M' using C and B. C is part of A, so C and A have homologous transform. Then the mosaic between A and B is accomplished. We test the last pair of images of the first group, getting very good results (see Fig. A.2 in the appendix A)

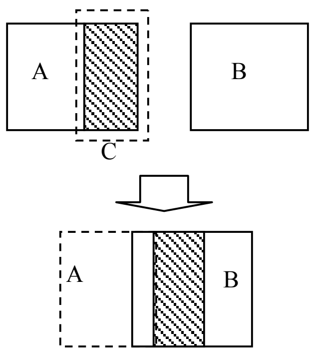


Figure 2.3 Local mosaic

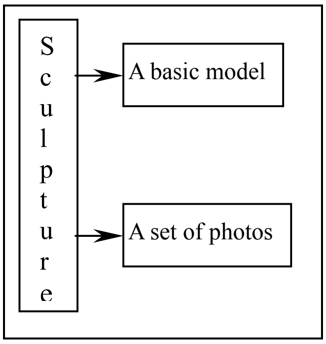
2.3. 3D MODELING BASED ON 2D IMAGES

Besides the mural, another art form of DAC is the painting sculpture. Due to their complex appearances, it is very difficult to make solid modeling of the painting sculptures. We use image-based rendering to express the sculptures of DAC.

IBR uses 2D information to represent the 3D scene. Now there are many researches on IBR. According to the different preconditions of images and process modes, we divide the IBR technique into four types: methods based on the panoramic view (Chen S.E, 1995), methods based on morphing (Seitz S.M, 1996), methods based on depth image information (Stephane L, 1995), as well as methods based on Light Field information (Steven J.G., 1996;Marc L, 1996). Each method has their unique features, but most of them are inefficient except for panoramic view based methods.

The model of one sculpture is shown in the left figure. Due to restrictions of the location (i.e. the distances between sculptures are very small), It is impossible to take the photos of sculptures from different viewpoints. We use morphing to solve the above problem.

The Field Morphing Method is based on the feature lines in images. The following figure is showing the morphing result of the head part of the sculpture in cave No. 85.



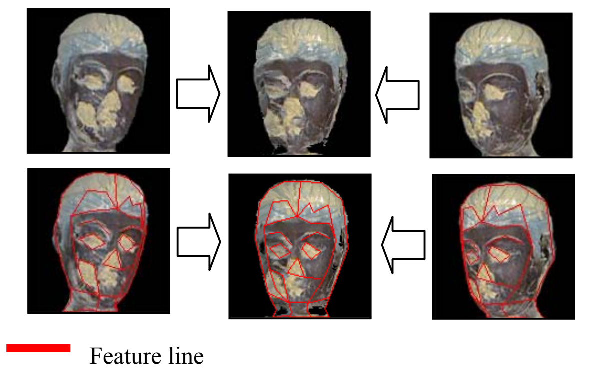


Figure 2.4 morphing based on feature lines

Using the above techniques, we have accomplished the modeling of 3D-construction architecture of DAC. But the main problem is that many minutial appearances have not been completely elaborated, such as the Buddha niche 's embellishment structure. Because of the limitations of image information, we can't guarantee the precise expression when applying 2D images to model 3D sculptures. We believe that it only can attain a better effect relying on 3D modeling, but it needs a great deal of artificial operations. However, taking the advantages of image information can solve the modeling problem, but will lose some 3D features.

In the next step, we will continue our works in several aspects, including constructing more accurate 3D models according to the original data, applying three-dimension reconstruction based on two-dimensional images to present some complex details, and preserving image presentation for local models.

3. Cave Virtual Navigating

Cave Virtual Navigating System (CVNS) will be a new tool to investigate the arts of DAC, and let more people enjoy the DAC. We integrate VR technology and DAC models to support virtual navigating. Since its birth in the 1940's, VR has been continuously developing. Technically**,** VR provides better apperception and display environment by keeping improving the performance of hardware, such as CAVE, HMD V8, and enhances the three dimensions of the environment and the efficiency of rendering by improving the rendering technology, such as SuperScape, SGI CosmoCreate, Paragraph Homebuilder, and QuickTime VR. In applications, VR has gained enormous achievements in many fields, such as data visualization, manufacture, education and training, medical treatment, historic sites, art, entertainment, architecture and so on. In the following subsections, we will discuss three key problems in navigation.

