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Virtual Dunhuang Mural Restoration System in Collaborative Network Environment

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Abstract

This paper introduces a virtual Dunhuang mural restoration system in collaborative network environment. It describes the style of Dunhuang mural, analyzes the reasons of mural spoilage, and presents the necessity to develop a collaborative mural restoration GroupWare. It describes the components and the workflow of mural restoration in detail, solves some key technologies in the system. In the end, it introduces the system architecture, and presents the system interface and some restored results.

1. Introduction

Dunhuang Art CAVE (DAC),which is situated beside the city of 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 Sixteen Counties (A.D. 304-439) to Yuan Dynasty (A.D. 1279-1368), which comprise about fifty thousand square meter murals and about three thousand painting sculptures. DAC is one of the most famous cultural heritage sites in the world, and has provided plentiful material for people to research on Chinese ancient art, history, culture and so on. The most important components of DAC are architecture, murals and painting sculptures, which possess not only great artistic value but also profound cultural significance. Therefore, DAC was ranked 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 UNESCO 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 engineering. Presently, the experts of Dunhuang Academy have already carried out a lot of projects, which investigate cultural relic preservation, restoration and reinforcement. These projects involve environment measurement and analysis, mural pigment analysis and pigment fading test,etc. 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.

With the rapid development of Internet, multimedia technique, image processing and optical storage, we try to develop a computer-based environment for the preservation, restoration and propagation of Dunhuang art. The purpose of our project, which is collaborated with Dunhuang Research Academy(DRA) and Fraunhofer-IGD in Darmastadt/Rostock (Germany), is just to provide new tools for DAC through synthesizing CG, VR, CV, MM, AI and network technologies. This paper mainly focuses on the virtually mural restoration in a network cooperative environment.

2. Style and Spoiling Factors of Dunhuang Mural

2.1. Mural Style

Formerly, the oasis town of Dunhuang lay at a crucial junction of the Silk Road, that ancient braid of caravan trails stretching for more than 7,000 kilometers from China to the Mediterranean, which served as a highway not just for merchandise, but also for ideas - religious, cultural and artistic. During the evolvement of permeation between western and eastern cultures, Chinese artists combined the foreign Buddhist painting art with the traditional painting art and created the Dunhuang Buddhist murals, which can be described from the following aspects [1, 2]:

(1) *The mural theme.* Almost each piece of Dunhuang mural has certain Buddhist theme. The mural theme determines

the mural content, and the mural content determines the painting form. Murals with the same theme were generally painted in similar composition and contained objects of the same type.

(2) *The shape of mural elements.* Mural elements are the basic units of mural composition. A kind of mural element has rather unique characteristics. In a sense, mural elements present the mural style. For example, Apsarases are the typical elements of Dunhuang murals (see Figure 1).

Figure 1: *The shape of Apsarase*

(3) *The geometric layout of mural.* The geometric layout reflects the arrangement of the elements in a mural. Most murals with the same contents generally have similar layout forms. For example, murals on the ceiling have a fixed geometric layout.

(4) *The color of murals.* After long time evolvement, Dunhuang murals show two kinds of color appearance. The first one is the original color style at the time when artists painted the murals. There are many different color sets in different social fashion. All colors can be mainly classified into soil red, soil yellow, stone green, stone blue, gray, black, white, gold, etc. Due to the natural affection, most colors have faded. The current colors are the second appearance seen by people now.

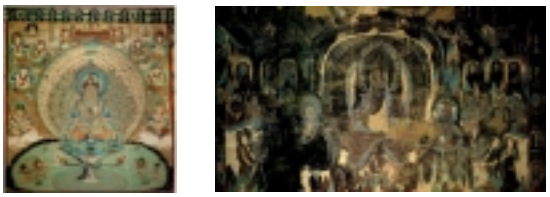
Based on above analysis, we can represent the style of Dunhuang mural as the following:

$$MuralStyle ::= < Theme, Shape, Layout, Color >$$

2.2. Mural Spoiling Factors

The mural spoilage can be categorized into two classes: color fading and mural desquamation.

The color fading is a common phenomenon in Dunhuang caves. Almost every color has faded to a certain extent. The cause of color fading is that the pigments contain the lead substance. The factors causing lead pigment change are very complicated. They involve some environment conditions, such as sunshine, oxygen, temperature and so on. The color spoiling degree is different under different environmental conditions. Figure 2 (a) is a little color fading mural, and (b) is a serious color fading mural.



