

Research on Pigment Analysis and Protection of Fahai Temple Murals Based on High-Resolution Multispectral Imaging Technology

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Abstract: The murals of Fahai Temple, as a treasure of Ming Dynasty art, face challenges in the identification of fine pigments and scientific protection due to the limitations of traditional methods. High-resolution multispectral imaging (HR-MSI) technology, which combines the advantages of imaging and spectroscopy, offers a new approach for non-destructive analysis of cultural relics. This paper reviews the technical system and points out that although it has been applied in the field of cultural heritage, there is a lack of systematic research integrating it with advanced algorithms such as deep learning for the murals of Fahai Temple. The paper argues for the necessity of applying this technology and proposes specific implementation suggestions: building a high-resolution spectral database of murals; using algorithms such as superpixel segmentation and pixel difference convolution to deeply explore the distribution of pigments and hidden line drafts; achieving precise diagnosis of pigment fading and diseases; and applying the results to guide preventive protection and restoration practices. This study provides a systematic technical solution and theoretical basis for the in-depth understanding and scientific protection of the murals of Fahai Temple, and is of great significance for promoting the innovation of high-level cultural relic protection paradigms.

Keywords: High-resolution multispectral imaging; Fahai Temple murals; pigment analysis; non-destructive testing; cultural heritage protection.

1. Introduction

The murals of Fahai Temple are outstanding representatives of Ming Dynasty mural art in China, renowned worldwide for their exquisite craftsmanship, grandeur and well-preserved condition, and possess extremely high historical, artistic and scientific value. However, after several hundred years of vicissitudes, the murals are now threatened by various diseases such as pigment fading, flaking and mold, and their preservation status is a cause for concern. Precise identification of mural pigments and in-depth understanding of the disease mechanism are prerequisites for implementing scientific and effective protection. Traditional analytical methods often rely on micro-sampling, which can provide accurate component information but cause irreversible damage to cultural relics and are difficult to obtain overall spatial distribution information. Therefore, the development of high-precision, full-coverage non-destructive analysis technology has become an urgent need in current mural protection research. High-resolution multispectral imaging (HR-MSI) technology combines the advantages of imaging and spectroscopy, and can non-destructively and rapidly obtain high spatial resolution multi-dimensional spectral data on the surface of cultural relics, providing a new technical approach for pigment identification, hidden information extraction and disease assessment. This paper aims to systematically review the principles of HR-MSI technology and its application status in the field of cultural heritage, focus on analyzing the limitations of existing research on the murals of Fahai Temple, demonstrate the necessity and feasibility of introducing this technology, and then put forward specific technical application suggestions for the refined research and scientific protection of the murals of Fahai Temple.

2. Literature Review

2.1. Current Status of Multispectral Technology in Protection of Cultural Heritage

Since the introduction of multispectral imaging technology into the field of cultural heritage protection in the 1990s, it has gradually developed into an important non-destructive analysis tool (Rong Yan, 2016)[6]. Its application scope is extensive, covering multiple aspects from material identification to the revelation of hidden information.

In the study of tomb murals, this technology played a crucial role in the initial screening and positioning. Zhao Jinli et al. (2022) were the first to apply the multispectral photography technique to conduct a large-scale survey of the murals when analyzing the historical protection and restoration materials of the Two Tombs of the Southern Tang Dynasty[8]. By observing the abnormal fluorescence response areas in the ultraviolet fluorescence images, they accurately located the distribution range of the later restoration materials. This work provided a precise targeted target for the subsequent use of micro-damage techniques such as infrared spectroscopy (FTIR) and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) for component analysis, establishing an efficient analysis mode of "multispectral screening - micro-damage verification", and providing important reference for the material research of similar tomb murals.

In the field of large-scale cave mural conservation, multispectral technology has been systematically applied to the investigation of the current situation and the study of production techniques. Chai Bolong (2013) detailedly expounded the methodology of multispectral image

investigation in the research of Mogao Caves[1]. By systematically collecting ultraviolet, visible light, infrared reflection and ultraviolet fluorescence images, and conducting critical comparative analysis, it successfully revealed the original line drawings that were invisible to the naked eye, the traces of successive restorations over the years, and the distribution conditions of different organic/inorganic materials in the murals. This research confirmed that multispectral imaging not only provides information on production techniques and materials, but also can provide data support for studying the correlation between existing damages and historical intervention behaviors, thereby avoiding the destruction of hidden information by protective interventions.