3.1. DEFINITION OF NAVIGATING METHODS

According to the navigating requirements for DAC, we defined two main methods.

Free navigation by user controls provides six free degree movements in the virtual space by user interactive controls, such as keyboards, mouse and so on. According to the parameters of the user's eye location, we project the cave model in such environment to create the scene. Also, we provide two control modes: one is continuous movement, and the other is jumping movement.

In pilot navigation by a specified path, the user will walk in the virtual cave according to the preset visiting path. The paths can be created by users with a certain tool, or recorded while users are navigating using the first method. It will record all the scenes changed during this navigation, and replayed in future. Obviously, this method can provide better display performance.

3.2. SCENCE RENDERING

The scene rendering is one of the most important problems in the virtual navigation system because it will directly affect the navigating performance, with a refreshed speed and the impression of three dimensions. In our system, we use two main technologies: one is the cave model rendering based on LOD, and the other is the painting sculpture rendering based on 2D images.

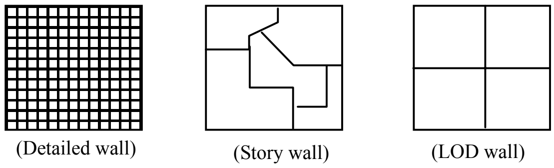


Figure 3.1 multiple layer models

In order to get good rendering impression in navigating, we must use the higher resolution textures. Certainly, they will reduce the rendering efficiency. So, we adopt the multi-resolution method to represent textures. We design multiple layer models of murals: one is the LOD model of murals, and the other is the story model of murals. During rendering, system will choose the corresponding cave model architecture according to the eye location. The cave story model is used for the efficient mural retrieval.

In the previous section, we have discussed the painting sculpture's model based on 2D images. In rendering, we just use this model to render painting sculptures. First, we should build a transparent template for supporting image textures, such as a rectangle. During navigating, this template will keep facing the user all the time with changes in the image textures according to the user's eye location. Figure 3.2 will show the method:

The mechanism of choosing photos: given a set of photos which are 360 degree views about the object O including those got by morphing. We assume there are N pieces of photos all together, tagged as 0, 1, 2, . N-1。And the interval angles between two contiguous photos are all the same, named as α, so $\alpha = 360 / N$. The coordinate of O is (Ox, Oy, Oz), and the eye location is (Vx, Vy, Vz),

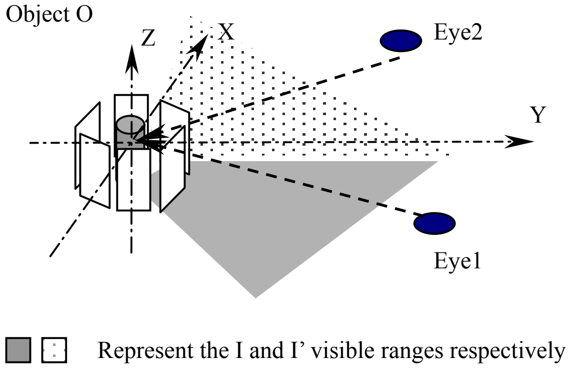
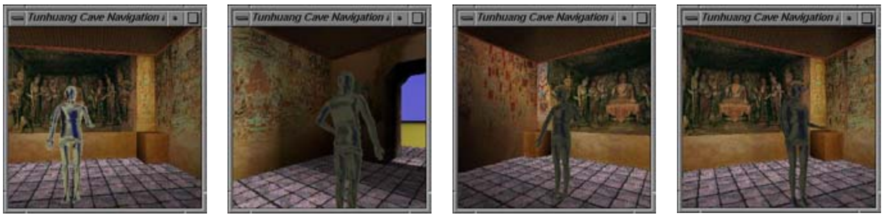


Figure 3.2 Painting sculpture rendering based on images



We use a set of 72 photos to represent the sculpture. The above images are taken from four viewpoints. 3DS MAX renders this sculpture.
Figure 3.3 painting sculpture rendering in the system

then Tangent θ = (Vx – Ox) / (Vy – Oy), if θ < 0; θ = 360 +θ, so the correct photo should be the one tagged with 'num', num = [θ / α]. It's easy to develop this solution to a full degree, that means to get both horizontal and vertical photos. So we can say if we have got enough photos, we will get a continuous movement in such environment. Figure 3.3 gives some samples from our system.

