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Digital Twin-Driven Tomb Mural Preservation and Virtual Exhibition

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Abstract As an important part of cultural heritage, the protection and display of tomb murals face the challenges of natural erosion, man-made damage and single means of display. This paper introduces the structure of different variational PDE class restoration models, and adopts the CDD model for mural painting restoration. By introducing geometric curvature function parameters to optimize the pheromone propagation mechanism and integrating geometric, physical, behavioral and rule models based on digital twin technology, it supports the dynamic evolution and multi-scenario application of mural paintings in their whole life cycle. The CDD model achieves the highest accuracy in different types of mask restoration, especially in the restoration of small masks, with a PSNR as high as 36.5265. Meanwhile, the CDD model still maintains a high level of performance in superimposed mask restoration, with a PSNR that exceeds that of the BSCB and TV models by 78.58% and 38.04%, respectively. The mean value of measurement error of scheme E (9.40m) is 49.11% lower than that of scheme A, and the standard deviation of its error distribution is also the smallest, which determines that scheme E can be selected.

Index Terms tomb chamber wall paintings, variational PDE class restoration model, curvature function, digital twin technology

I. Introduction

As a precious and non-renewable resource, the conservation of cultural heritage has always been a key area of concern in the cultural industry of various countries. With the passage of time, cultural relics are undergoing changes every moment, bearing the wear and tear brought by nature, and will inevitably go to extinction [1]. Cultural heritage protection includes preventive protection and salvage protection, the rapid development of national economic development accompanied by a large number of urban infrastructure, the local government in conjunction with archaeologists, the frequent excavation of precious cultural relics for protection, so that "salvage protection" has become the main strategy of cultural heritage protection [2]-[4]. For cultural relics that do not have on-site protection conditions, in order to prevent their further deterioration, it is necessary to carry out salvage excavation and relocation protection.

As for the tomb chamber murals, due to their rich artistic, historical, and cultural values, their conservation and display have received the attention of most archaeologists and tourists. In most studies of tomb chamber murals, it is shown that due to the influence of factors such as tomb passage collapse, flood erosion, micro-environmental changes, and damage by tomb robbers, which make the murals uncovered and relocated to an off-site location for preservation become a better conservation measure [5], [6]. The environment of the tomb chamber where the mural paintings are located before uncovering is relatively stable, and the storage environment after uncovering has changed considerably compared with the tomb chamber, which inevitably makes the mural paintings produce a series of lesion problems, and the main problems are crippling, displacement, deformation, fracture, cracking, cracking, armoring, detachment, cavitation, crispy alkali, mildew and so on [7]-[10]. The large number of tomb murals and their complex composition and structure, the restoration needs, heavy task, and the actual restoration difficulty, making most of the murals from the excavation to meet with the majority of tourists in a long cycle [11]-[13]. Another major factor leading to this status quo is the loss of cultural heritage restoration practitioners. With the upsurge of digital conservation of cultural heritage, the conservation and display of mural paintings in burial chambers have been given a new lease of life. Among them, digital twin technology applied to the conservation and display of cultural heritage is highly suitable [14]. Therefore, it is of great value to explore the digital twin technology in the protection and display of tomb murals.

This paper systematically analyzes the mathematical mechanism and restoration characteristics of three types of variational PDE models, BSCB, TV and CDD, and realizes the optimization of anisotropic propagation of effective pheromone based on curvature parameters. A multi-dimensional digital twin system architecture is constructed to establish an integrated digital twin model for the restoration of tomb chamber wall paintings. Taking a tomb chamber mural painting as the research object, verify the performance advantage of the CDD model through experiments, and focus on evaluating the restoration accuracy under different disease types. Optimize the installation scheme based on digital twin technology to explore the engineering applicability of the digital twin system.

II. The design of mural painting restoration program for tombs based on digital twin technology

The protection and revitalization of cultural heritage is an important issue in the development of today's society. As a carrier of ancient art and civilization, tomb murals have been affected by environmental degradation, microbial erosion and human factors for a long time, facing the risk of irreversible damage. Traditional restoration means rely on manual experience, there are strong subjectivity, low efficiency and other problems, and it is difficult to realize dynamic monitoring and multi-dimensional display. Digital twin technology provides a new solution for mural protection by constructing a real-time mapping between physical entities and virtual space.

