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Method of Hidden Strip Information Extraction from Hyperspectral Images of Ancient Paintings

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Ancient paintings are valuable historical heritages of human society with profound cultural connotations. However, the repairing of cracks by pasting rice paper on the back of paintings generates hidden strip information. To accurately extract the hidden strip information in ancient paintings, a method of hidden strip information extraction from hyperspectral images of ancient paintings is proposed. Firstly, we use the minimum noise fraction transform to remove the noise information and convert the image into bands arranged in order of decreasing signal-to-noise ratio. Secondly, we introduce the average gradient and cross-entropy as indicators to evaluate the informativeness of each band. A band that is richer in strip information has a larger gradient, which can be used as a reference for band selection. Finally, we combine the original image with the selected optimal band to complete the extraction of strip information. The results of our paper are expected to be useful in the protection, restoration, and identification of cultural relics.

1. Introduction

Owing to their profound cultural connotations and their relationship with the development of social history, cultural relics are valuable historical and cultural heritage of human society. They can provide a wealth of information for historical research. Among the numerous cultural relics, ancient paintings, which survive in widespread circulation, have strong research value in the fields of cultural relic protection and historical research.[1] However, owing to the use of fragile painting materials and pigments, ancient paintings are easily affected by environmental factors during storage, resulting in information loss such as fading, cracking, and incompleteness.[2,3] To solve the most common problem of cracking for ancient paintings, rice paper strips have often been pasted on the back of cracks to hide traces of repair. As a result, hidden strip information has been introduced through the process of restoring ancient paintings. Therefore, to assist the protection, restoration, and identification of ancient paintings, it is necessary to find an effective technology for identifying hidden strip information.

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For the extraction of hidden strip information of ancient paintings, information enhancement technologies are frequently used, which have a common disadvantage of only collecting a single type of data.[4–6] To compensate for the deficiency of traditional information enhancement techniques of extracting hidden strip information from ancient paintings, hyperspectral imaging has been widely applied in research on cultural relics, such as ancient paintings, manuscripts, and murals.[7–9] Owing to the advantages of this high-resolution, continuous-waveband, and non-contact approach, hyperspectral imaging can express spatial information and spectral information in a single image,[10,11] and it is suitable for extracting the hidden strip information of ancient paintings. However, there are a very large number of bands in hyperspectral images; thus, a preliminary screening method is required to eliminate redundant information and reduce the information dimension.

In general, the current main preliminary screening methods include principal component analysis (PCA), independent component analysis (ICA), and the minimum noise fraction (MNF) transform, which are widely used for extracting hidden information from cultural relics presented as hyperspectral images.[8,12,13] PCA uses a few comprehensive variables to replace the original multiple variables to reduce the data dimensionality, and this approach focuses on the comprehensive evaluation of the information contribution.[14] Peng *et al*. adopted PCA to automatically identify the patterns of relics in the form of painted pottery and murals.[15] However, for PCA it is necessary to acquire some prior information of the observation object in advance. ICA separates a signal into a large number of independent components to unmix data, and this approach focuses on the independence between signals.[16] Salerno *et al*. combined ICA and PCA to successfully extract faded text information in the manuscripts of Archimedes.[8] However, ICA has relatively high requirements for the original data, which will influence the results. The MNF transform can be used to identify hidden information of cultural relics and repair damaged information by transforming the spectral image.[17,18] It can analyze the spectral curves of each band to extract hidden information that cannot be distinguished under visible light. Hou *et al*. extracted the hidden patterns under sooty temple murals through the MNF transform.[9] The crucial issue of the MNF transform is to separate and reduce the dimensionality of the hyperspectral image and to focus the primary information into the first few bands. However, it is unable to separate strip information, giving it extremely limited use in extracting strip information in ancient paintings. In general, in the existing research on the hidden information of cultural relics, the use of the band selection process is still limited to manual assistance. For the multiple bands generated in the MNF transform, the lack of effective band selection indicators is reflected in the limited enhancement of the strip information.

Therefore, as a systematic and reliable method to extract hidden strip information in ancient paintings using hyperspectral images, we propose a method of extracting the strip information in the optimal band. Moreover, to extract the hidden strip information of ancient paintings accurately, the average gradient and cross-entropy are integrated to select the optimal band for extracting strip information.

2. Methods

Figure 1 shows the main technical route for extracting the hidden strip information of ancient paintings, which includes the following three key steps. Firstly, the main information is concentrated in the first few bands using the MNF transform, and the noise in the original data can be separated by eliminating the bands with low signal-to-noise ratios (SNRs). Secondly, according to the characteristics of strips in ancient paintings, the average gradient and cross-entropy are used as reference indicators to select the optimal band with the best enhancement effect. Finally, the optimal band of the image is smoothed by a median filter to obtain the corresponding mask, and the optimal band is combined with the color image to enhance the strips in ancient paintings.