(a) (b)

Figure 2: *Two murals with different color fading degree*

The second factor of mural spoiling is mural desquamation. Some regions in the murals have been peeled (see Figure 3). The cause, which leads to mural desquamation, is the incompactness of the soil of the cave wall. Under the affection of efflorescence, some pigments are peeled off the wall.

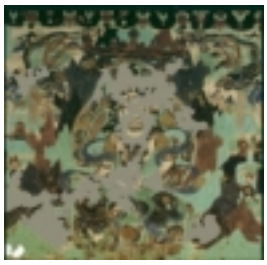


Figure 3: *A peeled mural*

2.3. Traditional Mural Restoration

The traditional mural restoration work in Dunhuang Academy can be classified into the physical preservation and mural facsimile.

The preservation experts mainly use chemical methods to analyze the components of pigment substance. They also use some instruments to observe the effects of temperature, humidity, and mildew to color fading. In addition to the pigment components analysis, preservation experts also analyze the cave soil and used some chemical reagents to enforce the soft soil to keep the murals from crash. In a sense, the preservation experts have provided a lot of knowledge to virtually restore the color of the murals. Based on their knowledge, we can not only learn about the original mural appearance, but also predicate the future of the murals .

As an alternative method of the physical preservation, The artists have painted a lot of mural facsimiles. Based on the art knowledge of the mural style, they can restore the original appearance of the murals. In order to keep the mural originality, their work is only performed on the facsimiles (see Figure 4). In order to restore the original color of murals, they also need some knowledge from domain experts. Today, this work is very time-consumptive. To repaint a new

facsimile, it will take an artist at least a half-year or one year in a cave. The cost is very expensive.

Figure 4: *The facsimile about mural*

Currently, Dunhuang artists are mainly dispersed in different places: Dunhuang, Lanzhou and Beijing. For some artists who don't live in Dunhuang, they have to take a long journey to visit Dunhuang to get some mural data. With the development of digital capture technology (such as digital camera, digital scanner, etc.), we can store the murals in digital form. The artists can access the data in a networking environment. Nowadays, some experts are coming to use some image processing software to restore Dunhuang murals. Due to the plenty of the mural content, one artist can only restore one kind of murals or some parts of a mural. In order to restore the whole mural, different artists often need to work cooperatively. However, most commercial image processing software are stand-alone oriented, they don't support cooperative image processing. For the restoration work of Dunhuang murals, it is very challenging to develop cooperative mural restoration software.

2.4. Cooperative Mural Restoration Methods

In order to restore murals effectively and conveniently, we have integrated all necessary tasks in a network environment. Our methods are as follows:

- Wire all the computers of different artists through Internet;
- Use image-processing technology to segment and extract the spoiled objects;
- Determine the original mural information used for each object with domain knowledge from substance.
- Provide a group of tools to support artists to restore the murals conveniently;
- Combine the restored objects together into one image so as to obtain the restored mural image;
- Develop a mechanism to manage the information in the cooperative system.

In order to implement above methods, our cooperative system should satisfy the following requirements:

- Support the diversity of the cooperative restoration stages;
- Support the division of cooperative work and access control mechanism;
- Support the distributed management and centralized control of the mural data;
- Support the diversity of cooperative applications;
- Support the awareness of multi-user information;
- Support information sharing.

3. Cooperative Components in Restoration System

The cooperative components are the key entities in a cooperative environment. These components are the basis of the cooperative mural restoration system. In the system, we divided these components into five kinds: restoration objects, cooperative users, cooperative roles, cooperative applications and cooperative tasks.

- **Restoration Objects**

A restoration object is defined as the region in a mural. A user, who participates in the mural restoration, can change the state of object attributes. The object can be segmented through manual extraction or automatic image processing tools, the segmentation results are determined by the complexity of mural composition. Moreover, an object can be divided into some sub-objects (see Figure 5). According to the style analysis of the Dunhuang mural, we organize the objects in a mural by tree structure (see Figure 6). The root node represents the whole mural. The middle nodes represent compound objects, which can be divided into some sub-objects further. Leaf nodes represent basic objects, which are the basic restoration units.