II. A.Variational PDE class restoration model

Variational PDE-type repair models are techniques that simulate thermal, fluid, or gas diffusion processes or energy convergence processes based on diffusion or variational equations for effective information transfer to the defective region, using the pheromone as the basic processing unit. Since both of them can be depicted in the form of higher order partial differential derivatives, they are combined and called variational PDE models.

(1) Digital restoration model of BSCB

The BSCB model defines the edge information to be filled by retrieving the information region to be repaired, and adopts the pheromone propagation mechanism to propagate the known information of the neighborhood along the direction of the iso-illumination line to the defective region. In order to simulate the manual repair process, pheromone clusters are constructed: $u^0(i,j)=[0,M]\times[0,N]\subset R^2$, and let $u_R(i,j)$ be the repair result after iterative output.

Let the information to be repaired be a discrete two-dimensional grayscale image I, then the region Ω is defined in the information to be repaired as the region with missing information in I, and $\sigma\Omega$ is the filled leading edge of the missing information region, and the pheromone propagation process is shown in Figure 1:

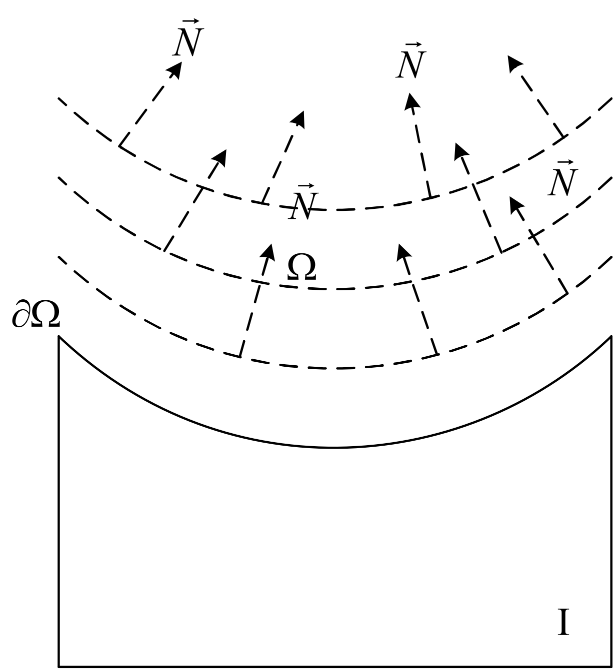

Figure 1: Pheromone propagation process

The restoration model can be represented as follows:

$$u^{n+1}(i,j)=u^n(i,j)+\Delta t\cdot u_t^n(i,j),\forall(i,j)\in\Omega \tag{1}$$

where, n denotes the number of diffusion iterations, (i, j) denotes the coordinates of the pheromone, Δt is the iteration step size, and $u_t^n(i, j)$ stands for the information $u^n(i, j)$ updating process. The pheromone diffusion process of the BSCB model simulates the process of fluid propagation, and the process of the information propagation is expressed as:

$$\vec{L}^n(i, j)\nabla^{\perp}u^n(i, j) = \frac{\partial^2 u_t^n(i, j)}{\partial x^2} + \frac{\partial^2 u_t^n(i, j)}{\partial y^2} \tag{2}$$

Propagate the known information along the filled edges to the area to be repaired. By referring to the fluid equations in analytical physics, the pheromone equation for digital restoration is established as by corresponding the BSCB propagation equation with the fluid Navier-Stokes equation to each other:

$$u_n^n(i, j) = \delta \overline{L}^n(i, j) \cdot \overline{N}^n(i, j) \tag{3}$$

where $\delta \overline{L}^n(i, j)$ is the amount of change in the information $L^n(i, j)$ to be propagated and $\overline{N}^n(i, j)$ is the direction of propagation.

