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Hyperspectral Imaging-based Extraction of Exfoliation and Degradation Areas in Dandan Oilik Murals

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Abstract: Ancient murals are invaluable cultural heritage, yet they commonly suffer from degradations such as flaking and cracking due to environmental factors. Addressing the issues of severe noise interference and low contrast between disease features and the background in murals from the Dandan Oilik site in Xinjiang, this paper proposes an automated hyperspectral disease area extraction method that integrates spectral dimensionality reduction with spatial enhancement. First, hyperspectral imaging technology was utilized to acquire "image-spectrum integrated" data of the murals. Principal Component Analysis (PCA) was then applied for feature extraction from high-dimensional bands, enhancing the visual saliency of latent diseases through false-color synthesis. Second, to tackle weathering noise on the mural surfaces, the bilateral filtering algorithm was introduced to perform smoothing while preserving edges, combined with the Multi-Scale Retinex with Color Restoration (MSRCR) algorithm to eliminate the effects of uneven illumination and widen the feature separation between diseased and healthy regions. Finally, the K-means algorithm was employed to perform unsupervised clustering within the enhanced feature space, achieving the precise extraction of disease masks. Experimental results demonstrate that when the cluster number is set to K=4, the method effectively isolates exfoliation areas while completely preserving the original linework of the murals. These findings not only provide a scientific reference for the on-site restoration of Dandan Oilik but also lay a foundation for subsequent virtual restoration and spectral information reconstruction of the murals.

1. Introduction

Ancient murals serve as critical carriers of human civilization. However, due to the influence of both natural and anthropogenic factors, degradation phenomena such as cracking and flaking are widespread, making conservation efforts a matter of great urgency. As a pivotal cultural intersection along the Silk Road and a strategic stronghold of the Yutian Kingdom during the Tang Dynasty, the Dandan Oilik site possesses immense research value. Nevertheless, due to prolonged burial beneath windblown sands, the site has suffered severe historical damage and material loss.

The precise extraction of degraded areas is the foundation of cultural heritage conservation and plays a critical "bridging" role in mural protection. On one hand, disease identification provides on-site restorers with scientific degradation distribution maps, guiding precise physical interventions and material applications[1,2]. On the other hand, accurate degradation extraction serves as the logical starting point for computer-aided virtual restoration; only by defining contaminated and missing regions can reliable computational constraints be provided for subsequent texture synthesis, color restoration, and spectral information reconstruction.

Early disease investigations relied primarily on manual on-site inspections by restorers, who recorded disease locations through visual observation and hand-drawn illustrations. This approach is not only time-consuming and labor-intensive but is also heavily influenced by the subjective experience of the investigator, making it difficult to achieve quantitative analysis of degraded areas. To explore degradation mechanisms more deeply, physical and chemical spectroscopic analysis methods were introduced. Techniques such as X-ray fluorescence (XRF) and Laser Raman Spectroscopy (Raman) can accurately identify mineral compositions and fading products on mural surfaces[3,4,5]. Although these methods offer extremely high spectral precision, they are mostly limited to "point measurements" and lack spatial structural information, making it challenging to obtain the macroscopic distribution characteristics of degradations across the mural surface.

With the advancement of computer technology, researchers have begun to utilize image processing algorithms, such as edge detection and threshold segmentation, to automatically extract mural pathologies with prominent visual features, including cracks and flaking[6,7]. However, since RGB images only contain information across three broad bands—red, green, and blue—their capacity for feature identification is limited and easily susceptible to interference from uneven environmental lighting.

To address the limitations of single spatial or spectral dimensions, hyperspectral imaging (HSI) technology offers significant advantages. It enables the simultaneous acquisition of spatial imagery and continuous spectral data of an object, achieving the "integration of spatial and spectral information" (spectral-spatial fusion). Research indicates that the rich spectral information provided by HSI can effectively identify subtle changes in mineral pigments, while the integration of spatial texture features further facilitates the exclusion of background noise[8]. Currently, the synergistic processing of spatial and spectral information using hyperspectral data has become a critical pathway for improving the identification performance of complex surface degradations.

2. Experimental Data Acquisition

2.1. Equipment and Preprocessing

This study employed the FigSpec-IQ-VISNIR portable hyperspectral camera, developed by FIGSPEC, for the digital scanning of the murals, as illustrated in Figure 1. The device features a spatial resolution of 1920×1920 pixels and a spectral resolution of 2.5 nm, capturing 300 continuous spectral bands across a broad wavelength range from 388.57 nm (visible) to 1010.44 nm (near-infrared). High-power halogen lamps with a smooth and continuous spectral energy distribution were selected as the illumination source. Their stable light output effectively suppressed noise interference and enhanced the signal-to-noise ratio (SNR).