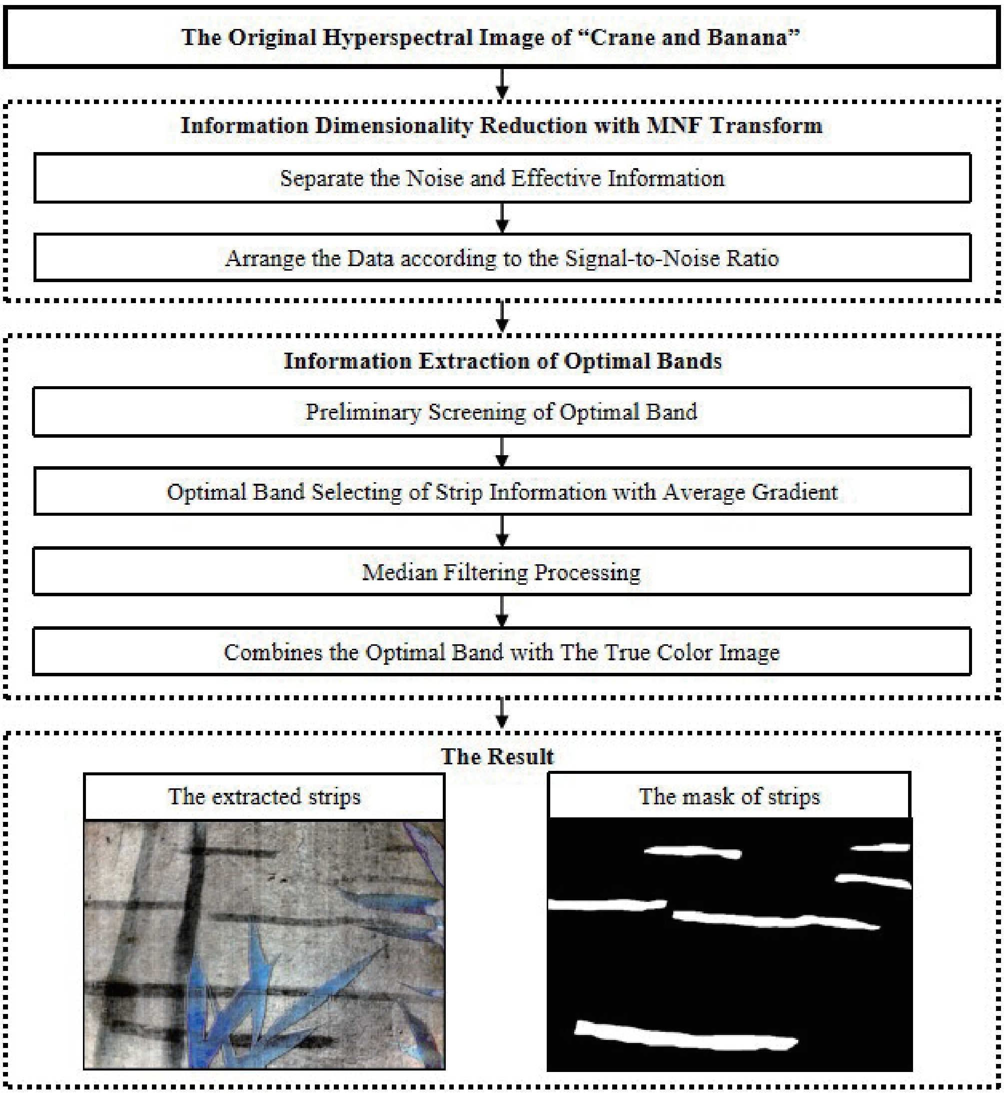


Fig. 1. (Color online) Technology of information extraction from ancient paintings.

2.1 Information dimensionality reduction with MNF transform

In general, there are thousands of bands in a hyperspectral image, and there is a strong correlation between the various bands. Therefore, to accurately identify the information we require in an ancient painting, the MNF transform is used to eliminate the bands with redundant information. Different from in PCA and ICA, the information in the vectors obtained by the MNF transform is not mutually correlated, and the bands are ranked in order of decreasing SNR. This process reserves the bands with high informativeness and less noise, which can reduce the influence of the noise signal on the identification of strip information.(19) The MNF transform is an orthogonal transformation method and can be regarded as a double PCA transform as follows:

(1) The first transformation uses a high-pass filter to effectively separate the noise and the effective information in hyperspectral data, obtain the noise covariance matrix, and diagonalize it, as shown in

$$\begin{cases} \boldsymbol{D_N} = \boldsymbol{U^T C_N U} \\ \boldsymbol{I} = \boldsymbol{P^T C_N P} \\ \boldsymbol{P} = \boldsymbol{U D_N^{-1/2}} \end{cases} . \tag{1}$$

Here, $\boldsymbol{D_N}$ is the diagonal matrix with the eigenvalues of the noise covariance matrix $\boldsymbol{C_N}$ in descending order, $\boldsymbol{U}$ is the orthogonal matrix composed of feature vectors, $\boldsymbol{I}$ is the unitary matrix, and $\boldsymbol{P}$ is the transformation matrix.

When processing the hyperspectral image of the ancient paintings, the original image should be projected into a new space between bands to eliminate the correlation. When the transformation matrix $\boldsymbol{P}$ is used in image X, the image will be projected into a new space Y with $Y = \boldsymbol{P}X$.

