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Exploring the HYPERDOC Database: Advancing Hyperspectral Imaging for Historical Document Analysis

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Abstract

The HYPERDOC database is a publicly available hyperspectral imaging resource for the analysis of historical documents and mock-ups of inks and pigments. It consists of 1681 hyperspectral datacubes, containing millions of reflectance spectra, covering the VNIR (400–1000 nm) and SWIR (900–1700 nm) spectral ranges, including different ink recipes and documents from the 15th to 20th centuries, preserved in two archives in Granada, Spain. We will present the data acquisition process and structure of the database, followed by a live demonstration of its functionality, guiding participants through its use. Additionally, three applications of the database will be summarized, including document binarization, ink classification using machine learning techniques, and ink aging analysis. The HYPERDOC database facilitates the integration of advanced imaging techniques into document analysis and preservation, contributing to the non-invasive study of historical materials.

Introduction

The study of historical documents is fundamental for the preservation of cultural heritage, which is essential for understanding the culture and evolution of past civilizations. For this reason, it is important to develop non-invasive techniques for the digitization and study of these documents. In recent years, digitization efforts have led to the creation of numerous databases containing digital images of historical documents [1]. The use of these databases has helped to develop significant advancements in image processing applications, including binarization [2], content extraction [3], and the enhancement of deteriorated materials [4].

Conventional digitization methods predominantly rely on RGB imaging, which captures visual data using three spectral channels: red, green, and blue. While RGB imaging has been widely used in document preservation and accessibility, it is very limited when analyzing complex materials, faded inks and other consequences of the aging process. Hyperspectral imaging, developed in the late 20th century, addresses these limitations by capturing hundreds of narrow spectral channels across a broader range [5]. With this technique, we can obtain the spectral reflectance of every part of the document in a single capture per sheet, providing significantly more information about the different materials in a non-invasive way.

Some applications of hyperspectral imaging in document analysis include ink identification [6] and improved binarization [7]. Additionally, unlike conventional spectroscopy, the fact that it also provides us with spatial information facilitates material identification and mapping, helping in restoration and conservation works and offering valuable insights into the authenticity of the document and its historical context.

Despite these advancements, the field still lacks a comprehensive hyperspectral database specifically designed for historical document analysis. Existing spectral databases often lack the necessary diversity and annotated Ground Truth required for robust computational analysis and the application of machine learning and deep learning techniques. Annotated hyperspectral datasets would not only enhance material identification but also improve the accuracy and efficiency of automated document analysis.

Here we present a publicly available database containing 1681 hyperspectral images of historical documents and mock-ups, created using traditional techniques and recipes, captured in two different spectral ranges. This resource is open to the public, so that heritage science researchers can use it for material classification, binarization, appearance simulation and other challenging topics in the field.

Materials and methods

Two hyperspectral images were acquired for each document, using two line-scan cameras from Resonon. The first was captured by a Pika L device [8] in the visible and near-infrared range (VNIR, 121 bands from 400 to 1000 nm), with a resolution of 900 pixels per line. The second image was obtained with a Pika IR+ [9] in the short wavelength infrared (SWIR, 161 bands from 900 to 1700 nm), with a spatial resolution of 640 pixels per line. Additionally, modern supports of mock-ups were also scanned with the Resonon Pika UV device [10] in the visible and near ultraviolet range (UVIS, 95 bands from 330 to 800 nm), with a spatial resolution of 1500 pixels per line, in order to observe the fluorescence of the different supports. For all three cameras, the vertical resolution varied depending on the document size, as the line-scan acquisition method captures one line at a time.

The illumination consisted of four halogen lamps positioned to avoid specular reflection. A schematic representation of the hyperspectral data capture setup is shown in Figure 1. The spectral data was flat-field corrected, and the noise of the dark signal was subtracted to obtain the spectral reflectance of the samples.