Following data acquisition, radiometric calibration was performed.The calibration process was based on the reflectance distribution, utilizing data from a standard white reference board with 99% reflectance and dark current data obtained by covering the lens. A reflectance calibration model was applied to convert the raw intensity values into standard relative reflectance values, as expressed by the following formula:

$$R = \frac{R_{raw} - R_{dark}}{R_{white} - R_{dark}} \times 99\% \tag{1}$$

where R is the calibrated image, R_{raw} represents the raw image, R_{dark} is the dark current data, and R_{white} denotes the standard white board data. To further eliminate noise and improve image quality, a Minimum Noise Fraction (MNF) transform was applied for denoising.

Figure 1. Experimental Apparatus and Equipment

2.2. Introduction of Experimental Data

The mural data used in this study was obtained from the Dandan Oilik site, located in Cele County, Hotan Prefecture, Xinjiang. The site is situated in the heart of the Taklamakan Desert, geographically positioned between the Hotan and Keriya Rivers. During the Tang Dynasty, Dandan Oilik was known as "Jiexie" (a transliteration of the Khotanese name) and served as a crucial strategic stronghold within the defense system of the Khotan military garrison, one of the Four Garrisons of Anxi. As a gateway controlling the southern route of the Silk Road, it was once a multicultural community inhabited by garrisoned troops, their families, and Central Asian merchants, witnessing the prosperity of the ancient oasis civilization[9,10].

Figure 2. Full mural image of CD4:04, Dandan Oilik site

Due to the dual impact of prolonged burial beneath shifting sands and intense weathering, the murals at the Dandan Oilik site have suffered extremely severe damage. To ensure the scientific conservation of this cultural heritage, the Joint Sino-Japanese Academic Expedition to Dandan Oilik

(2009) conducted the rescue-oriented detachment of these endangered murals during their investigation. The nomenclature of the experimental data in this paper follows the field numbering system established in the expedition report: the samples were sourced from the CD4 Buddhist Temple site in the western part of the ruins' northern sector. Specifically, the research subject is the CD4:04 mural fragment from the eastern wall of the temple. Figure 2 displays the complete pattern of this mural, while a specific sub-region selected for this study is shown in Figure 3.

Figure 3. Selected study area and magnified views of specific features.

3. Methods

3.1. Spectral Information Dimensionality Reduction

In this study, Principal Component Analysis (PCA) was employed to extract the core spectral information from the Dandan Oilik mural fragments. The primary objective of PCA is to identify a set of mutually orthogonal unit vectors in the original data space, such that the projection of the data onto these vectors maximizes variance. The first direction represents the axis of maximum variance in the original data, and the second direction represents the axis of maximum variance within the plane orthogonal to the first, and so forth[11]. The computational process of PCA is described as follows:

First, the original mural spectral data are centralized to obtain the matrix $\tilde{X}$; where μ is the mean vector of the original data.

$$\tilde{X} = X - \mu, \mu = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{2}$$

Subsequently, the covariance matrix Σ of the centralized data is calculated to measure the degree of correlation between different spectral bands:

$$\Sigma = \frac{1}{n}\tilde{X}^{\top}\tilde{X} \tag{3}$$

An eigenvalue decomposition is then performed on the covariance matrix to obtain the eigenvector matrix W and the diagonal matrix of eigenvalues Λ:

$$\Sigma W = W\Lambda \tag{4}$$

Finally, the original data are projected onto the principal component space using the resulting eigenvector matrix to obtain the principal component matrix Z:

$$Z = \tilde{X}W \tag{5}$$

After the extraction of principal components, the top three components with the highest contribution rates are selected for color space mapping. These components are mapped to the Red (R), Green (G), and Blue (B) channels, respectively, to synthesize a false-color image, thereby enhancing visual contrast for feature identification.

3.2. Spectral Information Dimensionality Reduction

After synthesizing the false-color images of the Dandan Oilik murals, direct clustering often results in significant fragmented misclassifications due to granular noise caused by natural weathering in the original imagery. Consequently, this study introduced the Bilateral Filtering algorithm to smooth the synthesized images. Unlike traditional convolutional smoothing filters, bilateral filtering incorporates a pixel value similarity component in addition to the spatial domain[12]. When processing objects with complex textures like the Dandan Oilik murals, this algorithm adaptively adjusts weights based on intensity differences between pixels. This allows it to smooth the image while preserving edges without the need for iteration, offering strong locality and ease of operation.