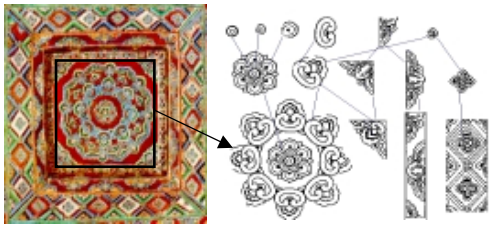


Figure 5: *The composition of a mural on the ceiling*

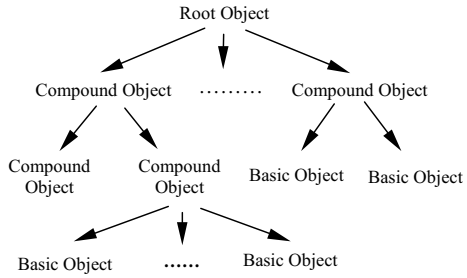


Figure 6: *The organization structure of mural objects*

Each object contains visual content, restoration knowledge, attributes, and some operation methods. A mural

restoration process can be seen as the state transformation of the visual content of objects under some operations. The visual content includes faded color, shape, line drawing, etc. Using the pseudo-code, an object can be represented as following:

Object {
Content:

$color, shape, line\ drawing$;

Restoration Knowledge:

$mural\ spoilage\ knowledge$;
$mural\ painting\ art\ knowledge$;

Attribute:

$dynasty, time, restorer, \ldots$;

Operation:

$op_1, op_2, \ldots$;

SubObjSet:

$object_1, object_2, \ldots$;

}

- **Cooperative Users**

In the cooperative restoration system, the cooperative users are the principal part of the whole system. The user's information can be represented by an eight-tuple:

$UserInfo ::= < UserID, UserName, Password, Role, Email - Address, PhoneNumber, FaxNumber, Specialty >$

When a user wants to access the system, he first needs an account (*UserID*) and a password to get the system authorization. Based on the communication address maintained in the system, he can communicate with others conveniently. The specialty is used to the assignment of restoration roles.

- **Restoration Roles**

In a cooperative mural restoration system, people have different contribution to the restoration work. In order to represent this variability, people can take on different roles. The roles describe the behavior of different people in a collaborative restoration system. Some roles may be taken by more than one person; some may only be performed by one. The role sets can be described as the following (see Figure 7):

$Roles = \{Chairman, Extractor, Preserver, Artist, Observer\}$

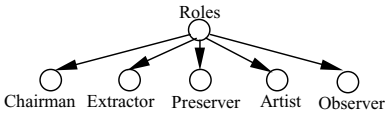


Figure 7: *The classification of cooperative roles*

The duties and rights of different roles can be described in Table 1.

Roles	Main duties and rights
Chairman	In the system, only one person can take on the chairman role. He is responsible for the creation of a restoration task, the convocation of restoration members, the assignment of restoration task, and the system management. He has the highest access rights to mural objects.
Extractor	Extractor mainly uses some system tools to segment the mural into some restoration objects, and add some attribute information to these objects.
Preserver	Preserver mainly provides semantic knowledge of mural spoilage to assist the artists to restore the mural visual information.
Artist	Based on the imagery information of Dunhuang mural design, the artist mainly uses some mural restoration tools to restore the color or shape information. Different artists have different specialties, so artist can be further divided into some sub-roles, each sub-role is responsible for one kind of Dunhuang mural.
Observer	Observer is the person interested in the mural results with read access only to any information and right to participate in the informal message exchange associated the mural results.

Table 1: *The main duties and rights of different roles*

- **Cooperative Applications**

Cooperative system should provide a lot of applications so that the mural restoration could be carried out effectively. The applications can be classified into two categories: cooperative mural editor, cooperative communication tools.

The cooperative mural editor will provide some color restoration tools, shape restoration tools, image segmentation tools and other image processing tools. The mural editor has two modes: local editing mode and shared editing mode. In the localing edit mode, users can do the restoration work in stand-alone environment. In the shared editing mode, users can do the restoration work together through Internet environment.

The cooperative communication applications can be divided into asynchronous communication tools (such as electronic mail, comment tools) and synchronous communication tools (such as white board, chatter tool).

The division of cooperative applications can be described by Figure 8.

- **Mural Restoration Tasks**

	Mural restoration application	Communication application
Asynchronous application	Local mural editor	Email tool, remark tool
Synchronous application	Shared mural editor	White electionic board, chatter tool

Figure 8: *The division of cooperative applications*

A cooperative mural restoration task is defined as the process in which several users, who take on some roles, use some cooperative applications to restore the spoiled objects and exhibit the restoration results. The restoration task can be divided into sub-tasks. For each sub-task, it is composed of mural objects, users, roles and system applications (see Figure 9).