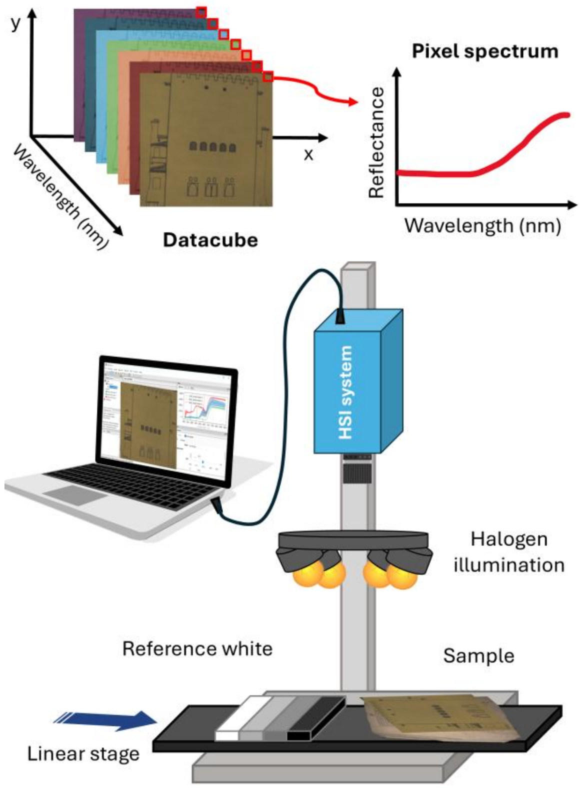

Figure 1. *Schematic representation of hyperspectral imaging capture setup and the resulting datacube for a document from the Alhambra plans.*

Some of the samples were spatially registered using the MATLAB Registration Estimator App, to align the captures of the VNIR and SWIR range. The SWIR capture served as the reference image, and the VNIR capture, having a higher spatial resolution, was transformed to minimize artifacts in the final registered image. Registration was based on one band from the VNIR (700 nm) and one from the SWIR hypercubes (1000 nm), selected through preliminary tests and positioned below 1200 nm in the SWIR range which was chosen to avoid proximity to the high reflectance region of metallo-gallate inks. The final document sizes ranged from [368 × 143] to [2485 × 615] pixels.

A series of representative regions of interest from each document, which we will refer to as *minicubes* from now on, were extracted to build the database. This step was necessary due to the large size of the hyperspectral captures. By dividing the data into smaller cubes, the storage requirements were reduced, and data processing became more efficient. The minicubes ranged in size from [34 × 33] to [181 × 508] pixels, representing a reduction of up to 94% in the number of pixels and significantly improving processing efficiency.

In *minicubes*, Ground Truth (GT) images were created semi-automatically with two different procedures. The first one, for ink samples, is based on [11]. The MATLAB function *bwskel* is used to obtain the skeleton of the stroke, and it is grown until it reaches the intensity of the edges, determined by a canny edge detector. The second, for samples with colored content, performs a color segmentation. First, we manually selected a representative area of each color in the *minicube*, and then, we used the MATLAB's Statistics and Machine Learning Toolbox function *classify* to pre-segment the image. After both procedures, a revision of the GTs is performed with the software GIMP, manually correcting any remaining errors.

Database overview

The HYPERDOC spectral database contains 1681 hyperspectral samples of different mock-ups and historical documents, captured in the VNIR and SWIR spectral ranges. Some examples of the database samples are presented in Figure 2. The database is divided into six different sets, according to the origin of the document:

Mock-up samples (1167 minicubes, 00001 – 01167)
Most of the samples in the database come from a collection of mock-ups produced in recent years using traditional recipes of known composition that were used from ancient Egypt to the Middle Ages. These mock-ups include graphite pencil marks and various inks, such as metallo-gallate, sepia, carbon-based inks, and their mixtures, prepared with Arabic gum as a binder. The materials were applied to a range of supports, including Somerset paper, watercolor paper, papers with different fiber compositions, and modern parchment. Some of the ink samples were also aged, exposing them to controlled conditions for up to 288 hours using an aging chamber or hydrochloric acid vapors, allowing for the study of their degradation over time.

