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Integrating innovative Spatial and Spectral Data Fusion strategies in Hyperspectral Imaging for Cultural Heritage

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Abstract. The study of cultural heritage (CH) objects benefits greatly from non-invasive techniques like hyperspectral imaging (HSI), which enables material identification and spatial mapping. Due to the heterogeneous composition of CH artifacts, combining complementary techniques is essential for comprehensive analysis. However, handling such high-dimensional datasets remains a challenge. We present a computational protocol that combines spatial and spectral dimensionality reduction to enable early-stage fusion and efficient analysis of fused data, through multivariate methods, with a focus on Uniform Manifold Approximation and Projection (UMAP). We introduce an open-source plugin for Napari viewer, which allows for UMAP-based exploration of fused multimodal datasets. Our approach is demonstrated in case studies involving reflectance and photoluminescence data fusion, showcasing its effectiveness in detecting degradation phenomena and revealing material complexity in both plastic artifacts and historical paintings.

1 Introduction

Scientific research on cultural heritage (CH) objects is essential to understand their material composition, artistic techniques, and conservation needs. In this context, hyperspectral imaging (HSI) has become as a powerful, non-invasive technique that gathers comprehensive spectroscopic data over the surface of an artifact. By combining spectroscopy and imaging, HSI makes possible to detect both materials and their spatial distribution, offering crucial information about the composition and the degradation in artworks. Due to the intrinsic complexity of CH artifacts – composed by various compounds, including original materials and degradation products – a single technique is often insufficient. Thus, a multi-analytical approach is required, integrating information from complementary imaging and spectroscopic methods [1].

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2 Multimodal imaging setup and analysis

Recent progress in multimodal systems allows for the collection of co-registered datasets from multiple imaging techniques using the same setup [2,3]. Traditionally, such datasets, once collected, are typically processed independently. However, early-stage fusion of multimodal datasets has shown promise in offering a more comprehensive understanding of materials [4]. Despite these developments, multimodal hyperspectral data cubes remain challenging to handle because of their high dimensionality, especially when dealing with merged data. Computational strategies that can reduce the dimensionality, preserving the important information, may help to address this problem.

3 Data fusion and computational strategies

We propose a protocol for the acquisition and analysis of multimodal imaging datasets. Dimensionality reduction techniques were applied to hyperspectral data cubes through wavelength selection and spatial optimization algorithms, exploiting discrete wavelet transform [5]. This reduces computational load while retaining meaningful information. The optimized datasets are then spectrally fused together and analysed using multivariate methods. Specifically, we utilize Uniform Manifold Approximation and Projection (UMAP) to visualize high-dimensional fused datasets in a two-dimensional space, enhancing interpretability and cluster separation. A key innovation in our approach is the development of an open-source Napari [6] plugin specifically designed for multimodal data analysis, integrating spatial and spectral dimensional reduction with UMAP analysis. Ultimately, we apply our workflow to case studies, demonstrating the effectiveness of our approach across diverse datasets and technique combinations. Specifically, we showcase the fusion of reflectance and photoluminescence datasets for the detection of degradation in plastic objects and for the study of complex paintings.

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