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Development of a technique based on multi-spectral imaging for monitoring the conservation of cultural heritage objects

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ABSTRACT

A new approach for monitoring the state of conservation of cultural heritage objects surfaces is being developed. The technique utilizes multi-spectral imaging, multivariate analysis and statistical process control theory for the automatic detection of a possible deterioration process, its localization and identification, and the wavelengths most sensitive to detecting this before the human eye can detect the damage or potential degradation changes occur. A series of virtual degradation analyses were performed on images of parchment in order to test the proposed algorithm in controlled conditions. The spectral image of a Dead Sea Scroll (DSS) parchment, IAA (Israel Antiquities Authority) inventory plate # 279, 4Q501 Apocryphal Lamentations B, taken during the 2008 Pilot of the DSS Digitization Project, was chosen for the simulation.

1. Introduction

The study of cultural heritage, archaeological, historical, artistic and archive, library or museum objects must be dealt with on an interdisciplinary level, making use of different experiences and skills necessary in achieving a common objective: preservation of the original object, both substrate and the media that contains the information on the object.

Conservation science is consistently striving to find better ways to preserve cultural heritage objects and to obviate damage liable to be caused by environmental or accidental factors. Materials constituting the cultural heritage object are subjected to changes over time, due to the interaction between the object and the physical factors (light, temperature, relative humidity, oxygen, particulates), the chemical factors (atmospheric oxygen, various pollutants) and the biological agents (bacteria, fungi, insects, mold). The monitoring of cultural heritage objects over time is critically important in order to alert the conservator when potentially damaging changes are occurring. The method described in this article follows a new approach in the context of cultural heritage aimed at the automatic and fast detection of a developing deterioration process, and its localization and identification. This requires the direct measurement of the reflectance spectrum of the artifact through a non-invasive method, leaving the object unchanged for successive examinations. While our current work involves texts on parchment and papyrus, the method is extensible to other objects.

The utilization of multispectral imaging and digital image processing can be beneficial for the preservation of cultural heritage objects. Modern imaging technologies have been having a significant impact on cultural heritage and archaeology in the last decade. A number of applications of multispectral imaging in the field of cultural heritage are present in the literature, mainly regarding characterization studies and artifacts analysis [1–4]. Spectral imaging of manuscripts has been used to improve historical documents readability [5–7].

For the case of the Dead Sea Scrolls, mostly on parchment, it is known that the changes in legibility are driven by changes in the parchment reflectance in the visible. Spectral imaging showed that the easy-to-read scrolls show significant differences between the ink and parchment spectra in the visible, while they are very similar for hard-to-read ones. However, for the illegible scrolls, the parchment reflectance increases significantly relative to the ink in the IR, which is why infrared photography of the scrolls, done in the early 1950s was successful [8,9]. These changes in reflectance suggest a natural way to monitor the scrolls for changes, namely monitor the reflectance through repeated imaging, analysis and comparison.

The spectral imaging process obtains a complete spectrum for each pixel of the image. The potential applications are innumer-

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able, and have already been applied in the fields of biology and biomedical applications, pollution control, and other disciplines [10–12].

There are two main methods of capturing spectral imaging data: one is to illuminate the sample with broadband light and filter the image detection, separating wavebands by filtering between the object and the camera, while the other method is to filter the illumination or use narrow waveband illumination in conjunction with an unfiltered camera. This second method has conservation advantages due to reduced light levels and heat compared to the former.

Chemometric techniques provide useful tools for extracting the systematic information from large and complex datasets. These methods have already been applied in the field of cultural heritage [13,14] for several purposes like provenance and classification studies, objects and manufacturing techniques characterization, monitoring and preservation.

A powerful tool to investigate surface degradation process of artifacts surfaces can be demonstrated through the application of the statistical process control (SPC) theory [15–18]. This has already been demonstrated in the monitoring of the conservation state of wooden objects and canvas painted with inorganic pigments, analyzed by Raman and IR spectroscopy [19,20]. The application of multivariate statistical process control approaches to image data was first developed for real-time process monitoring and control [21], for industrial [22] and agricultural [23] image-based problems.

A method based on multispectral imaging coupled to multivariate analysis is proposed here for monitoring the state of health of cultural heritage objects surfaces and, in general, for every kind of surface whose conservation state needs to be monitored. Industrial applications of the same technique can be easily envisaged for applications including the control of solid catalysts, ion exchange resins, raw and finite materials.