3.3. SHADOW OF PAINTING SCULPTURE

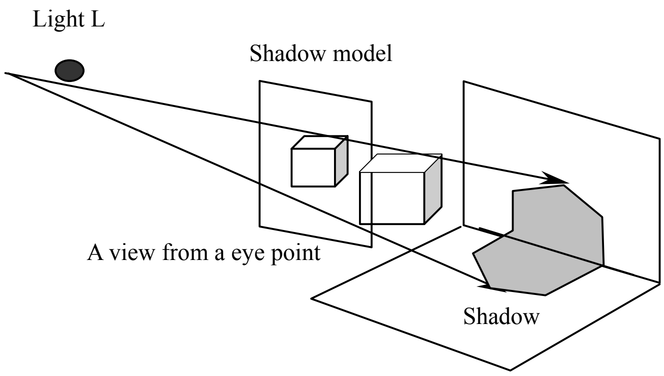


Figure 3.4 shadow of IBR object

For the painting sculptures of DAC, it's hard to generate shadows with rendering based on images because those sculptures have no 3D architecture. Bishop [Manuel M (1997)] studied a lighting database used to record all the scene information according to each light. This is used to resolve the 'Light Field Rendering'. But this needs a huge database and burdensome data collection. Here, we will introduce our idea: that is to use a simple model generated from the original object to play as shadow models (As shown in the figure above). During rendering, we use images of the sculpture to represent the 3D sculpture and project this shadow model onto other objects. So we can not only avoid computing the complex shadow but also support the dynamic lights with low influence on the performance.

Based on the above technique, we have implemented a prototype system for Dunhuang cave virtual navigating (refer to the fig. A.3 in the appendix A). We can see this idea does work although there are still some limitations. We think there are two main aspects that we will study more in future:

(1) Improving rendering efficiency**.** In Dunhuang cave virtual navigating, the main bottleneck is the requirements for rendering with high-resolution textures and plenty of painting sculptures. Integrating the 3D models and 2D images to represent the painting sculptures will improve the rendering speed.

(2) Enhancing 3D display**.** Shadows are always the key problem, especially for the object rendered based on IBR technology. We have only studied the hard shadow until now, but in the real world, most of shadows are soft ones. This will be our another future focus.

4. Mural Color Virtual Restoring

Mural Color Virtual Restoring System (MCVR) will be a very effective tool to investigate mural painting domain knowledge, pigment fading laws as well as rules of artists and painting skills. We integrate artificial intelligence and image processing techniques to develop an interactive system to restore the color of fading murals.

The related image processing technologies include the choice of color space(R. Weeks and G. E. Hague, 1997; Y. Kansi, 1998; H. Levkowitz and G. T. Herman, 1993), color image segmentation (A. Moghaddamzadeh and N. Bourbakis, 1997; R. P. Schuemyer and K. E. Barner, 1998; A. Tremeau and N.

Borel, 1997), edge extraction (D. Zugaj and V. Lattuati, 1998; E. Saber, A. M. Tekalp, G. Bozdagi, 1997), and so on. The reasoning based on rules, frames, and analogy, and the organization and representation of knowledge are the main artificial intelligent technologies used in our system. In this section, the analogy-based approach for color restoration will be introduced. The others are shown in the reference (D. M. Lu, X.Y. Li, B.G. Wei and Y.H. Pan, 1998).

4.1 COLOR VIRTUAL RESTORING BASED ON ANALOGY

The color changing extent of a lead pigment isn’t the same under different environment conditions. For example, there are two murals, whose contents are similar, in the 428th cave. The one toward the sun has been more seriously faded. Its yellowish pink color has changed into gray and vermilion changed into black. But the other remains original bright color because the niche for a sculpture of Buddha keeps out sunshine. The phenomenon arouses us to restore color-changing mural by analogizing colors between these two types of mural. In addition to the murals in the same cave having similarities, the murals, which are not in the same cave but were painted at the same age or dynasty, can be analogized. Because one type of painting skill which was widely used in one dynasty could be inherited by the artists after that dynasty, the murals, which do not belong to the same age or same dynasty but were painted using similar skill, can also be analogized. Therefore, to store and utilize the murals whose colors have not been changed seriously is one of the main functions in our system.

