

# 3D INFORMATION RESTORATION OF THE DIGITAL IMAGES OF DUNHUANG MURAL PAINTINGS

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## ABSTRACT:

Mogao Grottoes in Dunhuang are famous for its profound content and perfect art in the world. But various kinds of damage coming from mankind or nature brings Mogao Grottoes a lot of disease, which makes this large-scale historical cultural heritage in the world degraded and damaged constantly. It is very urgent to find out all kinds of measures to protect it. The processes to restore 3D information of the mural paintings by means of the digital close-range photogrammetry and computer-based image processing technology were expounded in this paper in order to digitally preserve the mural paintings in the original style. The uniform coordinate system of the Grottoes was set up, and the mural paintings of the Grottoes were close-range photogrammetried, furthermore, the films obtained from the close-range photogrammetry were scanned as digital images by a higher resolution scanner. The assistant spatial coordinate of the mural paintings in the each wall was then set up by the coordinate transformation. On the basis of this, by means of model orientation, kernel line resampling, image matching, the orthoimages of the mural paintings were created and the 3D information was restored finally. The processing results of the mural paintings showed that the residual error of the absolute orientation of all control points reached the millimeter accuracy level, and that the middle error of the digital surface model of the mural paintings. That is, the geometric correction of the images data of the mural paintings reached the millimeter accuracy level. It indicated that the 3D information of the mural paintings could be accurately restored by the close-range photogrammetry and computer-based image processing technology in order to protect and digitally restore the mural paintings and statues of Mogao Grottoes in Dunhuang forever. At the same time, it provided for us a new method and thought for relics protection, and new measures for the ancient costly relics protection, restoration and research.

## 1. INTRODUCTION

Mogao Grottoes in Dunhuang are famous for its profound content and perfect art in the world. In 1961 it was ranked as one of the first National key culture Relics Unit, and in 1987 it was ranked as one of the historical cultural heritages in the world by UNESCO. But various kinds of damages coming from mankind or nature brought Mogao Grottoes a lot of diseases, which makes this large-scale historical and cultural heritage in the world degraded and damaged constantly. The area of the mural paintings preserved in Mogao Grottoes is over 45000 m<sup>2</sup>, and more than half of them had been damaged. Many mural paintings are shelled, brushed off and faded, and even some of them disappeared. According to the introduction, the illness of the mural paintings in Mogao Grottoes is crisp-alkali disease which is called the cancer of mural paintings by experts.

The mural paintings of Mogao Grottoes are soil texture relics. Painted sculpture such as niche for Buddha is made up of soil, wheat, grass and wood, and dyes of mural paintings mostly are mineral substances, which are very fragile through thousands years' harden. After the reform and opening in 1978, as the development of tourism and constantly increasing of tourist arrivals, especially in the midseason of tour, thousands of people arrived at Mogao Grottoes and brought a great deal of animalcules, carbon dioxide, vapor and released heat to the grottoes. In the circumstance of high humidity, carbon dioxide and water combine and generate acidity materials which make the mural paintings faded; moreover, the combination of vapor in air and salinity in the lithosome, inflate and shrink time after time, which is the main reason of crisp-alkali disease the mural paintings got. These brought irresistible damage to the mural

paintings and sculptures. Besides these, noise, shake etc. threatened the weak relics. In the recent hundred of years, the climate condition in Dunhuang has changed, and leakage of rain in the grottoes happened occasionally. Therefore, it is very urgent to find out all kinds of efficient measures in order to preserve and protect this rare treasure in the world.

With the fast development of science and technology, the close-range photogrammetry and computer technology were applied widely in the field of relics protection. All departments of relics management have enhanced work of research and exploration in relics information protection with the close-range photogrammetry and computer technology. In China, as early as 1987, aerial survey and remote sensing corporation of coal department had ever taken photograph of two key culture relic units in Shanxi province. The two units are Dongyue temple in Xi'an and about 500 m<sup>2</sup> ancient mural paintings in Yaowang mountain of Yao county, and parts of the mural paintings were taken edge enhancement experiments by computer-based image processing technology<sup>[1]</sup>. Besides that, there were also the photogrammetry and remote sensing engineering of Qinshihuang Cemetery<sup>[2]</sup> and the computer storage and management information system of Dunhuang mural paintings<sup>[3, 4]</sup>. Lu Dongming and others<sup>[5, 6]</sup> had set up the 3D model of caves and developed database of the mural paintings by image processing and virtual reality etc., which restored the mural paintings and made the non-renewable Dunhuang caves relic digitally protected and rebuilt by way of computer intelligence and the collation of the mural paintings from artists. Dunhuang caves virtual navigation and restoration of the mural paintings system which had third dimension was set up and caused strong repercussion in the field of science and

technology when exhibited at 2000 international expositions in Hanover German. Abroad, there were also researches about relics protection by the close-range photogrammetry and computer technology. For example, in America digitized Michelangelo plan<sup>[7]</sup> recorded 10 large statues which mold by Michelangelo including David statue by 3D scanners; in Japan digitized work of the ancient villages in Shirakawa-go had been accomplished based on the close-range photogrammetry<sup>[8]</sup>.