(2) The second transformation performs the PCA transform on the noise data and obtains the transformation matrix of the MNF, as follows:

$$\begin{cases} \boldsymbol{C_{D\text{-}adj}} = \boldsymbol{P^T C_D P} \\ \boldsymbol{D_{D\text{-}adj}} = \boldsymbol{V^T C_{D\text{-}adj} V} \end{cases} . \tag{2}$$

Here, $\boldsymbol{C_D}$ is the covariance matrix of image X, $\boldsymbol{C_{D\text{-}adj}}$ is the matrix after the transform $Y = \boldsymbol{P}X$, $\boldsymbol{D_{D\text{-}adj}}$ is the diagonal matrix with the eigenvalues of $\boldsymbol{C_{D\text{-}adj}}$ in descending order, and $\boldsymbol{V}$ is the transformation matrix composed of the feature vectors.

2.2 Information extraction of optimal bands

In general, to extract the strip information on the back of ancient paintings after the MNF transform, the bands with rich information and high discrimination should be selected as the optimal bands. The selection of optimal bands only by the naked eye is inevitably subjective. To obtain authoritative band selection results, it is necessary to combine rigorous evaluation indicators to select the bands with the best information enhancement for the strips. The average gradient describes the average rate of change in the vertical and horizontal directions of a grayscale image, as shown in Eq. (3). The change in the grayscale image value can indirectly reflect the informativeness of a band. Therefore, the average gradient can be used to evaluate the enhancement effect of the strip information, where the average gradient has a positive correlation with the informativeness of strip information.

$$A = \frac{1}{M \times N} \sum_{i=1}^{M} \sum_{i=1}^{N} \sqrt{\frac{f_x^2 + f_y^2}{2}} \tag{3}$$

Here, A is the average gradient of the image, f_x and f_y are the gradients of the image in the horizontal and vertical directions, and $M \times N$ is the image size, respectively.

To make better use of the extracted strip information, we should ensure that the final image has a high similarity to the original painting. Cross-entropy indicates the similarity between two images.[20] It can reflect the enhancement of strip information for different processing methods by comparing the difference between the original true color image and the optimal band, as shown in

$$CE(p,q) = -\sum_{i=1}^{C} p_i \log(q_i)\,. \tag{4}$$

Here, CE represents the cross-entropy, p and q are the values of the same pixel in the two images, c is the number of categories, p_i is the true value, and q_i is the predicted value.

In this study, the true color image of the ancient painting is a full-color image, and the optimal band with strip information is a grayscale image. Therefore, to improve the texture information and color of the grayscale image, the important information in the two images is fused by using hue saturation value (HSV) fusion processing. HSV fusion converts the RGB image to the HSV color space, replaces the value of the true color image with the value of the optimal band, and then converts the result from the HSV space back to the RGB space through an inverse transformation. This process reveals the hue, saturation, and value of the image directly. The specific expressions for the hue, saturation, and value for converting RGB images to HSV color space are given in Eqs. (5)–(9).[21]

$$\begin{cases} C_{\max} = \max\left(R', G', B'\right) \\ C_{\min} = \min\left(R', G', B'\right) \end{cases} \tag{5}$$

$$\Delta = C_{\max} - C_{\min} \tag{6}$$

$$H=\begin{cases} 0^\circ & \Delta = 0 \\ 60^\circ \times \left(\dfrac{G'-B'}{\Delta}+0\right) & C_{\max} = R' \text{ and } G' \geq B' \\ 60^\circ \times \left(\dfrac{G'-B'}{\Delta}+6\right) & C_{\max} = R' \text{ and } G' < B' \\ 60^\circ \times \left(\dfrac{B'-R'}{\Delta}+2\right) & C_{\max} = G' \\ 60^\circ \times \left(\dfrac{R'-G'}{\Delta}+4\right) & C_{\max} = B' \end{cases} \tag{7}$$

$$S=\begin{cases} 0 & C_{\max} = 0 \\ \dfrac{\mathit{\Delta}}{C_{\max}} & C_{\max} \neq 0 \end{cases} \tag{8}$$

$$V = C_{\max} \tag{9}$$

Here, H is the hue of the image; S is the saturation of the image; V is the value of the image; Δ is the difference between the highest and lowest values; R', G', and B' are the normalized values of the RGB channel; $C_{\max}$ is the maximum value among R', G', and B'; and $C_{\min}$ is the minimum value among R', G', and B'.

3. Experiment and Results

In this study, the famous ancient painting *Crane and Banana* by Sima Zhong in the Qing Dynasty was selected as an experimental object that contains strip information. As shown in Fig. 2, although there are many obvious creases and cracks on the surface of the ancient painting, the strips behind the painting cannot be recognized by the naked eye. Figure 2(a) is an orthophoto of *Crane and Banana*. To study the strip information in the painting in a targeted manner, four different areas with rich information are selected. Areas 1–4 with obvious creases and cracks are shown in Figs. 2(b)–2(e), respectively.