The steps to restore a color-changing mural based on analogy (see Fig. 4.1) are as follows:

(1) Input a color-changing mural and its feature attributes;

(2) Retrieve the reference images from the database through analogy retrieving;

(3) Separate the color and segment the object from the color faded mural image and the reference image based on the color which are relative to color restoration;

(4) Determine the color transformation relationship between the restored color and the faded color and implement the color restoration;

(5) If the result is not satisfied, return to the first step again.

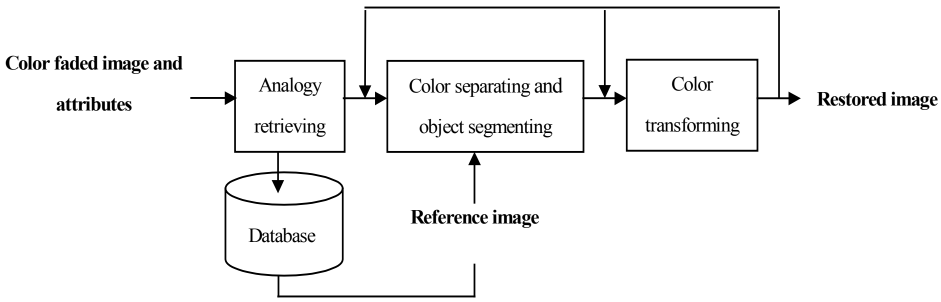


Figure 4.1 Color restoration based on analogy

4.2. DATABASE ORGANIZATION AND ANALOGY RETRIEVAL

As an analogy source, the image data and feature attributes are stored in the database. In order to retrieve the reference image from the database quickly and accurately, it is important to determine which feature attributes would be contained in the database and how the database is organized.

In addition to image data, we classify the database into three levels. They are called the color structure level, the painting skill level, and the environment condition level. On the color structure level, images are organized according to caves, ages, dynasties, and other features that determine the overall distribution of mural color. On the painting skill level, images are organized according to the murals' topic, content, style, and painting skill. On the environment condition level, images are organized according to the features that affect the extent of mural discoloration. They include the cave's size, temperature, humidity, sunshine, position, and so on. All images in the database are chained on the three levels. Actually, each chain and the feature attributes defined on it are an abstract expression of the mural color knowledge.

The analogy retrieval can be processed on a single chain or several chains simultaneously. Generally, the retrieval results obtained from multiple chains are more valid than from the single chain. However, it is more difficult to obtain results by the multiple chains retrieval because it usually has more restrictive conditions. At that time, the single chain retrieval is the only choice.

Each chain and its feature attributes are given different weights. Set i for chain. Then the chain's weight is ω_{Li} and its j th attribute's weight is ω_{Aij} . When there are more than one reference images to be retrieved, these reference images are arranged in size order of the sum of their attribute weights. The formula is:

$$S = \frac{\sum_{i=1}^{3}(\omega_{Li}S_{Li} + \sum_{j=1}^{n}\omega_{Aij}S_{Aij})}{\sum_{i=1}^{3}(\omega_{Li} + \sum_{j=1}^{n}\omega_{Aij})}$$

Where S_{Li} and S_{Aij} are used to express whether or not the chain and the attribute between the input image and the reference image are matched respectively. If they are matched, its value is 1. Otherwise its value is 0.

4.3. COLOR SEPARATING AND OBJECT SEGMENTING

A mural is composed of a set of patterns and each of them is composed of objects. Each object usually has its color or hue accurately. The color restoration of a mural is not directed against all of the colors and its aim is to restore the colors of lead pigments. In order to be convenient for color restoration, we first separate a mural image into several levels so that each of them has a hue and then extract objects on each level.

Separating a mural into multiple color levels can be fulfilled automatically based on its color histograms or manually by the user. Object segmenting or region extracting is based on the approach of region growing. Fig. 4.2 shows a result of color separating and object segmenting. For the region growing, the user indicates the location of seed by positioning it on the screen image. The following two criteria are used to determine if a pixel belongs to a region.

$$\begin{cases} d_{ptp}(C_i, C_j) \le \delta_{ptp} \\ d_{ptr}(C_i, \overline{C_R}) \le \delta_{ptr} \end{cases}$$

where C_i is the color value of pixel i. The color value of the pixel's neighborhood is C_j. $\overline{C_R}$ is the average color value of the growing region. δ_{ptp} and δ_{ptr} are the thresholds.