To test the algorithms a multispectral image of a Dead Sea Scroll (DSS) parchment, IAA (Israel Antiquities Authority) inventory plate # 279, 4Q501 Apocryphal Lamentations B (dated between 50-25 BCE [24]) was used. The applicability of the approach and its limitations were studied by generating virtual images of the parchment containing an artificially degraded region.

Then, the application of this monitoring technique to a real situation is briefly presented to show an example where a parchment was subjected to a real accelerated degradation process. The changes of the surface were investigated using the proposed approach.

2. Theory

2.1. Multispectral imaging

Multispectral imaging refers to the capture of multiple images of specific wavebands of the spectral region, with each image acquired at a different wavelength [25], obtaining a complete spectrum for each pixel of the image. The resulting dataset is a 3-way data matrix, also called CUBE, where *x* and *y* axes are the coordinates of the pixels of the image and in the third dimension there are the reflectances of the pixels at defined wavelengths. Full application of Multispectral imaging can typically span the wavelength range from 380 nm to 1100 nm, capturing ultraviolet (UV), visible (vis) and near infrared (NIR) spectral regions.

One of the reasons to acquire digital spectral data is the capacity to use image processing software to improve the visible contrast between ink and written or painted substrate and consequently enhance legibility of the text. There are several types of multispectral instruments including spectral scanners, that use electro-optical devices; spatial scanners, which use prisms, gratings or beam splitters to create spectral discrimination; interferometric analyzers, that typically acquire a 2D image and scan optical path differences to obtain a complete interferogram; hybrid instruments, such as computed tomographic imaging spectrometers and polarization-dependent rotogram devices [26].

A system that uses LED illumination to prove the spectral component, coupled with a 39 MP monochrome camera was employed for the real application example. Cold LED illumination eliminates a major objection to spectral imaging that uses broad band lighting and then filters the detection side. This method also lets us acquire high-resolution spectral images (7216×5412 pixels for each image, sensor array size of 49×37 mm), something that is not possible with other methods. Details of the system and its performance for both spectroscopy and color rendering are in the literature [27,28].

2.2. Principal component analysis (PCA)

The multivariate approach represents the only possible choice when datasets are characterized by a large number of variables and/or objects. In the present case the dataset is challenging, due to complex correlation patterns related to the use of a spectral description of the surface (obtained from the spectral imaging) [29,30]. A rationalization of the problem can be obtained by means of principal component analysis (PCA). PCA may allow the separation of the systematic information from the experimental noise and the natural fluctuations: this is true when systematic variations overcome the variability due to experimental error. PCA provides a new set of orthogonal variables, a linear combination of the original components, to describe the system under investigation in a very compact and efficient way. This analysis can provide several types of information useful for pattern recognition analyses. The most important are: the *scores* (**T** matrix), namely the projections of the objects onto the space given by the relevant PCs and the *loadings* or *weights* (**L** matrix), the coefficients of each original variable in the linear combination defining each PC.

In the present paper PCA is performed on the characterization data (3-way data arrays describing the sample when no degradation is applied) providing information on the sources of variability that characterize the dataset before the application of a damaging effect. The degradation images are then projected onto the relevant PCs calculated from the original characterization data. The analysis of the scores of the degraded images allows the identification of the presence of relevant changes caused by the degradation process, while the analysis of the loadings (calculated on the characterization dataset) may suggest the potential causes that produced the changes.

Using the subset of relevant PCs it is possible to rebuild the original dataset (matrix $\mathbf{X}'$). In this way it is possible to filter, for example, the experimental noise or the unnecessary information:

$$\mathbf{X}' = \mathbf{T} \cdot \mathbf{L}'$$

The difference between the original data **X** and the re-calculated data $\mathbf{X}'$ from the relevant PCs is called *matrix of the Residuals* (**R**) and contains the information not accounted for by the PCs used to recalculate $\mathbf{X}'$. The residual matrix is expected to contain only noise and random fluctuations when it is calculated from the same data used for calculating the PCs.

In the present case, the residuals matrix was calculated on degraded images after re-projection onto the space given by the relevant PCs calculated on the characterization data. In this particular case, the residuals matrix calculated on the degraded images may contain systematic information connected to the eventual presence of new species that were not present during the characterization step, species originated from the degradation process. The re-projection of the degraded images on the PCs calculated from