3.1 Preliminary screening of optimal band

To eliminate the influence of noisy data, we take Area 3 as an example, and the four areas are processed by the MNF transform. This process eliminates the interference of irrelevant information in image recognition, reduces the dimension of the image, and arranges the bands in order of decreasing SNR. This process results in the emergence of the hidden strips in each scene of *Crane and Banana*. The MNF transform not only removes the noise in the hyperspectral image but also performs segmentation processing on the richly informative band. This process

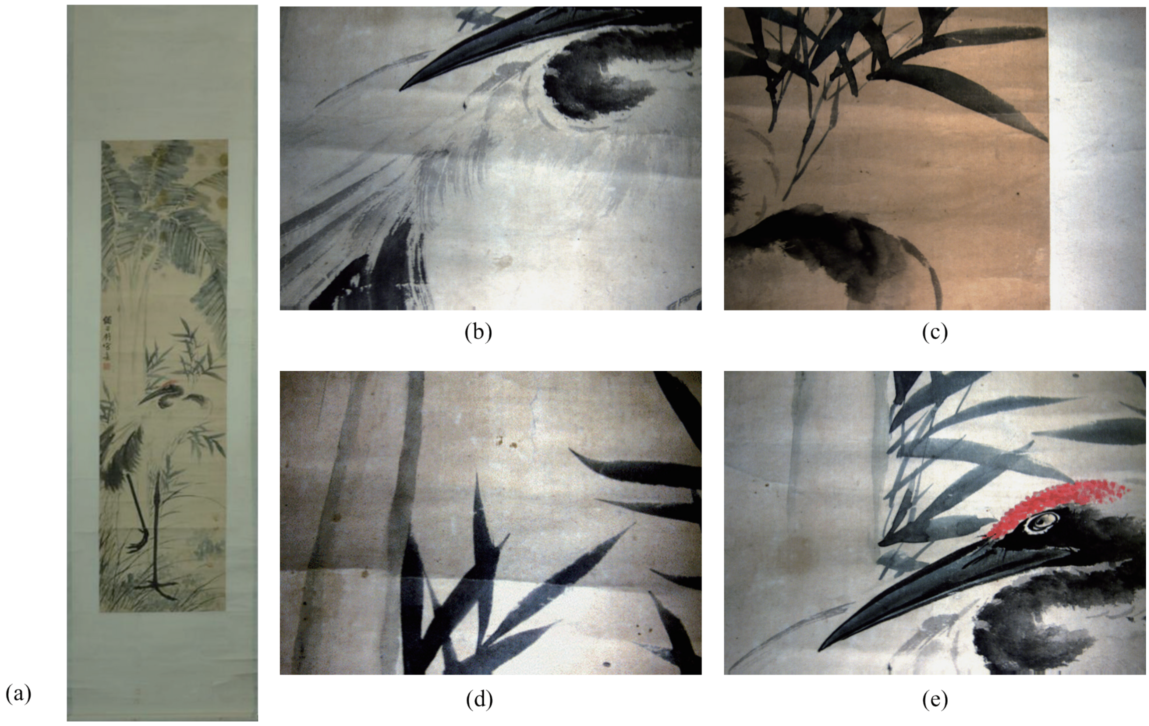


Fig. 2. (Color online) Hyperspectral images of *Crane and Banana*. (a) Panoramic image of the painting, (b) image of Area 1, (c) image of Area 2, (d) image of Area 3, and (e) image of Area 4.

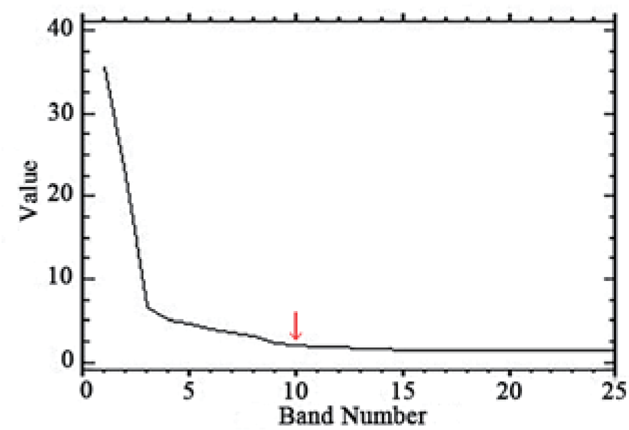


Fig. 3. (Color online) Eigenvalue curve of MNF transform result.

generates thousands of bands, which makes it difficult to select the optimal band. Therefore, it is necessary to perform a preliminary screening.

Figure 3 shows the eigenvalue curve of the MNF transform result, where the vertical axis indicates the information richness of each band and the horizontal axis shows the band number. The eigenvalue curve presents a downward trend, where the information richness first sharply decreases then gradually stabilizes after band 10. There are two turning points in Fig. 3, and the rate of decrease of the SNR slows after each turning point. This indicates that the band is increasingly affected by noise signals. Combining this result with the information distribution of the strips after the MNF transform in Fig. 4, we can confidently conclude that the noise information in band 10 will strongly disturb the image. Therefore, band 10 is a special inflection point, and the change in the amount of information in the bands after band 10 is negligible. As a result, the important information of *Crane and Banana* is basically concentrated in the top 10 bands.