The studies at home and abroad showed that there have been mature theories and demonstration researches on restoration of the relics' geometric configuration by the close-range photogrammetry and computer-based image processing technology. The mural paintings and painted sculptures such as niches for Buddha in the grotto c220 were works of late Tang dynasty. Grotto c220, which has a history of over 1300 years, is the typical representative of more than 400 grottoes of Mogao Grottoes in Dunhuang, and gets various diseases. This paper discussed the method of the 3D information restoration of the mural paintings, taking the grotto c220 as an example. Owing to the fact that most of the mural paintings are curved faces, this paper did not use the method of image information correction based on a plane used by Zeng Qunzhu<sup>[3]</sup>, Li Zhen<sup>[4]</sup> etc. because it was difficult to restore and rebuild the original appearance of mural paintings. The method used here is also different from virtual reality used by Lu Dongming etc<sup>[5, 6]</sup>. The 3D information of the grotto c220 of Dunhuang mural paintings could be accurately restored by the close-range photogrammetry and computer-based image processing technology in order to protect and digitally restore the mural paintings and statues of Dunhuang forever. Further more, this method was a kind of exploration to protect and digitally store other mural paintings of Mogao Grottoes and similar relics.

## 2. THE CLOSE-RANGE PHOTOGRAMMETRY AND THE ACQUISITION OF IMAGE DATA OF THE MURAL PAINTINGS

Grotto c220 of Dunhuang Mogao Grottoes is made up of corridor, front room, main room and niche for Buddha. Origin point was placed at the entrance of the grotto, while control points were basically placed along the connecting lines among four walls, four slopes and alga well of the main room. Control point was marked by cross lines. Each wall contained 8 control points, each slope 6 and each alga well 4. Moreover, the front room and the niche for Buddha also contained different number of control points. In this way, all control points were unified in a uniform Cartesian coordinate system.

The close-range photogrammetry of grotto c220 of Mogao Grottoes was accomplished by UMK camera made in German. This camera's focal length is 99.54 mm and the correction value of focal length is 2.97 and 4.24 mm. Photography took advantage of single piece horizontal photography and oblique photography, according to divided frame of mural paintings. In this way, axis of lens and the wall were approximately perpendicular to each other. When the mural paintings were obliquely photographed, obliquity of the slope would be measured firstly, and then the theodolite lens box of photography inclined relevantly. Each wall and slope was taken photograph twice from different points of view to get an image pair. The left-and-right sides of each wall and slope were photographed to get an image pair. And alga well would be photographed too. The front room would be photographed to get 4 image pairs from top, east, north, and south. The niche for

Buddha also could get 4 image pairs by photographed from top, north, south and west. In all, there were 68 photographs.

Films gained from the close-range photogrammetry were scanned by a scanner to finish A/D conversion. In order to ensure the quality of the images of Dunhuang mural paintings, scan resolution was defined as 1200DPI and pixel resolution was 0.021 mm. The storage format of image was \*.tif. Each image file size was about 150M.

## 3. COORDINATE TRANSFORM OF THE RESULTS OF RELATIVE CONTROL SURVEY

The basic thought of spatial model restoration to the Grotto c220 of Mogao Grottoes is: Stereoscopic pairs obtained from the close-range photogrammetry and control points as a result of relative control survey are used to generate DSM (Digital Surface Model) of the wall on the basis of reference frame model of the grottoes, and then each wall must do orthorectification in order to preserve fluctuant 3D spatial information of mural paintings of the wall.

To each wall of grotto, an assumed datum should be set up for creating DSM of each wall, and then original survey coordinates of control points should be converted to assistant spatial coordinates which are based on this datum. Origin point of each wall was placed at the left down corner of the assumed datum, and 3D assistant spatial coordinate system which took the datum as base plane was set up. Axis Z was perpendicular to the datum. To make the results of coordinate transformation clear at a glance, the value of Z obtained from original coordinate conversion should be positive when assumed datum was set up. Due to each origin point placed at the turning point of the outline of the grottoes and to ensure the value of Z positive, a larger frame of the outline which was based on the original coordinates of control points and the shape of the grottoes was established and then original coordinates of the control points after rotated could be on the datum whose origin point was the turning point of the new outline of the grottoes.