Furthermore, the application of this technology has extended to various fields such as Western oil paintings and Chinese calligraphy, being used to study the creative techniques of artists, authenticate authenticity, and assess the preservation conditions. These successful cases collectively demonstrate the powerful capabilities of multispectral imaging technology in identifying materials, revealing the humanistic information of artists, and conducting non-contact diagnosis of the health status of cultural relics (Rong Yan, 2016)[6].

2.2. Research on Murals in Faha Temple and Technical Limitations

The murals of Faha Temple, as a national treasure, have long attracted much attention from the academic community. The existing research can be roughly divided into two categories: one focuses on the exploration of art history and style studies. For instance, scholars such as Xie Shaowei (2017) conducted in-depth analyses from aspects such as its artistic style, composition features, and historical background, highly affirming its artistic value of inheriting the traditions of the Tang and Song dynasties and its exquisite craftsmanship. Ding Fang and Zhang Hao (2021) explored the significance of its material and technical studies from the perspective of "art technology studies" for the construction of the discipline and cultural inheritance[3]. These studies from a humanistic perspective profoundly expounded the value connotations of the murals of Faha Temple.

Another type of research has begun to attempt to use technological means to analyze the materials and diseases. Liang Ruihua et al. (2024) recently applied infrared thermal imaging and visible light imaging techniques to diagnose the cracking disease of the mural in the Great Buddha Hall of Fahaishi Temple[5], and focused on studying the optimized ratio of the reinforcement materials for the plaster layer, providing important scientific basis for the structural protection of the mural.

However, the current research has obvious technical limitations. Firstly, traditional pigment analysis, if it aims to make precise component judgments, often relies on sampling, which contradicts the highest-level conservation principles. Secondly, even with the use of non-destructive technologies such as infrared imaging, as in the research by Liang Ruihua et al. (2024), its focus is more on macroscopic structural damages (such as cracking)[5], and it is difficult to handle the microscopic, detailed distribution of pigment types, color fading patterns, and the identification of early microscopic damages. Thirdly, the existing research lacks the non-destructive restoration of the entire process of mural production, such as the fine extraction and interpretation of

underlying line drawings and modification marks. In summary, the current research on the murals of Fahaishi lacks a panoramic data collection and analysis method that can obtain high spatial resolution (to clearly see details) and high spectral resolution (to distinguish materials) without touching the cultural relics, thereby restricting the further deepening of its value recognition and protection practices.

2.3. Summary of Literature Review

In conclusion, the existing literature indicates that multispectral imaging technology has already established a certain application foundation in the field of cultural heritage protection in China, and has proven its effectiveness in material identification and process research in cases such as the Mogao Caves and the Two Tombs of Southern Tang. At the same time, although the research on the murals of the Faha Temple has begun, the existing technical means have deficiencies in terms of the refinement, non-destructiveness, and comprehensiveness of the analysis.

The current core research gap lies in the fact that although multispectral technology has been applied, there has been no systematic integration of the latest high-resolution multispectral imaging hardware and cutting-edge data processing algorithms (such as deep learning) to jointly tackle the top Ming Dynasty murals of Fahaishi. Specifically, the pigment classification method proposed by Chen Yamin et al. (2024)[2], and the line drawing extraction algorithm proposed by Zhang Huanhuan et al. (2024), which are frontier technologies, have demonstrated extremely high accuracy and reliability in laboratory simulations or other mural scenarios[7]. However, their combination with high-resolution multispectral data acquisition technology is still a blank in the academic research and conservation practice of Fahaishi murals. Therefore, integrating HR-MSI technology with these intelligent algorithms and applying them comprehensively to the case study of Fahaishi murals is not only a breakthrough of the existing technical limitations, but also an inevitable requirement to fill the research gap in this field. It will provide unprecedented technological support for the permanent preservation and in-depth interpretation of this artistic treasure trove.

3. Analysis of High-Resolution Multispectral Imaging Technology System

The high-resolution multispectral imaging technology system is a comprehensive system. It not only includes highly precise hardware equipment, but also a set of advanced data processing algorithms. When these components work together, they can extract from the surface of the mural a wealth of information far beyond what the naked eye can perceive.