The main difference between the BSCB model and previous image restoration algorithms is that it does not need to specify the pheromone source, can simultaneously fill multiple image regions with different structures and backgrounds, and the overall process is completed automatically without limiting the topology of the area to be restored. However, the model repairs point by point, the time complexity is higher, and the realization process is more complicated.

(2) Integral Variational (TV) Digital Repair Model

The overall variational repair model transforms the defect information diffusion process into the way of solving the spatial energy generalized function to complete the information propagation. The BV space is considered to be more applicable to the function space of non-texture information, so if the whole mural information is regarded as the bounded variational function BV space, the model of energy generalized function seeking for the minimal value established on the theory of low-level visual analysis is utilized to inverse the original information of the mural.

The TV model reduces a large number of iterations compared with the BSCB model, but the filtering effect of TV also leads to information blurring due to the gradual smoothing of the information transfer process.TV greatly reduces the time complexity due to the repeated iterations in the BSCB model by improving on the BV model, referring to the information around the defective region, and using it in the information filling process.

(3) Curvature-driven propagation (CDD)-based digital repair model The curvature-driven propagation CDD-based algorithm is a third-order variational PDE digital repair model. Because the conduction coefficient of the TV model is $g(\cdot) = 1/|\nabla u|_\alpha$, which relies only on the iso-illumination line intensity and is independent of other geometric information, the restoration process will have a smoothing effect on the information, and its core idea is to connect the edges with the smallest line segments (with the shortest distances), so it is prone to destroying the principle of connectivity in visual psychology.

The CDD model adds the curvature function parameter to the TV model, and increases the geometric information in the repair model to guide the anisotropic propagation of the effective pheromone.

The CDD digital restoration model is characterized by the diffusion process in the propagation process: the diffusion process becomes stronger where the curvature value is larger and weaker where the curvature value is smaller. The results of the reconstruction of the missing information of the mural paintings take full account of the curvature change process, which can realize the restoration needs of the slender structural regions in the mural painting information.

The variational PDE class digital restoration model takes the pheromone as the basic unit for the missing information projection, and its calculated result relies on the high-order partial differential equations designed by the restoration model, and the calculated result is the result of mathematical projection, and the restoration effect is more objective.

II. B.Digital twin modeling

II. B. 1) Digital Twin System Architecture

Digital twin technology, refers to a simulation technology that deeply combines information from physical models, sensor data updates and operational history. It simulates the entire lifecycle of a physical device or system by integrating interdisciplinary knowledge, multiple physical quantities, different scales and probabilistic analysis to create a dynamic digital copy of the device or system in a virtual environment. This concept is not limited to a specific technology, but covers the integrated application of multiple fields such as the Internet of Things, sensing technology, data analytics, and simulation, aiming to achieve a fine-grained management of physical equipment throughout its entire phase, from birth to decommissioning. Initially, the concept of digital twin was proposed for equipment lifecycle management, focusing on transforming physical equipment into digital form. However, with the development of technology, this concept has been further extended to the comprehensive digitization of people, things, objects and other elements of the physical world, aiming to build a virtual realm in cyberspace parallel to the real world, mapping each other, and realizing the close fusion of the physical and virtual worlds to achieve the digital twin of the "interconnection of all things". The concept of digital twin is shown in Figure 2:

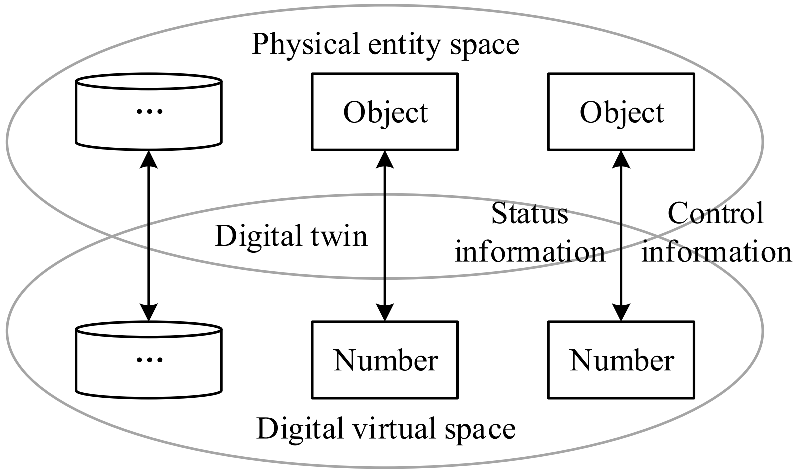

Figure 2: The concept of digital twin

The first task of digital twinning is to create a digital twin model of the application object. The digital twin 3D model is the physical entity, the virtual entity and the connection between the two. The addition of two new dimensions, twin data and services, allows the data twin to be further applied in more domains.

$$MDT = (PE, VE, Ss, DD, CN) \tag{4}$$

Here, the PE denotes the physical entity, the VE denotes the virtual entity, the Ss denotes the service, the DD denotes the twin data, and the CN denotes the connection between the components.

II. B. 2) Key Definitions of Integrated Digital Twin Models

In order to realize the all-round characterization of the physical space, it is necessary to establish an integrated digital twin model for tomb mural restoration. The full life cycle management and visualization of the tomb chamber mural painting restoration is still the key problem to be solved by the digital twin model, and the integration and fusion of multi-dimension, multi-scale, multi-scene, and multi-service is the main challenge for the construction of the integrated digital twin model, and the following key definitions are needed firstly in the process of establishing the integrated digital twin model:

Definition: integrated digital twin model (IDTMBM) for tomb mural restoration:

$$IDTMBM = \{M-DIM, M-SCA, M-SCE, M-SER\} \tag{5}$$

where $M-DIM$ is a multi-dimensional digital twin, $M-SCA$ is a multi-scale digital twin, $M-SCE$ is a multi-scene digital twin, and $M-SER$ is a multi-service digital twin.

The integrated digital twin model with multi-dimensional, multi-scale, multi-scene and multi-service features is a high-fidelity dynamic evolution model with a high degree of integration and fusion. The construction of the integrated digital twin model should firstly ensure the multidimensional features, and the multidimensional modeling is mainly based on the multidisciplinary modeling strategy of the digital twin, i.e., fusion of geometrical model, physical model, behavioral model and rule model; and then, the multi-scale and multi-scene features should be incorporated into the model construction process, and the incorporation of the multi-scale features refers to the model construction process should satisfy the model construction strategy from small to large, from local to global, and from simple to complex. The integration of multi-scenario features means that the model construction should take into account the multi-condition operation characteristics of the tomb mural restoration, and fully simulate all possible working conditions encountered in the process of the tomb mural restoration: the integration of multi-service features is in the late stage of the model construction, so that the model obtained by the construction of the targeted service characteristics, and to give the model a specific service task.

III. Analysis of the effectiveness of the restoration program of tomb mural paintings based on digital twin technology

III. A. Analysis of model validity

This paper takes a tomb mural as the research object, the whole mural is 3.22 meters high and 5.97 meters wide, due to the huge length, the mural is preserved in pieces by uncovering. The data were collected with SinarP2 camera, and the lens was Schneider APO lens. The shooting method is contactless, and each row is shot in order from left to right. The data of 650 mural paintings with rich texture details were sieved out to reach 6245 after data augmentation, of which 5045 were training data, 600 were testing data, and 600 were validation data.

One of the images is selected for analysis, and the comparison results of BSCB, TV and CDD models in terms of PSNR, SSIM and MSE are shown in Table 1.The CDD model outperforms the BSCB and TV models in terms of PSNR (25.028) and SSIM (0.8826), and its MSE is reduced by 42.39% compared with that of the BSCB, which is attributable to curvature-driven propagation. This is attributed to the fact that the curvature-driven propagation mechanism enhances the edge structure retention ability by introducing geometric curvature parameters, which more accurately balances the diffusion direction with the texture coherence during the energy generalization optimization process.