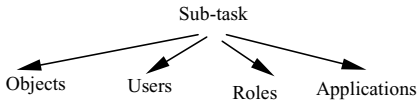


Figure 9: *The composition of sub-task*

According to the above cooperative components, we can divide these components into some information spaces: cooperative user space (*UserSpace*), mural object space (*ObjSpace*), cooperative role space (*RoleSpace*), cooperative application space (*AppSpace*) and cooperative task space (*TaskSpace*). One information space is the collection of a kind of components. For example, $UserSpace = (UserInfo_1, UserInfo_2, ..., UserInfo_m)$ and $ObjSpace = (Object_1, Object_2, ..., Object_n)$. The relationship of these information spaces can be described by Figure 10.

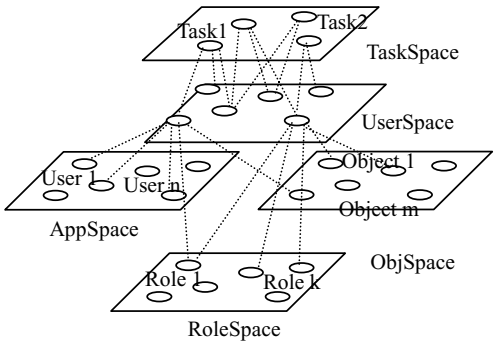
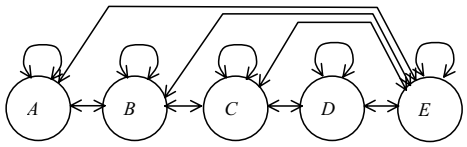


Figure 10: *The relationship among the cooperative components*

4. Workflow of Cooperative Mural Restoration

The restoration process of Dunhuang mural can be divided into some stages: the division of restoration roles, the analysis of mural spoilage, the segmentation of mural data, the repainting of mural data and the evaluation of mural restoration results. Each restoration stage corresponds to some restoration sub-tasks. When the work at a stage has been finished, this stage can step into the next stage. Sometimes, the work in the previous stages is dissatisfactory, the current stage may go back to the previous step. So the advancement and retreating of stages in a task is dependent on the restoration results of different users. The state transformation of restoration stages can be described by the following Figure 11.



Stage A: the division of restoration roles;
Stage B: the analysis of mural spoilage;
Stage C: the segmentation of mural data;
Stage D: the repainting of mural data;
Stage E: the evaluation of mural restoration results.

Figure 11: *The state transformation of restoration process*

In the stage of the division of restoration roles, the chairman initiates the system, and creates a cooperative mural restoration task. At the same time, he invites some users to participate in the mural restoration task. According to the specialties of different users, the chairman will assign a user some roles.

In the stage of the analysis of mural spoilage, the preserver will analyze the spoiling reasons. He will describe some semantic knowledge and provide some information for mural restoration artists.

In the mural segmentation stage, the extractors use image editing tools and segment the whole mural into some objects. When they finish the object segmentation, they will inform of the chairman to assign these objects to different artists. According to the specialties of the artists, the chairman specifies the artists to restore the object color, shape or drawing lines.

When the extractors have finished their restoration tasks, the process of mural restoration steps into mural repainting. Based on semantic knowledge of mural spoilage objects and the style knowledge of Dunhuang mural, the artists use mural editor to restore the spoiled mural in local sites. When an artist finishes his task, he can deliver his result to the others to restore the remainder tasks on his objects. When the whole restoration work has been finished, artists should submit their results to the chairman. At this stage, different artists can send or receive messages via some asynchronous

communication tools. When the chairman receive all the results, he will convoke all roles to evaluate the restored work, then the restoration process converts into the result evaluation stage.

In result evaluation stage, different roles can present their suggestions through synchronous communication tools such as white board, chatter tool. For artist roles, they can also restore their work in a shared mural restoration mode. Several artists can restore the same mural synchronously. When they have finished the synchronous restoration, chairman then merges all the restored objects and saves the restored mural in the end.

Based on above analysis of restoration, the process of the cooperative mural restoration can be presented by Figure 12.

