Study on Detection Method of Foxing on Paper Artifacts Based on Hyperspectral Imaging Technology

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Abstract Paper artifacts are contaminated by external factors in the process of preservation such as foxing. For the problem of backward technology of rapid detection of foxing on paper artifacts, a method based on hyperspectral imaging technology is proposed to detect foxing spots on paper artifacts. After selecting the region of interest and obtaining the corresponding average reflectance, the difference in the average reflectance is found after comparing the healthy regions with the diseased regions. Using band operation and minimum noise fraction to observe the characteristics of foxing image, although there is overlap in different parts, the distribution distinction between moldy and healthy regions is obvious; K-nearest neighbor method and BP neural network are applied to establish the spectral discrimination model of paper artifacts with foxing spots, and the overall discrimination rate of the two methods is 73.3% and 85%, respectively. The results show that hyperspectral imaging can be used for the identification of foxing spots, but the distinction between different parts is not good, and the discrimination effect still needs to be improved.

1. Introduction
The advent of papermaking enabled the Chinese people to use paper to preserve political, cultural, and military information, and valuable paper artifacts contain the crystallized wisdom of nearly 2,000 years of Chinese history. But in the process of preservation of paper relics, if the preservation method is not appropriate, it is very easy to suffer ‘foxing’ impact. Foxing usually appears as yellow, brown or rust colored spots, and is called ‘foxing’ because its fox-like cunning growth characteristics and the color of fox fur[1]. Foxing not only covers up the handwriting and affects the reading, but the effects can expand and even penetrate deeper into the pages of the book. As the current technical methods for cleaning foxing on the surface of cultural relics are very limited, therefore, foxing, once formed, is difficult to remove and will bring irreversible damage to cultural relics. The causes of foxing have not yet formed a unified conclusion, and there are mainly two theories: biological and inorganic. Biological theory that is mainly caused by fungi such as mold foxing on paper, mold cellulose in paper as a nutrient source,
through the secretion of cellulase, degradation and absorption of cellulose in the paper, resulting in a decrease in the mechanical strength of paper. At the same time, in the process of mold metabolism, the production of oxalic acid, citric acid and other organic acids to increase the acidity of the paper material inside, the secretion of pigments in the paper artifacts surface foxing. Inorganic theory that fox spots are the result of metal ions such as copper and iron deposited on the surface of the paper. The formation of foxing may involve complex biological and chemical reactions, both possibly related to the growth of one or several fungi and the possibility of inorganic deposition acting together\textsuperscript{[2][3][4]}. In addition to the cause has not been clarified, foxing in organic artifacts, especially paper artifacts on the surface of the invasion, spread, development pattern is less studied. For the traditional detection of foxing, it totally relies on manual visual observation, which not only has a lag in the identification of foxing disease occurrence, but also has the subjectivity of inspectors' judgment. Therefore, based on the concept of preventive conservation of cultural relics, there is an urgent need to develop nondestructive detection techniques for efficient and accurate identification of foxing, which will provide the basis for subsequent prevention and treatment.

Hyperspectral imaging technology combines the advantages of spectral and image analysis, with the characteristics of non-destructive, fast and efficient, and can quickly complete the acquisition of spectral data without damaging the sample, and can obtain different aspects of the characteristics of the sample such as spectrum, shape, color and composition in a single acquisition, which has great advantages and potential in detecting the characteristics of paper cultural relics research, and currently has preliminary applications in the detection of paper cultural relics. Such as: Wu Wangting of the Capital Museum \textsuperscript{[5]} used a hyperspectral camera to capture the image of Zhang Shibao's "Discourses of the Way" in the Qing Dynasty, and extracted the ink lines of the painting through minimum noise fraction rotation, principal component transformation, and masking; Zhou Xinguang of the Shanghai Museum \textsuperscript{[6]} tried to solve the problem of the overlap between the seal and the painting in order to improve the recognizability of the seal; Wu Fengqiang \textsuperscript{[7]} used hyperspectral imaging technology to analyze the pigment composition of ancient paintings, and correctly identified the pigment composition of painted art paintings by minimum noise fraction rotation, pure image element extraction, spectral feature fitting, and matching with a standard spectral library.