The specific mathematical definition is as follows: for a target pixel x and its neighboring pixel y in the false-color image, the output value $I_{filtered}(x)$ is determined by both the spatial proximity factor G_{σ_s} and the intensity similarity factor G_{σ_r}. Here, W_p represents the normalization weight term:

$$I_{filtered}(x) = \frac{1}{W_p} \sum_{y \in S} I(y) G_{\sigma_s}(\parallel x - y \parallel) G_{\sigma_r}(|I(x) - I(y)|) \tag{6}$$

To further enhance image contrast, the Multi-Scale Retinex with Color Restoration (MSRCR) algorithm was implemented. Based on the Retinex theory of human visual color constancy, this algorithm aims to eliminate the influence of environmental illumination from the observed image to restore the essential reflective properties of the object[13]. It ensures overall color continuity at large scales while accentuating flaking edges at small scales. Furthermore, to address the "color graying" phenomenon that may occur during multi-scale processing, the algorithm introduces a color restoration factor to dynamically correct the proportions of the RGB channels, maintaining the original color as much as possible.

The specific algorithmic model is as follows: for the i band in the image, the MSRCR output $R_{MSRCR_i}(x, y)$ can be expressed as:

$$R_{MSRCR_i}(x, y) = C_i(x, y) \sum_{n=1}^{N} w_n(log\, I_i(x, y) - log[F_n(x, y) * I_i(x, y)]) \tag{7}$$

where $C_i(x, y)$ is the color restoration coefficient, w_n is the weight for each scale, and F_n is the Gaussian surround function with a standard deviation of σ_n.

3.3. Unsupervised Clustering for Disease Extraction

The study employed the K-means clustering algorithm to achieve the automated extraction of damage masks for the Dandan Oilik murals. As a classic unsupervised machine learning algorithm, the core principle of K-means is to partition the dataset into K disjoint clusters through an iterative process, minimizing the sum of squared Euclidean distances between each pixel and its assigned cluster center[14].

The mural surface primarily consists of a yellow background, black line work, red pigments, and complex degradations. By setting different cluster numbers K, the study allowed the algorithm to automatically identify pixel sets in the feature space that exhibit similar spectral and spatial texture responses. Through the minimization of the objective function J, the precise isolation of the area to be restored was achieved:

$$J = \sum_{j=1}^{K} \sum_{i=1}^{n} \| x_i^{(j)} - c_j \|^2 \tag{8}$$

where $x_i^{(j)}$ represents the$i$ pixel point in the$j$ cluster, and c_j denotes the centroid of that cluster.

4. Results

4.1. PCA Extraction Results

Due to the severe damage of the site's murals and significant environmental noise interference, the original hyperspectral data exhibited extremely high correlation and information redundancy between adjacent bands. Through PCA transformation, the data were reconstructed into an orthogonal feature space, effectively achieving information condensation and noise separation, which highlights the exfoliation boundaries caused by weathering. As shown in Figure 4, the first three principal components (PC1, PC2, and PC3) enhanced the mural information to varying degrees.

Furthermore, by mapping these first three principal components to the R, G, and B channels for false-color synthesis, the results demonstrated a wider dynamic range and stronger color contrast compared to conventional RGB images. In the synthesized imagery, the latent exfoliation boundaries—previously difficult to discern with the naked eye—presented distinct color gradients. This not only clearly defined the extent of disease spread but also provided a high-quality visual reference for the subsequent extraction of damage masks.