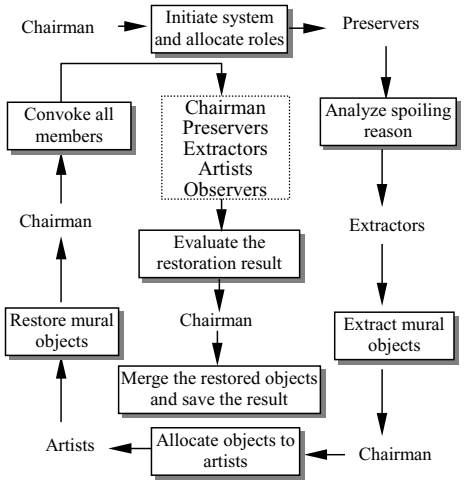


Figure 12: *The cooperative mural restoration process*

5. Some Key Techniques in Our System

5.1. Mural Restoration Methods

(1) Color restoration based on histogram threshold

For the color-spoiled mural image, its histogram contains many rugged peaks. The computer can not analyze the curve effectively. We use the Scale Space Filter (SSF) to separate the histogram into some intervals that are bounded by local extreme of its derivative. As scale value increases, the peaks and valleys of histogram will be smoother.

After the histogram is analyzed and the effective intervals are determined, a histogram table is generated. The table has four columns. The first three are HIS color values and the fourth is the number of pixels in the image with the particular color vector. In the restoration of faded color, only the saturation and intensity are increased, while hue remains its original value. As the faded colors are restored in the order of the histogram table, the higher the color ratio in the histogram is, the earlier it is processed.

From visual point of view, we assume that regions, which present similar color properties, belong to the same class, even if they are spatially disconnected.

(2) Color restoration based on color region

Edge detection and region growing approaches are combined to find large and crisp segments for coarse segmentation. For the region growing the user indicates the location of seed by positioning it on the screen image.

Segments can grow or expand based on several criteria for fine segmentation. The criteria can be defined from local, regional, global consideration according to a local analysis of neighborhood pixels belonging to the region. During the growing process, the growing region may leak to a neighboring region. To avoid this, a seed size of 3 pixels is chosen. The growing condition must be true for all the pixels in a 3*3 block

(3) Shape and intensive line restoration based on painting skill

The characteristic style and painting skill of Dunhuang are rich and colorful. They include:

- Faint dying used in human face modeling to stress the stereo effect;
- Hybrid pigments' faint dying for human skin;
- Color stratum layer to show the rough and uneven in entity's surface;
- Integration of line drawing and coloration.

5.2. Knowledge Organization and Representation

In our system, we provide some domain knowledge to aid preservers and artists to restore the spoilage objects. All the knowledge can be classified into two categories: one is about the restoration knowledge of pigment color, the other is the knowledge about painting art.

(1) Restoration knowledge of pigment color

Pigments in different ages and caves have their own special color fading and changing rules because of different chemical substances and the environmental condition [3]. In order to process the complex relationship between colors and pigments, we can set up typical color templates and some inference rules to restore the original color of pigments. A color template includes the following parameters:

- Chemical components of pigments;
- Environmental conditions;
- Age,dynasty and cave.

An inference rule reflects the color changing process of a kind pigment under different conditions, its input parameter is color template. Using the current color template and some

inference rules from the knowledge base, a preserver can get the original color of a pigment.

(2) Mural painting art knowledge

To restore the spoilage mural object with Dunhuang style, artists must have some mural painting knowledge. The same objects in different period have different coloring methods. We have defined some painting templates and painting rules. A painting template includes the following parameters:

- Object classification;
- Typical painting color sets;
- Painting methods
- Topics of mural;
- Age, dynasty, and cave;

During the period of mural repainting, if an artist's input parameters matching the parameters in a painting template, a painting rule will be activated to do a corresponding painting action.

We use a hybrid structure of frame and rule to organize and represent knowledge. The frame is composed of the following slots.

{

Name: frame name;
Trans: frame translation;
Father: pointer of parent frame;
Children: pointer of children frame;
Mcondition: matching condition of the frame;
AnameSet: set of attributes names;
AtypeSet: set of attributes types;
CTemplate: typical color templates;
PTemplate: typical painting templates;
RuleSet: set of inference rules;

}

The set of inference rules is composed of the production rules. The production rules are presented in the following way.

IF ($PR_1 \wedge PR_2 \wedge \ldots \wedge PR_n$) THEN ($CR_i$) With Confidence $W(i)$

Where $PR_1, PR_2, ..., PR_n$ are premise propositions or facts, CR_i is result proposition, and W is credit ability of the rule.