Spatial coordinate transformation of the image points means that the rectangular space coordinates (x, y, -f) of the image points would be converted to assistant spatial coordinates (X, Y, Z). This is the problem of coordinate transformation of the same image points in two rectangular space coordinates which have the same origin point. The expression shows as follows (1):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R \begin{bmatrix} x \\ y \\ -f \end{bmatrix} \quad (1)$$

where:

$$R = \begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix} = \begin{bmatrix} \cos Xx \cos Xy \cos Xz \\ \cos Yx \cos Yy \cos Yz \\ \cos Zx \cos Zy \cos Zz \end{bmatrix} \quad (2)$$

which is the rotational matrix of rotation transformation of spatial coordinate system.

The elements of matrix  $a_i, b_i, c_i$  ( $i=1, 2, 3$ ) mean direction cosine.  $a_1, a_2, a_3$  are the cosine of the included angle between X-axis and x-, y- and z-axis.  $b_1, b_2, b_3$  are the cosine of the included angle between Y-axis and x-, y- and z-axis.  $c_1, c_2, c_3$  are the cosine of the included angle between Z-axis and x-, y- and z-axis.

For all sides of wall and the top of alga well, every coordinate axes of assistant coordinate system and original coordinate system were parallel to each other, thus the values of x, y, z of the original coordinate system would be replaced according to the direction of X-, Y-, Z-axis of the assistant coordinate system and then translated the coordinates in order to do coordinate transformation.

Four slopes were more complex because of lack of essential known condition. In the actual process, for avoid complex rotation transformation, the original coordinates would be transformed to assistant coordinates of the wall and then transformed to assistant coordinates of the blank plane through plane coordinate transformation. The Second transformation just needs to calculate the included angle between blank plane and base plane. Table 1 shows the coordinate transformation result of control points in the east wall.

Control points				Coordinate translation		
Point	x	y	z	X''	Y''	Z''
Origin	0	0	0	9.75	0	14.25
10007	9.6562	13.9989	2.4233	0.0938	2.4233	0.2511
10009	6.9026	14.0058	3.7048	2.8474	3.7048	0.2442
10010	6.8854	14.0881	2.541	2.8646	2.541	0.1619
10011	4.2432	14.1367	3.8025	5.5068	3.8025	0.1133
10012	4.1231	14.2058	2.5066	5.6269	2.5066	0.0442
10013	4.0247	14.2103	0.6246	5.7253	0.6246	0.0397

Tab.1 The coordinate transformation result of control points in the east wall (unit: meter)

#### 4. 3D INFORMATION RESTORATION OF DIGITAL IMAGES OF THE MURAL PAINTINGS IN DUNHUANG

The close-range photogrammetry of the mural paintings of Grotto c220 in Dunhuang made use of UMK camera made in German which is a metric camera. That is to say, there is fiducial mark data, but the parameters of the original camera can't be obtained. Therefore, it would be taken as a non-metric camera. Under the condition of no focal length, theoretical coordinates of principal point of photograph and fiducial parameters, less than 6 coordinates of control points could calculate the elements of exterior orientation of images according to DLT (Direct Linear Transformation). The method of DLT, which can directly set up coordinate equation between coordinaograph coordinates and object space coordinates, doesn't need either fiducial mark on the image, or initial values of parameters of interior orientation elements. Figure 1 shows 3D information restoration process of the digital images of the east wall of Grotto c220 mural paintings.

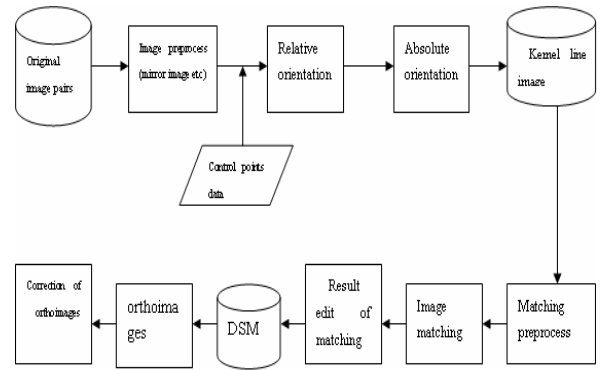


Figure 1. The flow chart of 3D information restoration of the digital images of the mural paintings in Dunhuang

#### 4.1 Create coverage and modeling

First, create coverage and input the coverage parameters. Remember to translate the unit of the data of control points from m to cm. The photograph scale is 1/25; the number of navigation channels is 1; the image type is the close-range photogrammetry; the grid interval of DSM is 5cm; the interval of contour lines is 5cm; the finished map scale is 1/1000; the orthoimage resolution is 400DPI; the pixel resolution is 0.063mm and the main image is left image. During the orthorectification, only the parameters of the control points need to be known and others can be set according to the circumstance and requirement.