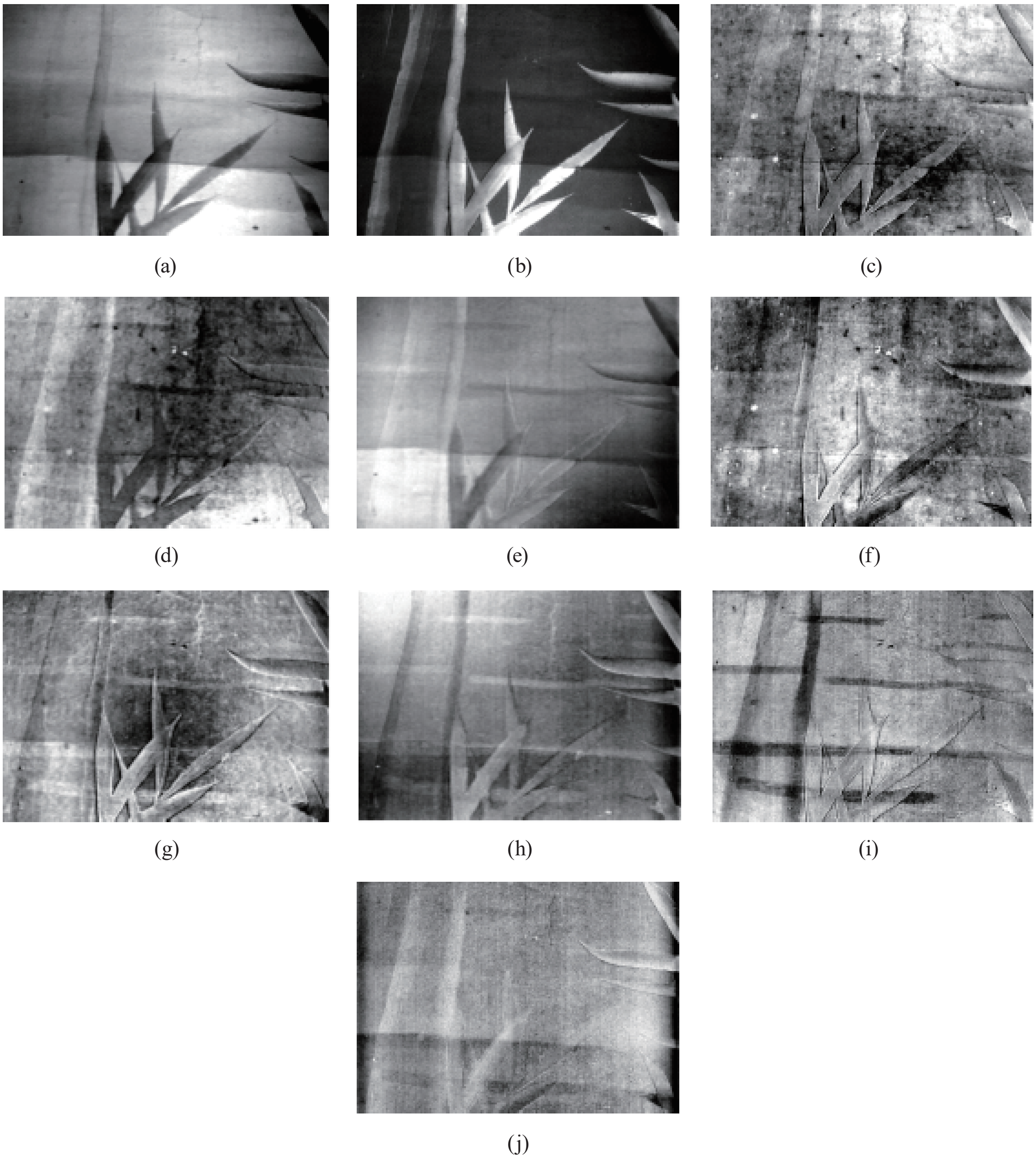


Fig. 4. (Color online) Information distribution of strips after MNF transform. (a) Band 1, (b) band 2, (c) band 3, (d) band 4, (e) band 5, (f) band 6, (g) band 7, (h) band 8, (i) band 9, and (j) band 10.

Therefore, we set the threshold of the MNF transform to 10 to preserve as much information as possible in the first 10 bands. Preliminary screening by the naked eye suggests that the strip information can be found in bands 4, 5, 7, 8, 9, and 10 of *Crane and Banana*, as shown in Fig. 4. Indeed, the strip information is relatively easy to distinguish in bands 4, 7, 8, and 9.

3.2 Selection of optimal bands containing strip information

After preliminary screening of the bands, it is essential to use rigorous indicators to select the optimal bands containing strip information. Among the evaluation indicators, the average gradient can quantify the contrast of details and the texture transformation in the image. The average gradient expresses the informativeness of each band in the image, which is proportional to the informativeness of the image. Therefore, the average gradient is used as the evaluation index of the optimal band in the painting, which can effectively reflect the enhancement effect of the strip information.

The average gradients of the four different areas in *Crane and Banana* are shown in line charts in Fig. 5. The horizontal axis is the band number of the four different areas and the vertical axis indicates the average gradient in the corresponding band. The average gradient tends to increase with the band number. The average gradients of bands 9 and 10 in Areas 1, 2, and 3 are significantly higher than those in the other bands. Also, in Area 4 the average gradients of bands 8 and 10 are significantly higher than those in the other bands. By combining these results with the results of visual interpretation, we demonstrate that the enhancement effect of strip information is greater for a higher average gradient of the band. However, in the case of too much noise, the enhancement effect of the strip information is poor; thus, band 10 is excluded from our consideration. The band with the largest average gradient excluding band 10 is selected. As a result, we find that band 9 is the optimal band in Area 3 of the painting.