All the knowledge is centralized at a knowledge-based server (KBS). After obtaining the permission from the KBS when preservers or artists access the KBS, they supply some background information relevant to the mural spoiling to KBS for reasoning, such as the time when the mural was originally painted, the current cave environment condition, etc. If enough information is submitted, the KBS would notify submitters and provide the possible reasons the mural were spoiled, and the originally painted information of the mural, such as the kinds of original pigments and styles used in different parts of mural. Depending on the feedback from the KBS, the artists would easily restore the spoiled mural.

5.3. Concurrent Control of Cooperation Operations

In the process of the cooperative restoration, concurrent control is used to manage the concurrent operation events on mural objects, which are taken care of by the multiple users. We can represent an event as a five-tuple: $E =< Op_e, Id_e, T_e, Side_e, Rid_e >$. Op_e is the event operation type; Id_e is the object identifier; T_e is the time of event deliver; $Side_e$ is the source site identifier of event deliver; Rid_e is the destination site identifier of event reception. We adopt the centralized control to deal with the multiple concurrent events so that each user can see a consistent event sequence through the global serialization of restoration operations and in certain time only one event can be dealt with. The simplest method is to add lock to the mural object. Lock can be added in different granularity. We adopt entity lock and object lock. To avoid an object being locked by a user forever, we define the longest time in which the user possesses object lock. Beyond this period, the object lock will be released automatically. The whole current operation events can be described in Figure 13.

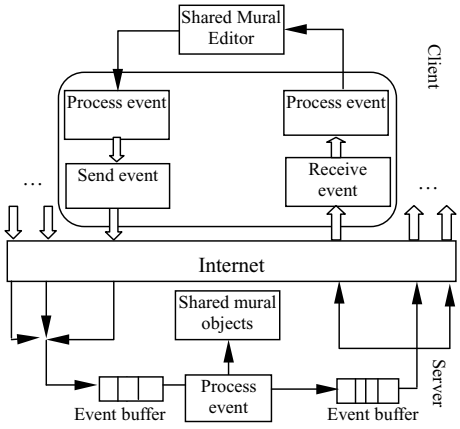


Figure 13: *The concurrent event processing*

5.4. Synchronous Cooperative Model

In the synchronous restoration conference, multiple users can perceive the others' actions through the sharing editor. And through the communication tools such as electronic white board, a user has a face-to-face feeling in a conference space. To guarantee the synchronization, all the users in the system should share the same view. In this way, they can know what the others are doing and a cooperative restoration is simulated as if a group of users are working on a piece of mural.

In the synchronous restoration conference, a view can be

defined as a five-tuple, $V =< C, A, V, T, D >$.C is the chairman of conference; A is the artist; V is the version number of this view; T is the current time; D is the restoration data. For the artists a_i and a_j, their views are $V_i =< c_i, a_i, v_i, t_i, d_i >$,$V_j =< c_j, a_j, v_j, t_j, d_j >$ respectively; If $c_i = c_j \in C, v_i = v_j \in V, t_i = t_j \in T, d_i = d_j \in D$; then $v_i = v_j \in V$. The users can leave and join in the conference at any time. If a user takes part in the conference, a copy of the present view should be transmitted to him. In order to guarantee the real-time synchronization, the operations on the data of the view should be transmitted to the others' view in time.

5.5. Mural Version Management Model

Version management is an important problem of the cooperative restoration system. System maintains the history records about the users' operations. Version can be applied in different granularity. In the cooperative restoration system, multiple versions should be organized in a certain mode to reflect the evolution process of the mural restoration. The version management can be divided into synchronous management and asynchronous management. The synchronous management is relatively simple. A final version will come into being in the end of restoration conference and the version information will be managed globally by the server. In the asynchronous restoration, different versions will be managed locally. The two methods are:

- **Serial version management**

Different versions are managed locally by the users. When a user is editing a mural restoration, the others can only read it. After a mural has been edited, the version number increases by one.

- **Central-copy version management**

In the process of asynchronous restoration, the server has the control of the different version. Different users maintain locally different copies of each version. First, the system will compare the local version identifier with the global version identifier. If they are equal, the version on the local system will take effect. Otherwise, the system will operate on a copy of the higher one in the server. We can set a version marker. When the others are operating on a mural, this user has to wait. After finishing the operation, the system should upgrade the current version.