Table 1: Comparison results of each test index

	BSCB	TV	CDD
PSNR ↑	20.8742	22.973	25.028
SSIM ↑	0.8372	0.8503	0.8826
MSE ↓	0.0092	0.0077	0.0053

Further exploring the results of the model for different types of mask repair, the performance level comparison of the three models on epitaxial mask, crack mask, small mask and large mask is shown in Table 2.The CDD model achieves the highest accuracy in all types of scenarios, especially in the repair of small mask, the PSNR is as high as 36.5265, which verifies the advantage of the curvature function in adapting to the elongated structure and complex topology.

Table 2: Comparison of mask repair results of different types

		BSCB	TV	CDD
Epitaxial mask	PSNR ↑	21.0583	24.6266	28.2867
	SSIM ↑	0.8042	0.8352	0.9037
	MSE ↓	0.0073	0.0066	0.0045
Crack mask	PSNR ↑	23.9275	29.0286	34.2975
	SSIM ↑	0.9042	0.9286	0.9663
	MSE ↓	0.0042	0.0031	0.0022
Small mask	PSNR ↑	25.3371	31.8742	36.5265
	SSIM ↑	0.9136	0.9301	0.9771
	MSE ↓	0.0021	0.0013	0.0007
Large mask	PSNR ↑	20.8635	24.1864	28.0039
	SSIM ↑	0.7028	0.8275	0.8993
	MSE ↓	0.0089	0.0059	0.0046

Due to the long-term underground environment of the tomb chamber murals, excessive humidity in the air and soluble substances in the groundwater tend to crisp up the walls, and these factors lead to irregular shedding of the murals. The influence of microorganisms can also cause damage to the mural paintings in the burial chamber. The analysis is carried out for murals with different types of diseases, and the performance levels of the three models on irregular mask, random mask and two kinds of disease superimposed mask are compared as shown in Table 3.The CDD model still maintains a high level of performance in superimposed mask restoration, and the PSNR exceeds that of the BSCB and the TV model by 78.58% and 38.04%, respectively, which proves that its multi-geometric information fusion strategy can effectively deal with the microbial erosion and physical spalling composite damage of complex disease patterns.

Table 3: Repair results of different types of disease masks

		BSCB	TV	CDD
Irregular mask	PSNR ↑	24.0284	27.8624	32.8621
	SSIM ↑	0.9026	0.9286	0.9463
	MSE ↓	0.0017	0.0012	0.0003
Random mask	PSNR ↑	21.0852	23.4372	26.8631
	SSIM ↑	0.8518	0.8936	0.9221
	MSE ↓	0.0033	0.0025	0.0011
Superimposed mask	PSNR ↑	15.5257	20.0853	27.7256
	SSIM ↑	0.7837	0.8862	0.9414
	MSE ↓	0.0094	0.0059	0.0008

III. B. Digital twin modeling

In this paper, in order to solve the problem of how to reasonably determine the LIDAR installation positions (O1, O2, O3), a series of field tests were carried out at the murals described in the case study. By comparing the actual heights and measured values of different measurement points in the mural, the effect of different installation positions on the scanning accuracy of LIDAR can be assessed, and the data consistency of the geometric dimensions in the digital twin can also be evaluated. The positional parameters of the different installation schemes are shown in Table 4.The distribution of O1 position is between 25~29m, and the difference in the distribution of O2 and O3 positions is smaller.

Table 4: LiDAR Position Information

Scheme Number	O1(m)	O2(m)	O3(m)
A	29	0.7	1.1
B	25	0.8	1.3
C	28	0.6	1.2
D	27	0.8	1.2
E	26	0.9	1.2
F	28	0.7	1.3

The measured values are then obtained from the digital twin system, that is, the coordinates derived from 3D reconstruction after LIDAR scanning. This paper compares the effect of different installation positions of LiDAR on scanning accuracy, and the results of the comparison between the actual value and the measured value error are shown in Table 5. The mean value of measurement error of scheme E (9.40m) is 49.11% lower than that of scheme A, and the standard deviation of its error distribution is also the smallest, which can determine the selection of scheme E, and proves the effectiveness of digital twin technology in optimizing the selection of restoration schemes.