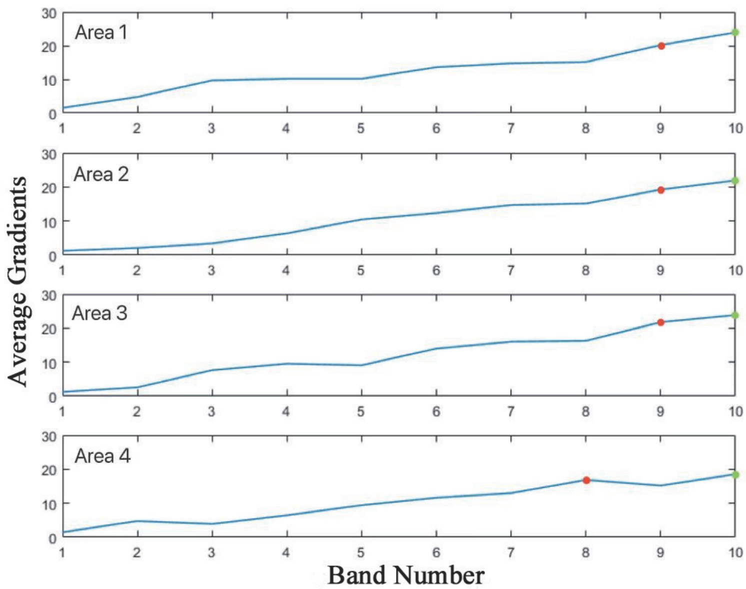


Fig. 5. (Color online) Average gradients of four different areas in *Crane and Banana*.

Images of Areas 1 and 3 are shown in Figs. 6(a) and 6(b), respectively. The top two images are the original images and the bottom two images are those for the selected optimal band. To make the strip information for the optimal band more convincing, we compare the original image with the optimal image. This comparison reveals a marked increase in the clarity of the strip information in the image for the optimal band.

3.3 Extraction of strip information

Although the strip information is obtained in a single band, it still inadequate to reflect the strip information in a painting. The use of a single band causes a loss of richness of the texture information of the ancient painting. To display the strip information clearly, the optimal band is processed with the true color image of *Crane and Banana* by HSV image fusion. This process combines the strip information with the rich texture information to improve the clarity of the strips. Since there are still noise signals in the optimal band of the ancient painting, median filtering is performed on the selected optimal band before HSV fusion. Figure 7 reveals the enhancement effect of the strip information in Areas 1 and 3 by comparing the original images with the resulting images. Figure 8 shows the mask of the strip information, which is extracted from Fig. 7 on the basis of experience. Then the mask is built to calculate the band number.

Figure 7 shows an excellent enhancement effect in the resulting image, allowing the strip information to be recognized clearly. By comparison with the original image, the strip

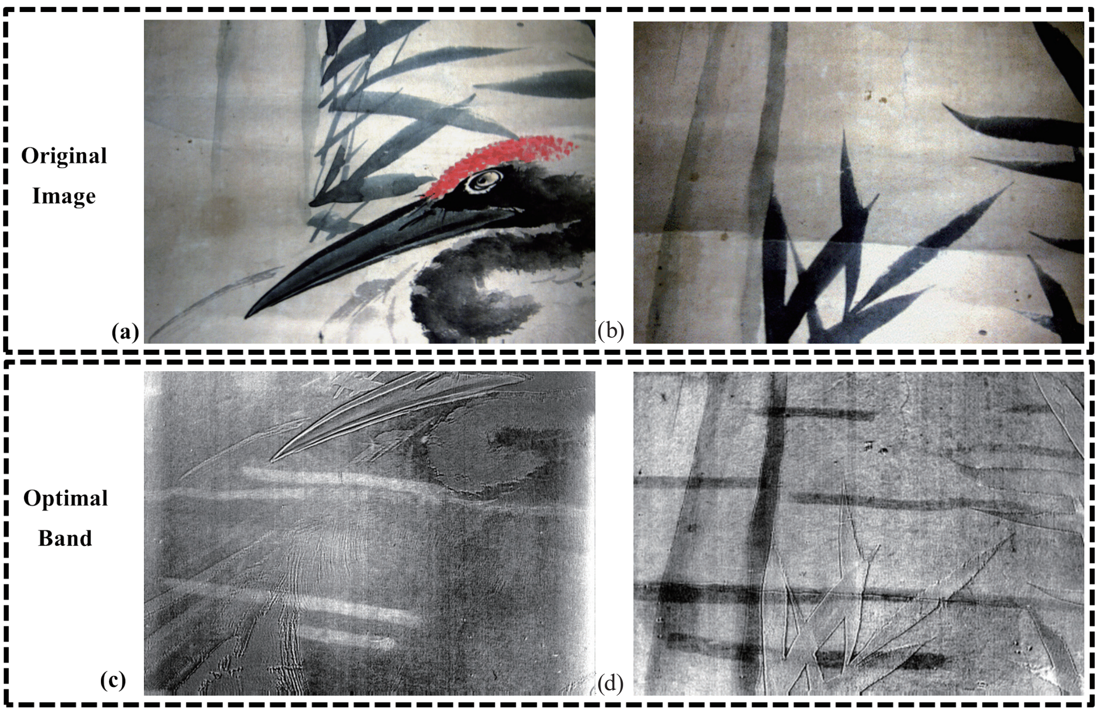


Fig. 6. (Color online) Enhancement effect of strip information. (a) Original image of Area 1, (b) original image of Area 3, (c) optimal band of Area 1, and (d) optimal band of Area 3.