6. Experiment System and Restored Results

6.1. System Architecture

We adopt client/server mode and design the layered architecture of the cooperative restoration system in the Internet environment. See Figure 14.

In the client side, the top layer is user interface. It integrates the asynchronous mural editor, synchronous mural editor, e-mail, and comment tool, white board, chatter tool. Asynchronous cooperative restoration environment is composed of local mural editor, comment tool, and e-mail. The mural data in asynchronous repainting stage is stored in the local mural database. Synchronous cooperative environment is made up of shared mural editor module, white board and chatter tool. All the data sent to server is encoded in data representation layer. In this layer, the data from the server side will be decoded and is dispatched to different application tools. The data format is composed of data header and data body. The data head contains application identifier (AppID), command identifier (ComID), and command data length (ComLen). The data body is the operation data of commands. In network control layer, it mainly calls the network socket function to implement the message reception and send from/to Internet.

In the server, there are four layers. The network layer and data representation layer are just the same as the client side. The proxy server layer maintains the tool requests as received from the clients, dynamically processes them, and dispatches them to the different server and system management applications. In the management layer, it is composed of task management module, mural management module, and user management module and role management module. The cooperative task management module mainly maintains the state of information of a cooperative restoration task, such as the establishment and deletion of a restoration task. It also deals with the concurrent operation to a mural in synchronous mural restoration. The management module of mural information mainly maintains the relevant information of mural, such as the mural data, mural spoiling reason, mural object information, mural restoration knowledge. The user management module is responsible for the user addition, the user deletion and the update of user information. It also checks the user register information. The role management is responsible for the role addition, the role deletion and the update the operation rights of different roles.

6.2. User Interface Design and some Restored Results

Presently, we have implemented our mural restoration using Microsoft Visual C++ 5.0 on Windows NT server/client platform. Because our system is used for Dunhuang experts, we use a Chinese windows interface. Before user starts the restoration work, he needs the system authorization. Figure 15 (a) is the interface of user login. Here, the user should specify the mural sever address, input his account and password. Figure 15 (b) is the asynchronous mural environment, here, an extractor is segmenting a mural into some objects. Figure 15 (c) is the interface of a shared mural restoration. In a synchronous environment, different users have different tele-cursor to represent his identity.

Based on the knowledge from the preservers, our system can presents the color change process in different periods. Figure 16* (a)–(f) is the restoration process of skin color of human objects from Xiliang Dynasty (about A.D. 400) to

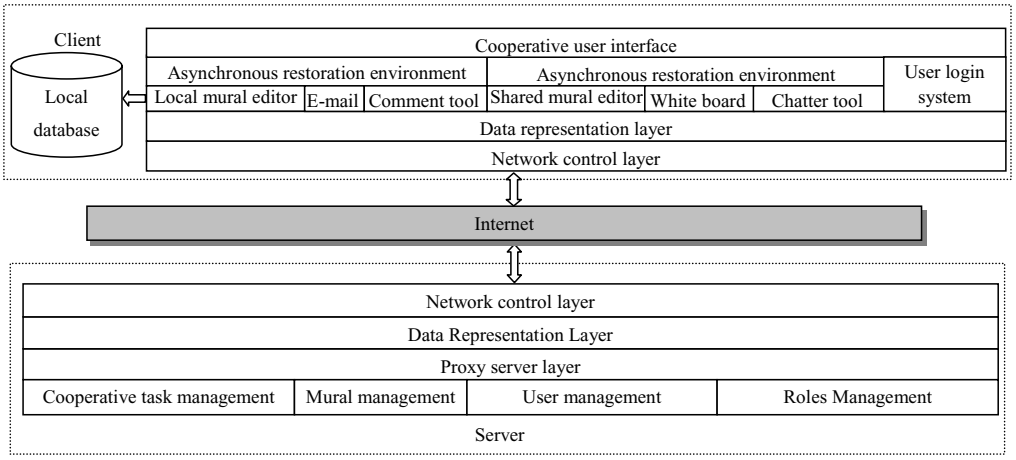
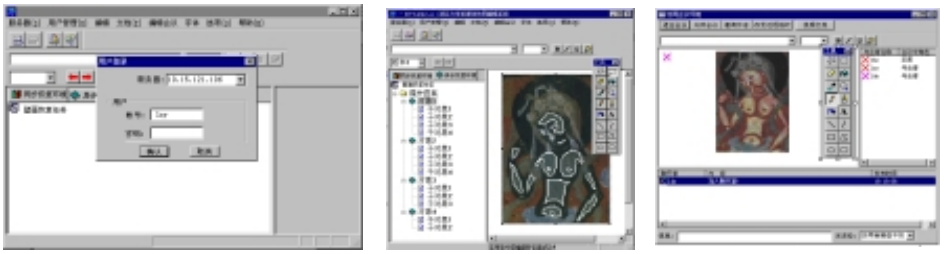