To address the above status quo, this study intends to obtain a non-contact hyperspectral foxing detection system for paper relics by establishing a spectral analysis method to provide effective data support for foxing disease risk prevention and control, and at the same time, expand the application area of spectral detection technology in the field of heritage conservation.

2. Materials and Methods

2.1. Sample Preparation
The core of the foxing detection system is the GaiaTracer-V10 hyperspectral camera from Zolix. As shown in Figure 1, the system mainly consists of a halogen light source, a 1D scanning sample stage, a hyperspectral camera, an imaging lens and a PC with acquisition and control software, and is suitable for object identification and analysis in a laboratory environment.
Paper cultural relics foxing detection system

Figure 1 Paper cultural relics foxing detection system

Paper artifacts simulated experimental samples provided by the China Three Gorges Museum in Chongqing, the samples have mild foxing, foxing is scattered brownish-yellow dots, the sample local foxing occurrence is more serious, large area connected into pieces as shown in Figure 2.

Figure 2 Part of foxing sample

2.2. Image Processing Methods
The minimum noise fraction rotation (MNF rotation) \[^8\] can be used to determine the number of image data dimensions, the number of bands, to separate the noise in the data and reduce the amount of computation in processing. MNF is essentially two superimposed principal component analysis (PCA) \[^9\]. The first PCA is used to separate the noise in the data, and the transformed noisy data are only related to the minimum variance. The second PCA is a standard principal component transformation of the noise-whitened data.

2.3. Feature Band Extraction
The hyperspectral data consists of 256 spectral channels of data with a resolution of 2.38 nm. Since the data in the 360 nm ~ 450 nm band are full of noise information and cannot be used for feature judgment, the first 38 bands of data are removed. Spectral data often exhibit a high degree of correlation with a large amount of redundant information. The feature band extraction method extracts the spectra related to the sample foxing from the original spectral data, reduces the number of input data dimensions using PCA \[^10\], reduces the covariance of information and data redundancy, and analyzes and compares the models established by the selected feature bands to select the optimal feature band extraction method.

2.4. Data Modeling
After randomly dividing the sample set into training and test sets, the KNN algorithm \[^11\] and BP neural network \[^12\] are applied to establish a discriminative model for simulating foxing on paper artifacts; then the established discriminative model is used to discriminate the test machine samples, and the model
performance is evaluated and compared according to the discriminative accuracy, and finally a better data modeling method is selected.

3. Result and Discussion

3.1. Spectral Analysis of Hyperspectral Images of Simulated Paper Artifacts

Figure 3 shows the average spectral information of the inkblot and healthy area and the area infected by foxing, and it can be seen from the figure that the average reflectance difference between the healthy area and the infected area is obvious. Paper artifacts simulated sample spectrum in the full wavelength range changes more regularly, and in the wavelength range of 450nm ~ 600nm, the simulated sample foxing and the background of the paper part, ink part of the difference is larger. This shows the feasibility of foxing detection analysis of paper artifacts based on spectral characteristics.

![Figure 3](image)

Figure 3 Paper cultural relics reflection spectrum and average reflection spectrum

The spectral images of the simulated samples of paper artifacts at 464 nm and 767 nm bands are shown in Figure 4. In Fig.4(a), the difference between the surface foxing and the paper background is large in the 464 nm band, while in Fig.4(b), the surface foxing have been "buried" in the paper background in the 767 nm band. This situation is consistent with the differences in the spectral profiles of the different parts, but the special band images alone are not sufficient to extract the characteristics of the foxing on the surface of paper artifacts, and further processing is required.

![Figure 4](image)

Figure 4 Paper cultural relics feature band image. (a) 464nm band image; (b) 787nm band image

3.2. Band Math Based on Raw Hyperspectral Images

The band math [13] enhances the small difference between the target and background spectral features, suppresses the effect of illumination difference in the image, highlights the reflected features of the target and the spectral differences between the target and the background. To further distinguish the healthy region from the infected region, band math are performed on the characteristic waveband image, as shown in Figure 5. While there was an overlap between the stamped part and the infected area, the distinction between the distribution of the infected area and the healthy area was more obvious, especially in Figure 5(c) and Figure 5(d), where the foxing part showed white color and was more prominent and easy to discriminate. Most of the infected area can be better distinguished by wave band
math, wave band method paper foxing identification, conducive to the implementation of effective paper foxing diagnosis monitoring and scientific prevention and control.