3.1. Technical Principles and Data Collection

The basic principle of high-resolution multispectral imaging is that different materials exhibit unique reflection and absorption characteristics when exposed to light of different wavelengths. These characteristics are akin to the "optical fingerprints" of the materials. The multispectral imaging system collects images of the mural in different wavelength bands through multiple narrow-band filters. These images form a three-dimensional data cube. The two dimensions are spatial dimensions, namely the length and

width of the image, and the other dimension is the spectral dimension, representing different wavelength bands.

To achieve high-quality imaging, the data acquisition process is crucial. First, a high-resolution camera sensor is needed to ensure clear spatial details in the image. This is particularly important for artworks like the murals at Fahaishi Temple with delicate brushwork and complex patterns. Secondly, the lighting must be uniform and stable to avoid shadows and reflections that could interfere with data analysis. For the interior of the Great Buddha Hall at Fahaishi Temple, a special lighting scheme may be necessary. Finally, super-resolution reconstruction algorithms can further enhance image quality. Guo Yufei's (2018) research shows that through computational imaging methods such as compressed sensing, the spatial resolution of the image can be improved at the software algorithm level without significantly increasing hardware costs, thereby presenting the pigment particles and fine cracks of the murals more clearly[4].

3.2. Key Technologies for Data Processing and Information Extraction

The massive raw multi-spectral data collected must undergo a series of advanced algorithms before it can be transformed into valuable information.

The first key technology is pigment classification and identification. Traditional classification methods may not be able to effectively handle the transitional areas of pigments in murals. Chen Yamin et al. (2024) proposed a classification method based on multi-scale superpixel segmentation[2]. This method first intelligently segments the mural images, combining adjacent pixels with similar colors and textures into irregular "superpixel" blocks. This is more in line with the true contours of the pigment areas than fixed-sized windows. Then, using machine learning classifiers such as support vector machines, these superpixel blocks are classified. This method achieved a total accuracy of 98.84% in experiments, proving its reliability. Applying it to the murals of Fahaishi Temple can precisely draw the distribution maps of different mineral pigments (such as stone blue, stone green, and cinnabar, etc.), and even distinguish the same pigments of different particle sizes or origins, providing precise data support for the study of Ming Dynasty pigment techniques.

The second key technology is hidden information extraction, especially line drawing extraction. The underlying line drawing of the mural is an important clue for studying the painter's creative intention and techniques. However, most of it has been covered by the upper pigments and is invisible. Zhang Xianxian et al. (2024) developed a deep learning algorithm that integrates pixel difference convolution to extract the line drawing. This algorithm can enhance the edge gradient information in the image and effectively suppress noise interference. Even in areas where the mural has severe fading and high noise, clear and coherent line drawings can be extracted. Applying this technology to the murals of Fahaishi Temple is expected to reveal its exquisite underlying sketches, unadopted original compositions, and traces of successive restorations, thereby deeply interpreting its artistic creation process and historical changes.

The third key technology is data fusion and enhancement. Zhang Xianxian (2023) also adopted a method combining spatial and spectral information in the research to enhance the image. By algorithmically fusing the useful information from different bands, the contrast of faded areas can be

significantly enhanced, making blurry patterns and line drawings clearly visible. This is of great significance for the analysis of those areas in the murals of Fahaishi Temple that have become dim due to age and high noise.

3.3. Summary of Technical Advantages

Applying the above technical system to the study of the murals at Fahaishi Temple can bring unprecedented advantages. Firstly, it is non-destructive. Throughout the process, the equipment does not come into contact with the surface of the murals, fully complying with the highest principles of cultural relic protection. Secondly, it is highly precise. The combination of high-resolution imaging and intelligent algorithms enables clear viewing of minute physical details while accurately identifying materials through spectroscopy. Finally, it is panoramic. This method can obtain high-spectrum data of the entire wall and even the entire temple's murals, generating a comprehensive component distribution map, thereby avoiding the potential pitfalls of point-based analysis and achieving a systematic cognitive leap from the local to the overall.

4. Suggestions for Protection of Murals in Fahai Temple

Based on the characteristics of the high-resolution multispectral imaging technology system and the research needs of the Fahe Temple murals, we have put forward the following four specific research suggestions to systematically promote the scientific protection and in-depth study of this top-level cultural heritage.