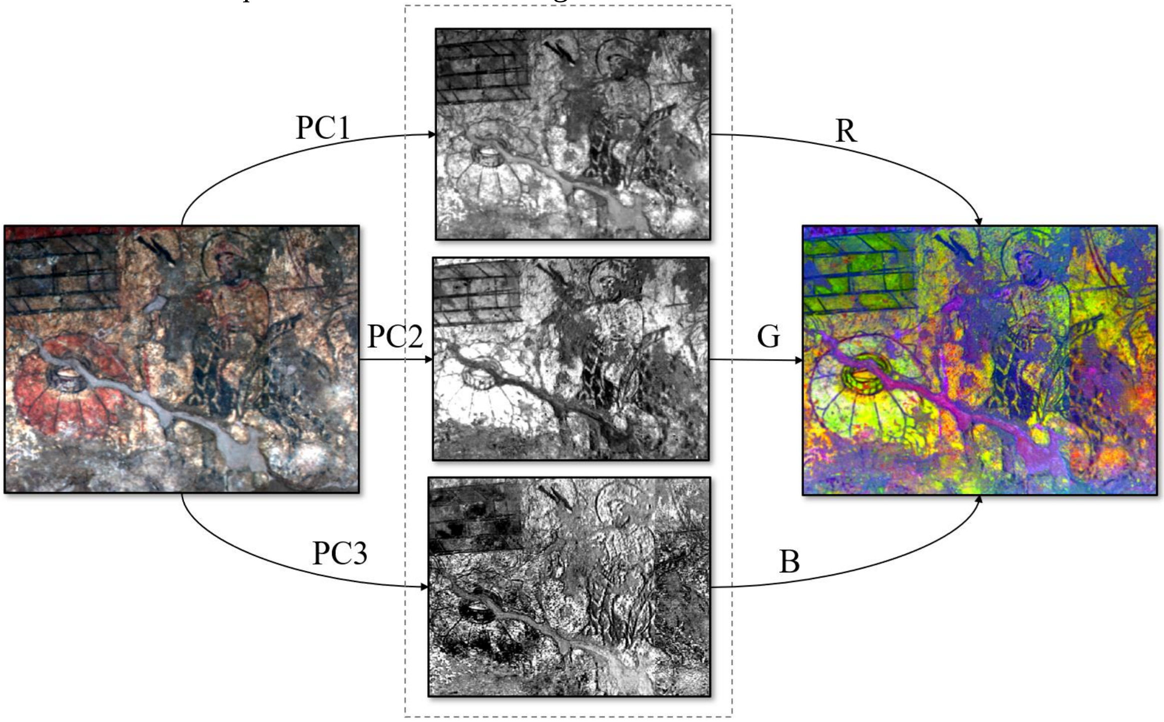

Figure 4. PCA extraction results and False Color Composite (FCC) image of Dandan Oilik murals

4.2. Spatial Enhancement Results

Through bilateral filtering, the mural surface noise was effectively filtered while maximizing the morphological integrity of the exfoliation areas in the fragments. As shown in Figure 5, the mural fragments processed with bilateral filtering appear visually smoother and cleaner.

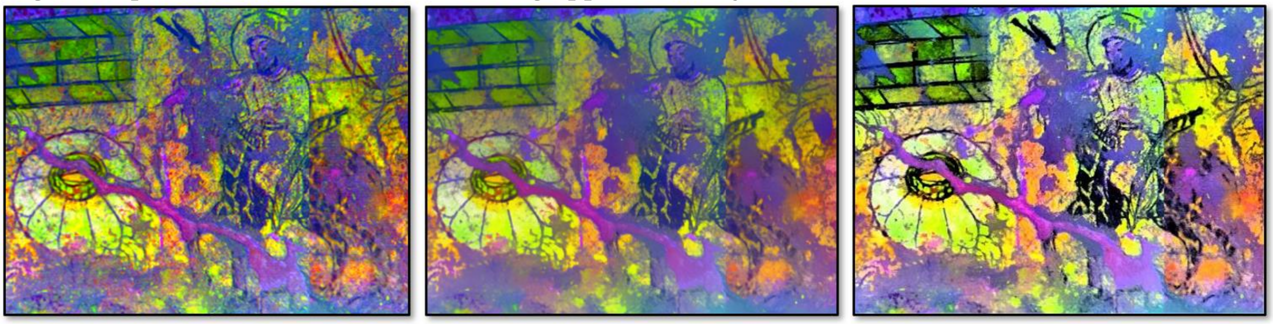

Figure 5. Enhancement results of the Dandan Oilik mural false color image (Left: Original image; Middle: Bilateral filtering result; Right: Retinex processing result)

Subsequently, through MSRCR enhancement, the feature separation between the damaged areas and the healthy background of the Dandan Oilik murals was further widened. In the enhanced imagery, the contrast at the disease edges was significantly compensated, making the originally blurred exfoliation contours clear and continuous despite complex background interference. This "edge-preserving denoising" effect not only improved the signal-to-noise ratio (SNR) but also directly optimized the capability of subsequent segmentation algorithms to capture disease boundaries.

4.3. Degradation Extraction Results

Figure 6 illustrates the classification results. Through this algorithm, the complex mural imagery was transformed into a category map with explicit semantic information. The cluster representing the damaged areas was extracted and binarized to generate the final mask for restoration. Comparative experiments on the clustering parameter K revealed significant variations in performance:

1) At K=3: The algorithm suffered from a "feature capture" phenomenon due to excessively coarse classification granularity. Specifically, the exfoliation areas and the critical black outlines of the murals were merged into a single category, causing the mask to include a large amount of non-disease structural information.

2) At K=4: Although preliminary separation between the background and diseases was achieved, significant misclassifications occurred in the facial regions of the figures. Such misidentification could lead the restoration model to destroy original facial contours during the reconstruction process.