#### 4.2 Model orientation

As the mural paintings in Dunhuang are not treated as a metric camera, it does not need to interiorly orient, but just relatively orient and absolutely orient. The process of relative orientation is to search the homologous control points in the control points file in the left and right image pairs of the relative orientation model, and making a precise orientation to make sure the residual error of each control point and RMS minimized. Relative orientation is done after accurately orienting by at least 6 control points. During the process of relative orientation of the left wall, the number of auto-matched points are 246; the RMS is 5.5mm and the residual error of the control points is in  $\pm 0.010$ . Most of the residual error of absolute orientation of left wall is small, reaching 1/10 millimeter accuracy level (Table 2).

Control points	Residual error dX	Residual error dY	Residual error dZ	Residual error mx	Residual error my	Residual error mxy	Residual error mz
10007	0.002	-0.001	-0.002	0.015759	0.008215	0.01777 2	0.02600 3
10009	0.000	-0.006	0.015				
10010	0.000	0.005	-0.009				
10011	0.017	0.011	-0.027				
10012	0.021	-0.004	0.031				
10013	0.004	-0.003	-0.006				

Table 2 The residual error of absolute orientation of control points in the east wall (unit: cm)

#### 4.3 Kernel line resampling

After calculating the parameters of relative orientation, the kernel line queues for the origin digital image, that is, make resampling of the origin images according to the kernel line correlative theory, eliminate vertical parallaxes along Y-axis to

get the kernel line image pairs, and make preparation of auto-matching. As the vertical parallaxes have been eliminated, the process of searching the homologous images in 2D is transform to search process in 1D along the kernel line, which will make good enhancement to the efficiency and reliability of the image matching.

#### 4.4 Image matching

Some preprocessing work should be done before image matching. Mostly, the areas that are more difficult to be matched need to preprocess. For instance, the parts of the four corners of the image which are enclosed by shadows and the top of niche for Buddha with a sudden change are the positions where may not have a good matching result. You have to preprocess it to get a better matching result and reduce the work of matching edit.

During image matching, the image data is in a pyramid data structure, and the total image matching method [11] is the layered relaxation algorithm based on bridging mode. This algorithm can eliminate the influence of geometric distortion before correlation to get the good matching results. After the image matching, some parts where are not content with should make stereo edit and correction.

#### 4.5 Create DSM for Dunhuang mural paintings

DSM can be created after the absolute orientation and matching edit. DSM based on parallax data of image matching, result parameters of orientation, other parameters etc. is used to calculate the 3D space coordinates of the antipodal object points with space resection algorithm and then creates DTM (digital terrain mode) and DSM of the regular grids. DTM is the irregular grids made by the parallax grid's projection to ground coordinate system after matching. And then interpolation calculations are done to set up DSM of the rectangle grids.

#### 4.6 Generating orthoimages(3D infomation restoration )

According to the correlative parameters and DSM, by using the relevant imaging equation or a certain mathematical model to calculate the control points, the orthoimages can be obtained from the digital images of the original non-orthoimage projection. In this paper an opposite method (the indirect method) is used to create orthoimages by way of digital differential rectification. And at last some distorted parts (for example faintness, ghosting etc.) should be settled by correction. The table 3 shows the middle error of DSM of the east wall.

Control points	10007	10009	10010	10011	10012	10013
Middle error	0.531	-0.053	-0.650	0.087	0.145	0.096

Table 3 The middle error of DSM of the east wall (unit: cm)

It can be seen from Table 3, the middle error of the east wall is less than 1cm, which means the middle error of the elevation of the paintings' surface reaches millimeter accuracy level. Therefore, the error of the elevation of the paintings' surface is basically in accordance with the middles error of DSM. Figure 2 shows the isoline map of the east wall, and the figure 3 shows the overlay of isoline map and orthoimage of the east wall.