4.1. Establish High-resolution Multispectral Database for Murals of Fahaishi Temple

The primary task is to carry out systematic data collection and establish a comprehensive and standardized digital archive of the Buddhist murals at Fahaishi Temple. It is recommended to formulate a detailed collection plan and use high-resolution multispectral imaging systems to conduct full coverage and multi-band image data collection of the murals. The collection scope should include multiple spectral regions such as ultraviolet, visible light, and near-infrared, to ensure the capture of the optical characteristics of different materials. During the collection process, metadata such as lighting conditions, camera parameters, and filter specifications should be strictly recorded to ensure the reproducibility and comparability of the data. The final database will not only contain the original image data but also standard data products that have undergone geometric and radiometric corrections. This database will become the permanent digital asset of the Buddhist murals at Fahaishi Temple, providing the most fundamental and authoritative data support for current and future research, and also providing the highest precision basis for the restoration of the cultural relics in case of damage.

4.2. Deeply Explore Production Techniques and Historical Information of Murals

Based on the database, it is suggested to focus on applying advanced intelligent algorithms to deeply explore hidden information. The algorithm proposed by Zhang Xianxian et al. (2024), which integrates pixel difference convolution for line drawing extraction, can be adopted to systematically extract and analyze the underlying sketches of the entire mural[7].

This work is expected to clearly reveal the sketching techniques, line usage, and possible composition modification processes of the Ming Dynasty painters, providing direct evidence for art history research. At the same time, using the multi-scale superpixel pigment classification method proposed by Chen Yanmin et al. (2024), pixel-level classification of pigment distribution on the mural can be conducted, and a precise mineral pigment distribution map can be drawn[2]. By analyzing the distribution patterns and overlapping relationships of the pigments, the scientific inference of the painting process at that time, team division, and pigment usage hierarchy system can be made, thereby elevating the research on the Fohai Temple murals from the level of art appreciation to that of the history of science and technology.

4.3. Achieve Precise Disease Diagnosis and Assessment

This technical system has unique advantages in assessing the health status of murals. It is recommended to use multispectral data to conduct long-term monitoring of the spectral responses of different pigments. By comparing the changes in spectral characteristics, the degree of fading and color change of the pigments can be quantified. For example, cinnabar (HgS) may transform into black chalcocite under certain conditions. This change can be reflected by characteristic changes in the spectral curve. Through algorithms, it can be identified and marked, thereby achieving early and accurate diagnosis of the disease. Moreover, multispectral imaging also has the ability to identify certain microbial metabolic products or pollutants, which can be used to assess the distribution and severity of biological diseases. By superimposing the disease information with the distribution map of pigment components, the correlation between specific diseases and specific materials can be studied, thereby providing key scientific data for revealing the disease mechanism and promoting the protection work to shift from "empirical restoration" to "pathological precise intervention".

4.4. Guide Preventive Protection and Restoration Practices

The research results should directly serve the conservation practice. Firstly, in the selection of restoration materials, this technology can provide in-situ assessment methods. For example, before the actual application of the ground reinforcement materials studied by Li Ruihua et al. (2024), experiments can be conducted in a less obvious area, and then the multi-spectral imaging can be used to assess whether the new material has an impact on the spectral characteristics of the underlying pigment and whether there are potential compatibility risks[5], thereby achieving safe and controllable restoration. Secondly, it is recommended to incorporate the processed multi-spectral images, especially the clear line drawings and pigment distribution maps, as the "reference base map" into the preventive conservation monitoring system. In the future, mural data can be collected regularly and automatically compared with the "reference base map" to achieve automated and high-precision monitoring of micro changes and the development of diseases,

providing powerful technical tools for the preventive conservation and risk management of cultural heritage.

5. Conclusion

High-resolution multispectral imaging technology represents a revolutionary paradigm shift in the field of cultural relic cognition and research. It has advanced non-destructive analysis from macroscopic observation and single-point detection to a new stage that is microscopic, panoramic, and equipped with component identification capabilities. This article systematically discusses the necessity, feasibility, and implementation path of applying this technology system to the research of the murals at Fahaishi Temple.

Studies have shown that although multispectral technology has made progress in the field of cultural heritage, combining it with the latest high-resolution imaging and deep learning algorithms, and systematically applying it to the research of this world-class treasure, the Fahaishi Temple murals, remains an area that urgently needs to be filled. By constructing high-precision digital archives, deeply analyzing the production process, accurately diagnosing the condition of damage, and scientifically guiding protection and restoration, this technology is expected to fully reveal the profound historical, artistic, and technological values contained in the Fahaishi Temple murals, providing the most solid scientific support for their sustainable preservation.

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