Additionally, the database includes a set of 156 samples of pigments, dyes, and their mixtures applied to parchment and cotton-linen paper, bound with Arabic gum and egg glair.

Selva notebook (32 minicubes, 01168 – 01199)
These samples were extracted from a manuscript book of finances and receipts, originating from the town of Selva, in the Balearic Islands (Spain). The notebook, made of rag paper, was written between 1682 and 1683 with different inks, identified as metallo-gallate inks with different proportions of sulphate and a series of mixtures of similar composition, which probably means that they are mixtures of iron gall with some carbon-based ink.

Alhambra plans (65 minicubes, 01200 – 01264)
All the samples in this set were taken from a series of architectural plans of the Alhambra in Granada made by different architects between 1923 and 1936 to plan restoration work on the monument. In all cases, the supports are translucent cellulosic supports that have obtained their transparency through different techniques. As for the drawing materials, most of the plans are painted with unidentified inks and pencil, and one of them contains red and black crayons.

Nasrid alamas (23 minicubes, 01265 – 01287)
This set is a collection of documents that have in common the presence of alamas, which are short phrases in official documents that were drawn as signatures by the sultans. The samples were extracted from two original documents and one forgery, originating between 1454 and 1492. In all of them, different black inks were used for their writing, probably mixtures of metallo-gallate inks and an organic ink in greater proportions. As for the supports, both parchment and Arabic paper are present in this set.

Provincial Historical Archive manuscripts (84 minicubes, 01288 – 01371)
Five different documents preserved in the collection of the Granada Provincial Historical Archive were captured for this set: four of them are notarial documents from between 1488 and 1494, and the fifth one is a religious text of which no date is known. Different inks have been detected: Mixed inks with unidentified components, mixtures of earth with iron gall and carbon inks, pure carbon and pure iron gall. The support has been identified as linen paper.

Royal Chancellery Archive illuminated manuscripts (244 minicubes, 01372 – 01615)
The samples for this set were extracted from a collection of documents preserved in the Archive of the Royal Chancellery of Granada. Seven of the documents have parchment support and contain lawsuits of nobility between 1459 and 1608, and samples from four maps on linen and cotton papers are also included. By using different techniques, it has been possible to identify the presence of several pigments, such as cinnabar, azurite, lead white, minium, malachite, verdigris, lead-tin yellow, orpiment, gamboge, carmine and cobalt blue smalt. The presence of dyes has also been detected but they have not been identified.

***Figure 2**. Examples of the database samples for each set.*

Genealogies book (66 minicubes, 01616 – 01681)
These samples were extracted from a collection of documents from the 16th and 17th centuries preserved in the Archive of the Royal Chancellery of Granada. All of the documents have rag paper support and in previous analysis it has been possible to identify the presence of two inks, one of them being carbon black and the other a mixture of sepia and iron gall inks.

The database is hosted in a Google Drive folder accessible from the Color Imaging Laboratory website: https://colorimaginglab.ugr.es/pages/hyperdoc/database. The folder contains two Google spreadsheets and a "Samples" folder. The first sheet, "HYPERDOC Database information" contains specific information about each of the *minicubes*, such as a description and foreground materials. The second sheet, "Materials labels and palette assignment" contains a list of every one of the materials included in the Ground Truths with their corresponding indexes and their RGB color map.

The "Samples" folder contains three subfolders: The first one is the "GT" folder, with the Ground Truth of the samples with pixel-wise labelling of the present materials in .png format. The "RGB" folder is also included, with false RGBs of each of the *minicubes*, using the wavelengths [645, 565, 440] nm for the VNIR range, and [1600, 1200, 1000] nm for the SWIR range. Finally, the "*minicubes*" folder contains all of the hyperspectral images as .h5 files containing the spectral hypercube and its corresponding metadata, which includes the following information:

- number: Identifying number of the *minicube*.
- name: Name of the *minicube*.
- range: 3x1 logical indicating the capture range: 1 0 0 for UVIS, 0 1 0 for VNIR and 0 0 1 for SWIR.
- cubeinfo: Information about the sample, with details about the extraction zone and present materials.
- GT_cmap: Colormap of the GTs.
- GTLabels: Indexes and name of the materials present in the GT, if it exists.
- pixels_averaged: Number of pixels averaged for obtaining the reflectance of each material present in the GT, if it exists.
- spectra_mean: Average reflectance spectra of each material present in the GT, if it exists.
- spectra_std: Standard deviation of the reflectance spectra for each material present in the GT, if it exists.
- parent_cube: Capture of the full document from which the *minicube* was extracted.
- position: Coordinates of the *minicube* in its corresponding parent cube.
- texp: Capture exposure time in milliseconds.
- device: Hyperspectral camera used for the capture.
- stage: Translation stage used to perform the capture.
- illumination: Illumination used during the capture.
- reference_white: Reference used for the flat-field correction.
- height: Height of the *minicube*.
- width: Width of the *minicube*.
- bands: Number of spectral bands in the *minicube.*

- date: Date of origin of the document.
- aged: Aging condition of the document. Possible values: “No” (not aged), “Art.” (artificial aging, with details of the method and hours), and “Nat.” (naturally aged).
- restored: Indicates whether the document has been restored or not.
- substrate: Substrate or support material of the document.
- wl: Wavelengths of the *minicube*.

Applications

The database presented offers multiple options for exploration. Algorithms can be developed to improve readability using historical documents in the database that show varying degrees of degradation, enabling virtual restoration and digital rejuvenation. It can also be used to analyze ink distribution in the mock-ups by examining areas with higher and lower ink density (square areas and written strokes) and the use of different writing instruments (brush and pen). Additionally, simulations of document appearances under various illuminants are possible. The development of binarization algorithms or text-background separation, material identification algorithms (including inks, pigments, dyes, and supports), and the study of the effects of artificial aging on sample colors are also feasible. A summary of the main results from the last three applications, developed at the Color Imaging Lab, is provided. The aim is to illustrate the potential of this database for the analysis of historical documents from different perspectives

Document binarization

The segmentation of handwritten ink in historical documents using a subset of the HYPERDOC database was performed using both spectral ranges, VNIR and SWIR. A total of 226 samples were analyzed, including selections from the *Mock-up samples* set, and the *Alhambra plans*, *Nasrid alamas* and *Selva notebook* sets of historical documents. The study compares the performance of two traditional binarization algorithms (Howe and Sauvola) with a DeepLabV3-based deep-learning segmentation approach.

The evaluation was conducted using two test sets: an "easy test," which included minicubes extracted from the same documents used for training, and a "hard test," consisting of aged and degraded documents not included in the training phase. Binarization performance was assessed using peak signal-to-noise ratio (PSNR), pseudo-F measure, and distance reciprocal distortion (DRD). Additionally, comparisons were made between single-band and three-band (false-color) images, as well as an analysis of computational complexity in terms of execution time and parameter tuning.

Results indicate that while traditional binarization methods such as Sauvola and Howe perform well on single-band images, the DeepLabV3 model provides greater reliability and improved segmentation when utilizing the full hyperspectral cube, outperforming the three-band approach. However, its performance is affected by the fading of iron gall ink in the SWIR range. Future work may explore multi-band processing for traditional algorithms and further optimization of deep-learning models to enhance segmentation accuracy.

Preliminary results from this study were presented at Archiving 2024 [12], while additional findings reported here are currently under review for publication [13].

Ink classification

A different subset of the HYPERDOC database, including samples from the *Mock-up samples* set, the *Provincial Historical Archive manuscripts*, *illuminated manuscripts from the Royal Chancellery Archive* and the *Genealogies book* collection, was used to train and test Machine Learning models in order to perform ink classification.