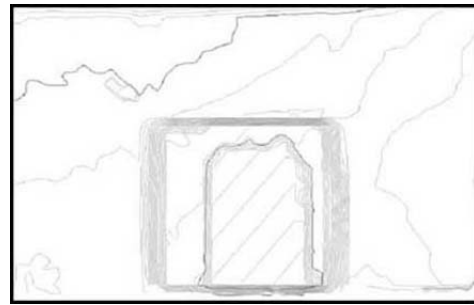


Figure 2. The isoline map of the east wall



Figure 3. The overlay of isoline map and orthoimage of the east wall

The orthorectification of other walls is similar with the east wall. From the results, the residual error of absolute orientation of control points is relatively small, reaching 1/10 millimeter accuracy level; the middle error of DSM is less than 1cm, which means the orthorectification of the images data of Dunhuang mural painting reaches millimeter accuracy level. At last, the coordinates of the orthoimages of mural paintings will be transformed to the original uniform coordinate system by space coordinate transformation equation, and then the original space structure of Grotto c220 and the true appearance of mural paintings will be rebuilt by 3D display software.

## 5. DISCUSSION AND CONCLUSION

To protect the mural paintings, there are only very few control points are on the wall of the mural paintings. Most of them are on the edge of the wall. For the image of a certain wall, the distortion in the district of control points is more visible which will affect the precision of the final image processing and 3D information restoration. And second, although every wall and slope has 8 or 6 points, some of them have been brushed off because of photography or photograph flush. The district of control points is all black, so in fact only 5 to 6 points can be found on the images of the walls, and less on the images of the slopes. These certainly will cause incapability of orthorectification and 3D information restoration.

The camera parameters are precondition in the process of image processing of the mural paintings. But some precise parameters of the metric camera can be obtained all along, for instance the distance parameters of fiducial marks and theoretical parameters of principal point of photograph. So we have to treat it as a non-metric camera. In such condition, at least 6 points are needed to do orthorectification and 3D information restoration; otherwise the work can't be done.

To the corrected orthoimages, the correction results of the relatively flat mural paintings are better, and have better precision. But the results of some typical curved mural paintings such as the niche for Buddha are not so good. The more serious the distortion is, the worse the precision is. The restoration of the true 3D geometric configuration of irregular curved face is the key problem has to be solved by researchers of the digital photogrammetry, and also is one of the puzzles in the field of the close-range photogrammetry.

In this paper, the experiment shows that the 3D information of Dunhuang mural paintings can be accurately restored by the close-range photogrammetry and computer-based image processing technology in order to protect and digitally restore the mural paintings and statues of Dunhuang forever. This method is just in test phase at home and abroad, but it has booming vitality, and has been subjected to the extensive concern. It provides us a new method and thought for relics protection, and new measures for the ancient costly relics protection, restoration and research.

#### REFERENCES

- Hirayu H, Ojica T, Kijima R, Construction the historic village of Shirakawa-go in virtual reality [J], IEEE Multimedia, 2000, 7(2): 61-63.
- Jin Weixian, Yang Xianhong, Shao Hongchao, Photogrammetry[B], The publishing house of science and technology university of survey and mapping of Wuhan, Wuhan, 1996.
- Levoy M, Pulli K, Curless B, The digital Michelangelo project: 3D scanning of large statues (B), ACM press, 2000.
- Li Zhen, Chen Jianming, The image processing in the computer storage and management system of Dunhuang mural paintings[J], Acta Geodaetica et Cartographica Sinica, 1998, 27(1).
- Lu Dongming, Pan Yunhe, Chen Ren, Dunhuang cave virtual rebuilding and mural restoration simulating[J], Acta Geodaetica et Cartographica Sinica, 2002, 31(1), 12-16.
- Lu Dong-ming, Pan Yun-he, Image-based virtual navigation system art caves [J], The International Journal of Virtual Reality, 2000, 4(4), 40-45.
- Non-topographic Photogrammetry[B], The publishing house of survey and mapping, Beijing, 1985.
- Song Dewen, Yang wengang, Zhao Peizhou, The photogrammetry and remote sensing engineering of Qinshihuang Cemetery[J], Acta Geodaetica et Cartographica Sinica, 1990, 19(1), 48-56.
- Wang Wenying, Zhao Peizhou, Wu Zhengchun, Engineering and the close-range Photogrammetry[B], The Geological publishing house, Beijing, 1994.
- Zeng Qunzhu, Li Zhen, Research on the computer storage and management information system of Dunhuang mural paintings[J], Journal of remote sensing, 1997, 1(4).
- Zhang Zuxun, Zhang Jianqing, The digital Photogrammetry[B], The publishing house of science and technology university of survey and mapping of Wuhan, Wuhan, 1997.