Figure 4.2 The result of color separating

4.4. COLOR TRANSFORMATION

After extracting color regions from the input image and the reference image, color histograms corresponding to the two color regions can be generated in the HSI color space and their color distributions can be known. We adopt a simple linear transformation method to determine the color of pixels in restored region. Set (HM_s, SM_s, IM_s) and (HM_c, SM_c, IM_c) are the extrema of H, S, and I at the peak of the color histograms of the input image and the reference image respectively. The color of pixel i in the restored region can be calculated using the following formula:

$$\begin{cases} h_i = HM_s \\ s_i = s_i + (SM_s - SM_c) \\ I_i = I_i + (IM_s - IM_c) \end{cases}$$

In Figure 4.3, there are three images used to show the color restored result of a person's skin. The left image is the color changing one, the middle is the reference one retrieved from the database, and the right is the restored result.

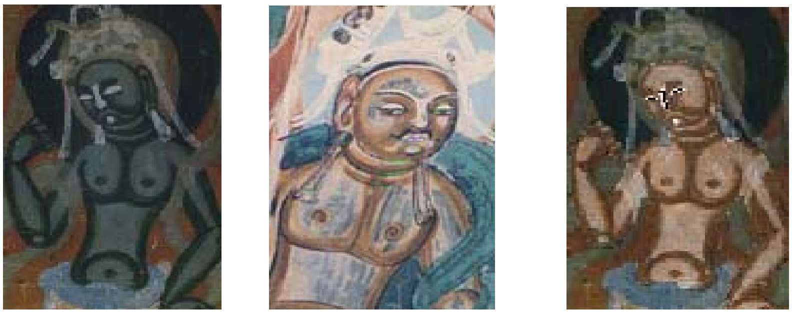


Figure 4.3 The restoration of color changing mural

Based on the above techniques, a prototype system has been implemented to virtually restore the colors of murals based on analogy. Color processing accords with the way humans see color because the HSI color space is chosen. The restored color keeps the color level relationship of the original image.

Although the color restoration is good in general cases, the linear transformation approach does not achieve ideal effect in the region whose hue changing is severe. The mural image is more difficult to process than other types of image because of covering and penetration between different pigments as well as the partly dropping of pigments. Our further work is to find the nonlinear color transformation approach and the color image processing techniques which include the computation of the color difference between two similar hues, the choices of weight values for different color parameters in the conversion from one to other spaces, and so on.

5. Dunhuang-Style Pattern Designing

Intelligent pattern design system will provide new methods for Dunhuang pattern research and applications. Since the sixties, computer aided pattern design technologies have developed into several main methods, i.e. Algorithm Based Technology, Interaction Based technology, Knowledge Engineering and Expert System Based Technology (F. Lin, Z.J He and Y.H.Pan, 1987), and Synthesis Based Technology (Y.H. Pan, 1996).

We have improved our existing pattern design techniques and systems based on features of Dunhuang murals. In the following subsections, some key techniques will be discussed.

5.1. ANALYSIS OF DUNHUANG PATTERN STYLE

In order to design new patterns with a Dunhuang style, we should extract the style features from the plentiful typical patterns in Dunhuang murals, and represent them. Presently, we have described a pattern's style in the following aspects:

(1) Pattern content. Murals in different caves with the same topics generally were painted in similar composition and contain elements of the same types. For example, the Illustration of Maitreya on the eastern wall of cave No. 9 is quite similar to another one on the southern wall of cave No. 148. Therefore, the content of one mural will be important factors to define a style.

(2) Geometric composition. Most murals with the same contents generally have unique forms in layout. For example, patterns on the ceiling have a fixed geometrical layout. Therefore, geometric composition of a pattern is another important factor to define a style.

(3) Color composition. After the evolvement of about one thousand years, the colors of Dunhuang mural have some particular lasting appeal on the whole. Then, the color feature will be one factor to define a style.

(4) Elements of pattern. Elements of Dunhuang murals also have a unique lasting appeal. In a sense, elements can reflect the style of one pattern. For example, apsaras is the typical mark of Dunhuang murals. So, elements can also be used to define a style.