Table 5: Comparison results of errors between actual values and measured values(m)

Serial number	Actual height	Error					
		A	B	C	D	E	F
1	48	12	16	-9	-7	11	8
2	72	8	15	-12	9	-5	7
3	66	9	17	25	13	12	-9
4	92	21	-7	16	12	6	-3
5	756	17	7	3	15	12	21
6	552	25	21	14	26	17	12
7	618	21	25	15	27	-6	13
8	803	15	11	24	13	15	-19
9	1022	12	14	15	-8	14	-17
10	1128	33	-9	12	16	8	8
11	1205	27	23	-9	14	-3	4
12	1311	12	21	12	-9	9	6
13	836	26	16	15	-11	-7	9

14	905	15	-9	11	-5	11	-5
15	75	24	21	17	16	5	7
Average error		18.47	15.47	13.93	13.40	9.40	9.87

III. C. Digital Display Design of tomb Chamber murals

Exhibition activities are a carrier of information exchange. The curator conveys various relevant information through display mediators in a specific display environment, while the participants have an acceptance problem in the process of receiving the information, that is, the problem of reaching a consensus between visual reception and psychological reception. Finally, the curator's expression communicates with the audience's mind through graphic mediators to achieve the effect of communication.

In the era of mobile Internet, digital display has become a cultural form in the context of The Times, with the aim of effective information dissemination and providing cultural experience and consumption activities. Digital display design is evolving with the development of digital twin technology, expanding from traditional visual images to multi-dimensional immersive and emotional experience displays, and from static presentation of exhibits to dynamic communication. Through the iteration of digital twin technology, display media have emerged such as the Internet, mobile terminals, interactive device experiences, and virtual immersion, greatly expanding the cultural forms of information exchange and enriching the emotional experiences of the audience. It has promoted the transformation of the concept of traditional exhibition design from the "language era" of exhibition media to the "information culture".

Tomb chamber murals, as a World cultural heritage site, possess world-class cultural value and are also the carriers of the Chinese nation's spirit and culture. The most common digital display methods of tomb murals at present include digital restoration, digital images, digital animations, interactive experience design, etc. The use of digital twin technology to integrate the content of the murals gives the audience a new multi-sensory display experience of sight, hearing, touch and entertainment, which also makes digital display design more competitive in cultural inheritance.

On June 9, 2018, the Dunhuang Academy and Tencent jointly created a demonstration project through "technology + culture", which included innovative Dunhuang elements, H5 display, digital image display, game interface design, etc. It greatly enriches the popular science explanation of the murals, and also creates cultural and creative designs in the application of murals' colors and patterns. Through multiple channels, it enables people to display Dunhuang and encourages users to actively explore the cultural value and contemporary significance of the murals.

IV. Conclusion

This paper utilizes digital twin technology to digitally protect the murals in the tomb chamber, and specifically conducts application and exploration from two aspects: digital restoration and digital display. In terms of digital restoration, digital twin modeling is used to precisely establish different types of data such as mural images, colors, and diseases, providing data support for mural research and restoration. In terms of digital display, through methods such as digital images, digital animations, and interactive experience design, digital twin technology is used to integrate the content of murals, providing audiences with a new multi-sensory display experience including visual, auditory, tactile, and entertainment.

With the rapid development of information technology, the utilization of advanced digital twin technologies such as artificial intelligence, virtual reality, multimedia, broadband networks and databases can provide more powerful means for the protection of tomb murals. However, digital protection technology still faces challenges. Future research can be carried out from the following three aspects: Firstly, at the basic research level, a complete knowledge system for the digital protection of murals should be established to provide comprehensive and systematic theoretical support for it. Secondly, at the technical level, it is necessary to continuously deepen the research level of computer-related disciplines, improve existing digital conservation technologies, and develop new technologies. Finally, in terms of application, we should widely absorb the advanced research results from other disciplines, rely on multi-disciplinary cooperation, learn from each other's strengths to make up for our weaknesses, and better achieve the protection and inheritance of cultural heritage.

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