Figure 14: *The system architecture of cooperative mural restoration*



(a) (b) (c)

Figure 15: *The interface of the experiment system*

now. Figure 17* (a)–(b), Figure 17* (c)–(d), and Figure 17* (e)–(f) are three pairs of results of the faded murals on the ceiling and restored murals.

6.3. Future Work

We have implemented the mainly cooperative restoration function after three years hard work, however, some cooperative issues still need to study further, such as cooperative undo action. In order to support other similar restoration work, Dunhuang mural restoration application and knowledge base should be customized for the whole system. Compared with the most WWW-based cooperative system, our system is implemented using Microsoft Windows interface. The reason is that we can use Visual C++ to easily implement mural image processing and develop a friendly user interface. Now, with the popularity of WWW, we are planning to port our system using Java language to support WWW access.

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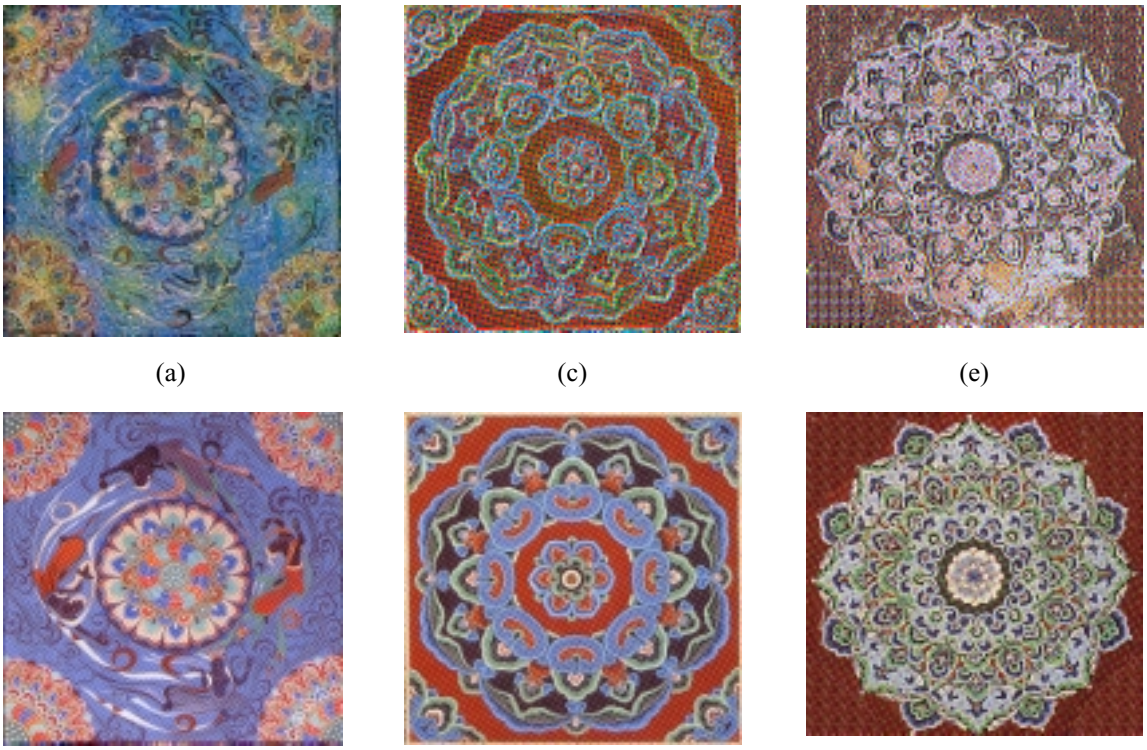
(a) (b) (c) (d) (e) (f)

Figure 16: *The skin color change process based on preservers' knowledge*



(a) (c) (e)

(b) (d) (f)

Figure 17: *The contrast between spoiled murals and restored murals*