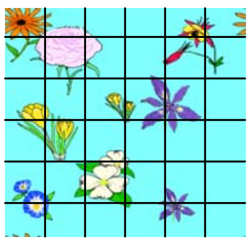
5.2. MULTI-LAYERS PATTERN STRUCTURE REPRESENTATION

According to the above analysis, we propose a multi-layer structure to represent Dunhuang murals, including content. composition and elements. Then, the pattern knowledge can be defined as three-tuple as follows:

$$K=<D, M, E>$$

where D is the description of pattern content, M is the structure of pattern composition and E is the elements used in the pattern.

(1) Content description: It contains the text description for pattern content, including title, hue, purpose as well as a set of sample patterns.



$$\begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Figure 5.1 pattern and its composition matrix

(2) Composition structure: It uses the matrix model to represent the lattice of pattern and also contains some layout features, i.e. lattice symmetry degree, lattice denseness, element proportion, rotating angle, shear degree etc.

(3) Elements set. It contains all elements' features and the sample elements, i.e. apsaras, honeysuckle, pegasus and etc.

5.3. RULE BASED PATTERN DESIGN

The pattern design is based on the rule inference process, which is shown in fig. 5.2

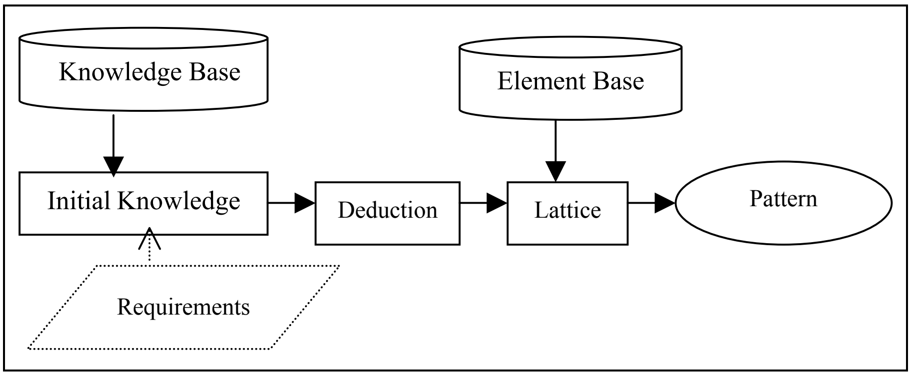


Figure 5.2 Model of Pattern Design

According to the design requirements for a pattern, the system first generates the initial knowledge $K_0 = <D_0, M_0, E_0>$, which represents the requirements. According to the design requirements, the system first will select one or several items of initial knowledge from the knowledge base to obtain initial knowledge set $K_{init}=(K_i, i=1...n)$. Then the system will be deduced to get the pattern's lattice. Finally, the system will select proper elements from the element base and place them in corresponding positions, and then get the pattern.

5.4. DISCUSSION ON DESIGN RESULTS

The first example is a plain-chess pattern (Appendix B, Fig. B.1). Here, the requirement is to design a pattern with the style of chess. The system has used the layout style of cave No. 428 and only changed the elements.

The second example is a pattern reflecting the scene about animals and the rising sun (Appendix B, Fig. B.2). Here, the requirement is to use various animal figures as elements. The system has used the local mural on the eastern top of cave No. 285 as the template.

The third example is a group-flower pattern (Appendix B Fig. B.3). Here, the requirements are to use the layout of ceiling pattern and to use flowers as elements. The system has reflected the style of pattern on the top of cave No. 320.

Presently, we have summarized more than several kinds of Dunhuang pattern geometrical layout and hundreds of Dunhuang pattern elements. But, these are still too few, compared with the plentiful Dunhuang murals. We will continue our work in the following aspects:

(1) Further investigate the pattern style of DAC and collect more typical layouts and elements.

(2) Deal with Dunhuang mural color style processing in pattern designing;

(3) Invent new design mechanism to overcome the limitations of rule inference.

5. Conclusion

Integration of multimedia and intelligent techniques can supply new ideas, technologies and tools for the preservation, investigation, restoration and design of DAC. With DAC as the application background, we have investigated and developed a series of key technologies.

(1) Mosaicking of adjacent mural photo images;

(2) 3D modeling of painting sculpture based on 2D photo images;

(3) Mural rendering based on LOD and painting sculpture virtual view generation based on 2D photo images;

(4) Painting sculpture shadow dynamic process based on the modeler;

(5) Analogy based virtual mural color restoration;

(6) Rule based Dunhuang style pattern design.