The study evaluated the performance of five traditional Machine Learning algorithms, including Support Vector Machines (SVM), K-Nearest Neighbors (KNN), Linear Discriminant Analysis (LDA), Random Forest (RF), and Partial Least Squares Discriminant Analysis (PLS-DA), as well as a Deep Learning-based model. These models were applied to classify three types of inks: pure metallo-gallate, carbon-containing, and non-carbon-containing inks, using both spectral ranges, VNIR and SWIR (from 400 to 1700 nm), through low-level data fusion.

Classification maps were generated, and model performance was assessed using micro- and macro-averaged accuracy, precision, recall, and F1-score. All models achieved a micro-accuracy above 90% on the test set, with the DL model demonstrating the highest performance, reaching a macro-averaged F1-score over 98%. Among traditional models, SVM achieved the best results, with a macro-accuracy exceeding 97%. While traditional models, particularly SVM, provided reliable and computationally efficient results, the DL model offered superior accuracy but required specialized hardware.

Extended results from this study have been recently published and can be found in [14].

Aging effect

Metallo-gallate inks are highly susceptible to fading and can accelerate the degradation of paper due to natural aging. In particular, these inks can cause corrosion of the support material, a phenomenon known as “iron-gall ink burn”. Understanding the aging behavior of inks is essential for developing predictive models that assess degradation and inform restoration and conservation strategies.

To investigate these processes, a subset of the HYPERDOC database, specifically artificially aged metallo-gallate inks from the *Mock-up samples* set, was analyzed through colorimetric and spectral techniques. Three different ink formulations were studied: pure iron gall ink, a 50:50 mixture of iron gall ink and lampblack, and iron gall ink with added copper sulfate. These inks were applied to hemp paper and subjected to two distinct aging processes: exposure to an aging chamber (80°C, 65% relative humidity, and 550 W/m² radiation) and exposure to hydrochloric acid vapors. The samples were aged over four time intervals: 0 (control), 72, 144, and 288 hours.

Spectral variations in both the VNIR and SWIR ranges were examined to assess the impact of these aging conditions. Acid vapor exposure resulted in significant darkening of the paper while lightening the ink. In contrast, the effects of the aging chamber were less pronounced, suggesting that a longer exposure time may be necessary to observe distinct spectral changes. All inks exhibited color variations after aging, with the mixed ink samples showing the most noticeable fading. This was attributed to the lower mechanical resistance of carbon-based inks, which are more susceptible to abrasion and air movement in the chamber. In all cases, a stabilization phase was observed, where color differences slightly regressed toward the values of the non-aged control samples [15].

Developing an accurate aging model requires a comprehensive understanding of how different degradation mechanisms affect the spectral signatures of various ink formulations. This study represents a preliminary step toward this objective and highlights the potential of the HYPERDOC database for this application, contributing to the broader effort of characterizing material stability and degradation in historical documents through spectral analysis.

Conclusions

The HYPERDOC database represents a significant advancement in the study of historical documents, providing a publicly available hyperspectral imaging resource for document preservation. By incorporating a diverse set of historical and mock-up samples captured across the VNIR and SWIR spectral ranges, the database enables the application of advanced imaging techniques for different purposes. In this work, the results for three different applications are summarized: document binarization, ink classification, and the study of ink aging.

Through the use of the HYPERDOC database, binarization methods have been refined to improve ink segmentation in degraded documents, demonstrating the advantages of hyperspectral imaging over traditional single-band and three-band approaches. Similarly, machine learning models trained on the database have successfully classified historical inks with high accuracy, showing the potential of spectral data fusion for material identification. Additionally, the study of artificially aged metallo-gallate inks using spectral and colorimetric analysis has provided valuable insights into ink degradation mechanisms.

The interdisciplinary potential of this database extends beyond document analysis, supporting the collaboration between conservators, historians, imaging scientists, and data analysts. It facilitates the application and development of models to study historical documents. Future work will expand the applications presented here, and hope to serve as a database for extending the use and applicability of this hyperspectral imaging in archives and museums.

Ultimately, the HYPERDOC database serves as a valuable tool for heritage science, bridging the gap between traditional document analysis and modern computational approaches, and ensuring that historical documents can be studied, preserved, and understood with greater precision than ever before.

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