In contrast, the selected clustering result at K=4 demonstrated the optimal interpretation performance, enabling the relatively complete extraction of exfoliation areas. Figure 6 also presents the spatial overlay of white masks generated by different k values onto the enhanced imagery. As observed in the figure, the black line work was accurately delineated under this method, effectively preserving the original linear structure of the murals.

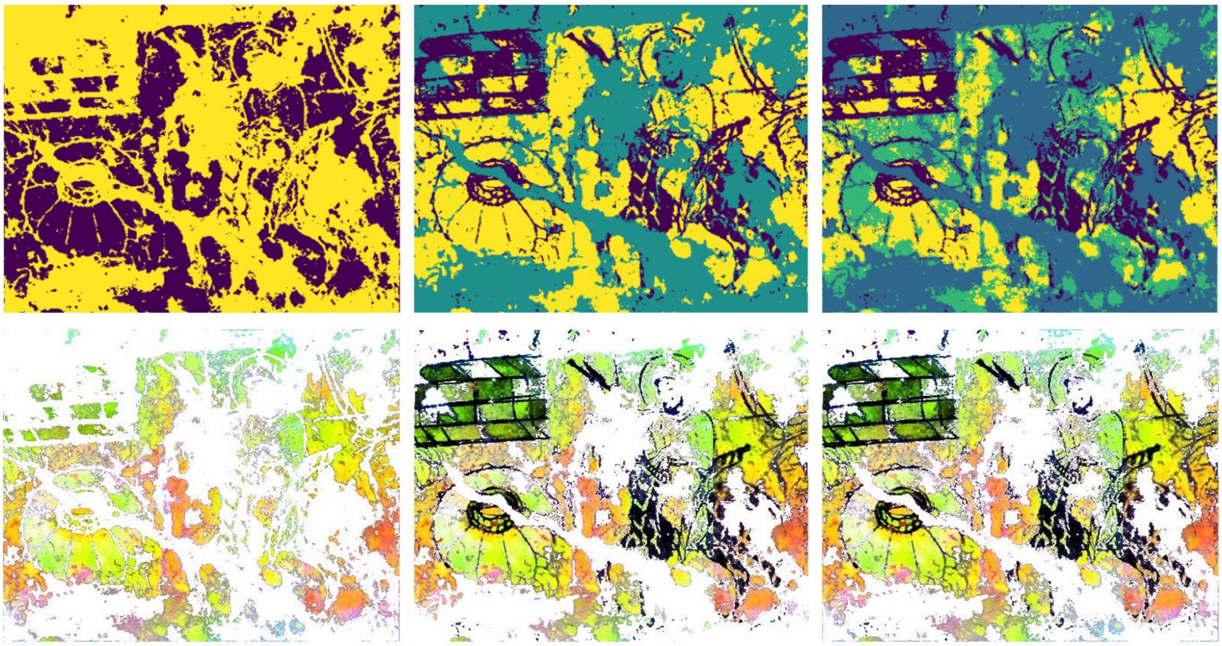

Figure 6. Classification results and mask overlays under different K-values (Left: K=2; Middle: K=3; Right: K=4)

5. Conclusion

This study addressed the challenges of high noise and low contrast in the murals of the Dandan Oilik site. By leveraging hyperspectral spatial-spectral analysis and image preprocessing techniques, a degradation extraction workflow tailored for severely damaged murals was established. The primary findings are as follows:

First, hyperspectral imaging provides multi-dimensional data for the non-contact identification of mural pathologies. By reconstructing high-dimensional spectra through Principal Component Analysis (PCA), redundant bands in the raw data were effectively condensed. This achieved a preliminary separation of degraded areas from healthy pigments within the feature space, demonstrating the efficacy of "spectral-spatial fusion" in capturing latent exfoliation features.

Second, the synergistic application of bilateral filtering and the MSRCR algorithm optimized the input quality for unsupervised clustering. Experimental results indicated that bilateral filtering effectively suppressed surface weathering noise while preserving the gradient information of exfoliation boundaries. Simultaneously, the MSRCR algorithm mitigated uneven illumination through dynamic range compression, objectively widening the feature distance between degraded regions and the background. This approach reduced the overlap of feature distributions, enabling the clustering algorithm to more clearly capture the evolutionary boundaries of different materials, thereby generating degradation masks with more continuous physical contours.

Finally, the workflow established in this study provides fundamental support for the digital preservation of murals. Utilizing computer-aided technology to extract degradation areas significantly enhances the efficiency of manual mapping. The resulting distribution maps not only serve as a scientific reference for formulating on-site restoration plans but also provide essential spatial constraints for subsequent virtual restoration and spectral information reconstruction.

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