Based on the above technologies, we have implemented the prototype systems, such as Dunhuang Cave Virtual Rebuilding and Navigation System, Dunhuang Mural Color Interactive Restoration System, Dunhuang Style Pattern Intelligent Design System, etc. The experiments have shown the effectiveness of key technologies as well as their limitations. We are now researching into new approaches to overcome the limitations.

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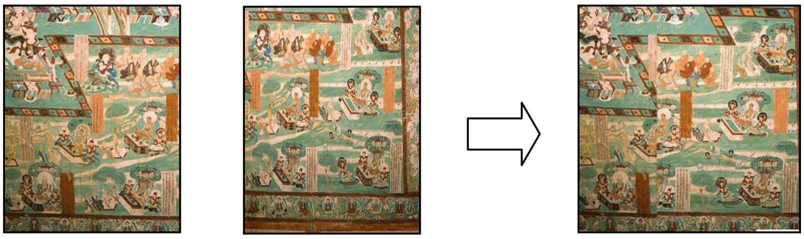
Appendix A

Good samples



Bad sample

The last sample has fewer overlapping areas, so the result isn't as good as the former two.

Figure A.1 Dunhuang murals mosaicking samples

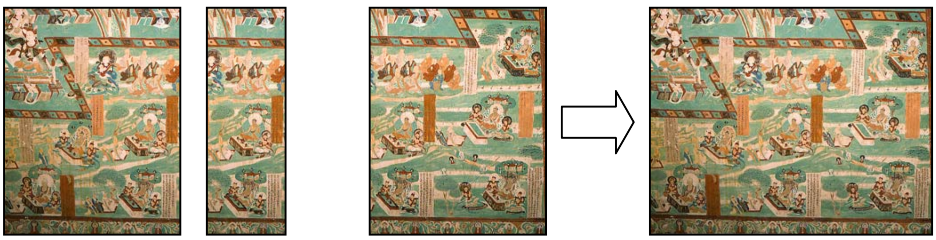
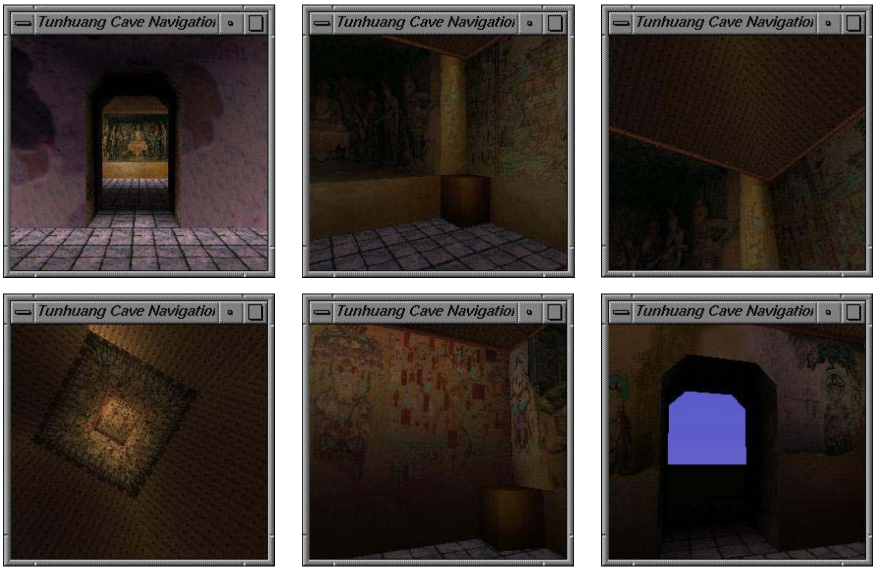


Figure A. 2 local mosaicing sample



These six images show the snapshots from defferent view points with ‘roof lamp’ lighting modeling

Figure A.3 some demo views from the navigation system

Appendix B

The left one is designed by the computer, while the right one is taken from cave 428.

Figure B.1 Plain-Chess Pattern

The left one is designed by the computer, while the right one is taken from cave 285.
Figure B.2 Animals and the Rising Sun

The left on is designed by the computer, while the right one is taken from cave 320.
Figure B.3 Pattern on the ceiling