![Image](image.png)

**Figure 5** Calculation results of band math of paper cultural relics. (a) 464nm-767nm image; (b) 464nm/767nm image; (c) 767nm-464nm image; (d) 767nm-464nm image

3.3. Minimum Noise Fraction Rotation Based on the Original Hyperspectral Image

Figure 6 shows the hyperspectral images of foxing samples (360 nm to 970 nm) after minimum noise fraction (MNF) rotation. The first, second and seventh components of the MNF-transformed RGB color image were selected to show a distinct blue color of the infected area compared with the image observed by human eyes, which can visually distinguish the size and distribution of the foxing, and the more serious the disease is, the darker the color is.

![Image](image.png)

**Figure 6** The images of the simulating sample after MNF transformation. (a) MNF-band 1; (b) MNF-band 2; (c) MNF-band 7; (d) RGB image after MNF transformation

3.4. Discriminant Analysis of Foxing on Paper Artifact Simulated Samples

A foxing discrimination model was developed using 180 pieces of hyperspectral data (450 nm to 970 nm) of foxing samples, randomly divided into 120 data as the training set and 60 data as the test set. The samples contain 3 types of paper part, inkblot part and infected part. And two classification methods, K-nearest neighbor (KNN) and BP neural network, are used to build the foxing discrimination model. The foxing spot discrimination model was constructed by using 120 hyperspectral data, which were analyzed by pre-processing and feature wavelength extraction, as the input of KNN and BP neural network models, and then the model was validated by using 60 sample data from the test set. The foxing discrimination model was constructed by using 120 hyperspectral data, which were analyzed by pre-processing and feature wavelength extraction, as the input of KNN and BP neural network models, and then the model was validated by using 60 sample data from the test set.

The results are shown in Table 1, the KNN model discriminated 79.1% for the infected part of the test set, 57.1% for the paper part, and 60% for the inkblot part; the BP neural network discriminated 83.8% for the infected part of the test set, 63.6% for the paper part, and 83.3% for the ink part. The results of the BP neural network are more correct and better than the KNN model. In general, the hyperspectral images have a higher discrimination rate for the foxing part and can be used for the identification of healthy samples and foxing occurring samples, but the differentiation result for paper is poor due to the difference of paper itself.

![Table](image.png)

**Table 1** Results of the KNN and BP models for different parts of simulating sample

| Type        | KNN train set discrimination rate/% | KNN test set discrimination rate/% | BP neural network train set discrimination rate/% | BP neural network test set discrimination rate/% |
|-------------|-------------------------------------|------------------------------------|-----------------------------------------------|-----------------------------------------------|
| infected    | 79.1                                | 57.1                               | 83.8                                          | 63.6                                          |
| paper       | 57.1                                | 60.0                               | 83.3                                          | 83.3                                          |
| inkblot     | 60.0                                | 63.6                               | 83.3                                          | 83.3                                          |
4. Conclusion
Based on hyperspectral image, the spectral image characteristics of paper artifact simulated samples infested with foxing were studied, and it was found that the spectra of foxing were significantly different from it of the background. The hyperspectral image of the simulated samples in different bands were subjected to waveband math, and the results of the waveband math was found to be able to extract the features of the areas infected by foxing. After the hyperspectral images with the minimum noise fraction rotation method, the infected regions were distinguished more significantly. The results of the discrimination model based on K-nearest neighbor method and BP neural network show that the hyperspectral images have a high discrimination rate (>79%) for foxing, which can be used for the determination of foxing on paper artifacts. The research results show that hyperspectral images can be used for nondestructive detection of foxing on paper artifacts, especially hidden foxing that are difficult to identify with the naked eye after being covered by stamps, ink and pigments. This study can provide a new technical mean for the efficient nondestructive detection of foxing and reveal their distribution development pattern. Subsequent studies can carry out more in-depth experiments in terms of spectral image pre-processing and optimization of modeling methods to improve the detection accuracy.

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