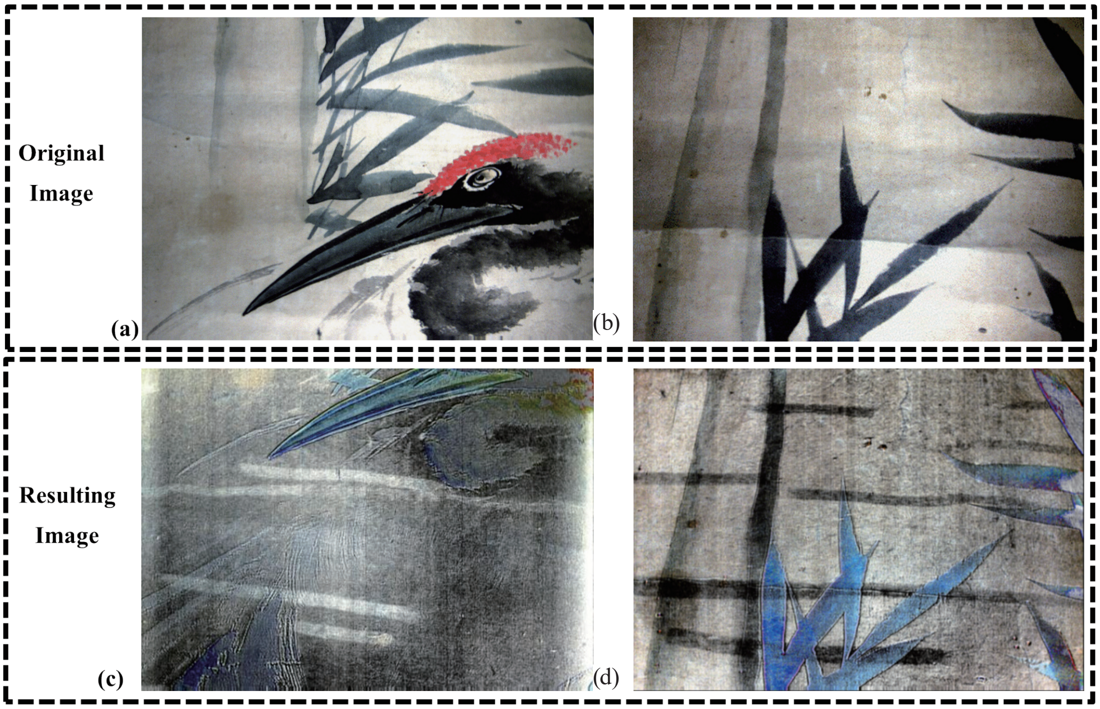


Fig. 7. (Color online) Enhancement result of strip information. (a) Original image of Area 1, (b) original image of Area 3, (c) resulting image of Area 1, and (d) resulting image of Area 3.

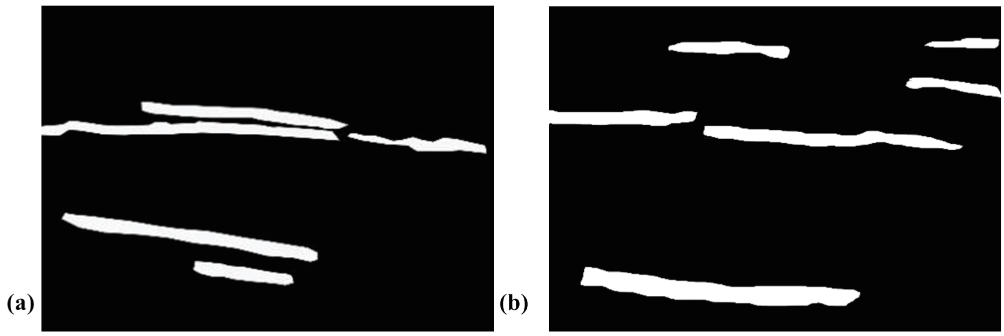


Fig. 8. Mask of strip information. (a) Mask of Area 1 and (b) mask of Area 3.

information in *Crane and Banana* can be clearly identified in the processed image. This reveals that the method effectively enhanced the strip information and indicated the position of strip information in the ancient painting.

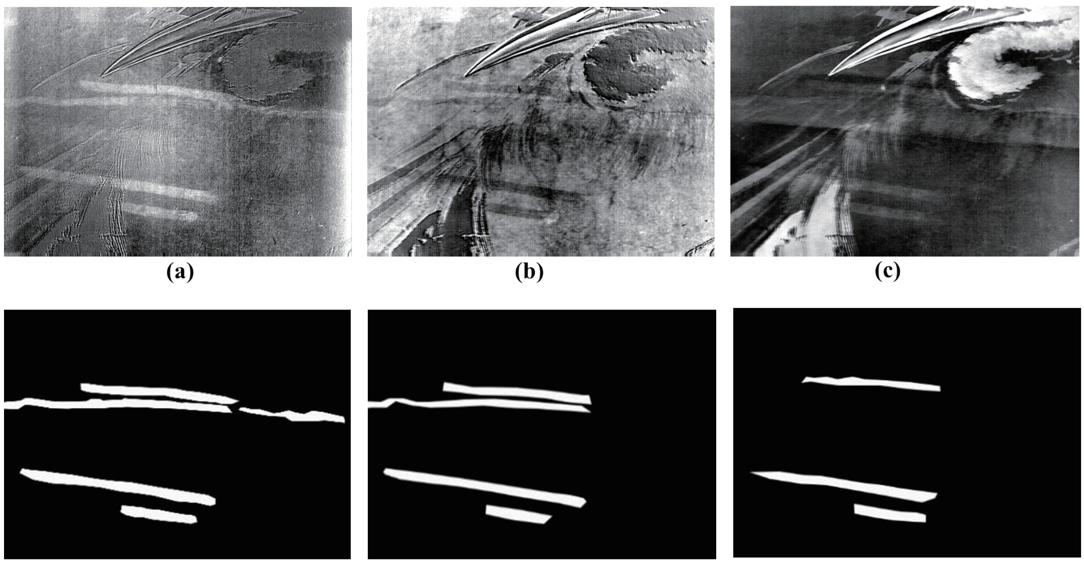
Careful observation of the strip information in the painting revealed that the strips are mainly distributed in the middle and bottom parts of the painting. It is speculated that the painting has been alternately hung for display and rolled up for storage many times during the preservation process. In the process of display and storage, the paper of the painting is repeatedly stretched, destroying the structure of the paper. In addition, the cumulative effects of unsuitable preservation conditions for the paintings, the aging of the painting materials, and other factors have caused the fragile painting materials to crack. Therefore, to prolong the life of the paintings, craftsmen have repaired these cracks, and the strip information is the repair traces of these cracks. This discovery can provide auxiliary information for the identification of ancient paintings and a reference for their future protection and restoration, increasing the comprehensiveness of information about ancient paintings.

3.4 Comparison and analysis

In addition to the MNF transform, methods such as PCA and ICA are also widely used in the research on extracting hidden information from painted cultural relics. To verify the effectiveness of the strip information enhancement method using the MNF transform, the hyperspectral image of Area 1 in *Crane and Banana* was processed by this method, and the result was comprehensively compared with those of PCA and ICA, as shown in Fig. 9.

Compared with PCA and ICA, the enhancement of the strip information in the image processed by the MNF transform is the clearest. Using only the naked eye, it is not possible to accurately compare the enhancement effect of the strip information. Therefore, the cross-entropy is used to evaluate the results. It can reflect the difference between the original image and the processed image and thus evaluate the information enhancement because of its positive correlation with the enhancement effect on strips. Therefore, the cross-entropy is used as an indicator to evaluate the enhancement effect of strip information.

Table 1 shows the value of the cross-entropy and the number of strips for each method. As shown in Table 1, the cross-entropy of Area 1 of the image processed by our proposed method exceeds that of the images processed by PCA and ICA. Comparing the masks obtained after the



(a) (b) (c)

(d) (e) (f)

Fig. 9. (Color online) Enhancement results of PCA, ICA, and the strip information enhancement method. (a) Result of the strip information enhancement method using MNF transform, (b) result of PCA, (c) result of ICA, (d) mask of the strip information enhancement method using MNF transform, (e) mask of PCA, and (f) mask of ICA.

Table 1
Comparison of enhancement results between PCA, ICA, and our method.

	PCA	ICA	Strip information enhancement method
Cross-entropy	0.1089	0.0281	0.2707
Strip number	4	3	5

enhancement result, we find that the number of strips for the MNF transform is also larger than that for the other methods. Therefore, the strip information enhancement method can achieve satisfactory strip information enhancement, and the visual effects of the strip information in *Crane and Banana* exceed those when PCA and ICA are employed. This indicates that the MNF transform has unique advantages in processing the strip information in ancient paintings.

4. Conclusion

The extraction of hidden information in painted cultural relics is an arduous but meaningful task, which can provide sufficient background knowledge and reference for their identification and restoration and related scientific research on cultural relics. The traditional information enhancement technologies have a common disadvantage that they can only collect a single type of data. Hyperspectral imaging is an effective way of extracting strip information in a non-contact manner and expressing the spatial information and spectral information in a single image. Therefore, a method for extracting the hidden strip information in hyperspectral images of ancient paintings is proposed to obtain an in-depth understanding of the strip information of the ancient painting *Crane and Banana*. The main points of this study are summarized as follows.

(1) Hyperspectral images can be effectively used to extract repair traces hidden in ancient paintings in a non-contact manner and provide strong support for the restoration of cultural relics.

(2) Compared with image processing methods such as PCA and ICA, our proposed strip information enhancement method is more convenient to employ. There is less irrelevant noise information in the result and greater enhancement of the strip information.

(3) To obtain authoritative band selection results and enhance the information of strips, the average gradient is used as an evaluation indicator to select the optimal band with the greatest enhancement of strip information. Also, the number of strips is positively associated with the enhancement effect, which will provide statistical support to testify the extraction effect of hidden information. In addition, the cross-entropy is used as an indicator to evaluate the resulting enhancement of the image. All of our results demonstrate the superiority of our method to other methods.

(4) The proposed method highlights the enhancement and distribution of the strip information in the ancient painting, allowing the positions of the strips in *Crane and Banana* to be clearly identified. Moreover, the number of strips identified in the mask reflects the enhancement effect of strip information.

The results of our study have profound application value in the protection, restoration, and identification of cultural relics. In addition, our discovery will facilitate the study of other ancient paintings to reveal the strip information and determine the condition of the paintings. In the future, the information enhancement method can be combined with the pigment recognition method. To distinguish information through different pigment spectral curves, we will extract more reliable strip information.

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