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Original article

Hyperspectral imaging combined with data classification techniques as an aid for artwork authentication

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ABSTRACT

In recent years various scientific practices have been adapted to the artwork analysis process. Although a set of techniques is available for art historians and scientists, there is a constant need for rapid and non-destructive methods to empower the art authentication process. In this paper hyperspectral imaging combined with signal processing and classification techniques are proposed as a tool to enhance the process for identification of art forgeries. Using bespoke paintings designed for this work, a spectral library of selected pigments was established and the viability of training and the application of classification techniques based on this data was demonstrated. Using these techniques for the analysis of actual forged paintings resulted in the identification of anachronistic paint, confirming the falsity of the artwork. This paper demonstrates the applicability of infrared (IR) hyperspectral imaging for artwork authentication.

1. Introduction

According to a recent studies, in 2014 the global art market reached its highest ever-recorded level of just over €51 billion worldwide [1]. This represents a 7% year-on-year increase from €47.4 billion recorded in total sales of art and antiques in 2013, consisting of more than 36 million transactions [2]. The vast majority of these high value dealings were made without scientific or forensic testing to assure the authenticity of the traded objects. Non-scientific art expertise – known in the art world as connoisseurship – is a common practice to assess the authenticity. Nevertheless, an experienced specialist can only evaluate a limited amount of the artwork and when not supported by additional scientific tests, that evaluation is subjective and as such it is not infallible [3,4]. Services using scientific approaches to determine the authenticity of artworks are available; however, these can have perceived issues, including the time involved and the need to remove sample material for a number of the techniques [3]. There is consequently a need for efficient, portable and cost effective non-destructive methods of art analysis to serve a broader range of the market. In some cases, due to the high value and unique nature of the objects, the paint sampling required by certain types of examinations may also be restricted. Non-destructive tests provide the possibility to use complementary techniques and obtain more information from the same sample. Several such methods, for instance X-ray fluorescence and FTIR (Fourier Transform Infrared) or Raman spectroscopy, exist and are applicable for studying artwork [5,6]. Although these methods are commonly used for scientific art investigation as well as for some other applications, there is still a need for new, non-invasive techniques that could extend the amount of information obtained from the artwork analyses and limit the number of invasive testing required. In this research, Hyperspectral Imaging (HSI) combined with chemometrics algorithms is proposed as a novel, non-invasive analysis method for classification and mapping of paints and pigments. The aim is that these tools will serve as an aid for artwork evaluation and specifically, the identification of counterfeits.

In recent years Hyperspectral Imaging has undergone significant development. There is an increasing amount of camera technologies that, with different configurations, provide many ways to obtain hyperspectral data over several spectral ranges. This emerging technology is rapidly finding applications in different fields, including pharmaceuticals [7], agriculture [8] and food quality control [9–12], as well the art world, for material identification and mapping of the works of art [13–18]. To date, most

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applications of hyperspectral (and multispectral) technology are for the restoration and conservation of paintings [19–22]. Pigment analysis provided by HSI systems coupled with dedicated classification algorithms allows the identification of "restored zones" in the painting and differentiates these from significant areas of the original painting which the system then suggests for pigment analysis [18,19,23,24]. The use of HSI in the infrared spectral range has also helped to reveal features of artists' techniques such as their preparatory drawing [22,25]. Due to the very broad range of wavelengths available for hyperspectral systems, the transmittance and reflectance response of different layers of paintings and drawings is frequently observed during data analysis. When material that is transparent at a specific wavelength range (but opaque at others) covers material that is reflective within the same spectral range, the underlying material can be detected by the HSI system and is hence revealed in the data acquired. Empowered by signal processing techniques this facilitates a detailed study of the artwork creation process and enables identification of the materials used [26]. Spectral selectivity of HSI data was also used on various occasions to analyse texts of historic value [27–29]. Identification of pigments and inks facilitated by HSI has also been used to aid in dating of manuscripts [27]. Furthermore, HSI technology empowers the recovery of erased and overwritten scripts as well as allowing the determination of appropriate bands for monitoring laser and non-laser cleaning processes [28].

Alongside the aforementioned benefits for art conservation, the potential of hyperspectral imaging in forgery detection has also been recognised. The application of HSI to address the challenge of forensic analysis of documents was successfully applied in the past [30–32]. Classification of different inks after obliteration of the text and the 'crossing lines problem' [30] were studied and analysed with chemometrics-based tools. These techniques applied to HSI data have had a significant impact on forgery recognition and provided objective results compared to traditional visual inspection based judgments [30]. Other forensic applications of HSI were also reported, such as fingerprint detection [33] and for blood stain dating at crime scenes [34].

The implementation of hyperspectral imaging in the aforementioned applications gave access to the rich dataset, however the conclusions drawn from this data were based on subsequent signal processing making it difficult to use by non-experts. In some cases the use of pure spectroscopic techniques achieved sufficient results [25], while in others, more advanced algorithms were applied in order to analyse the data [23,24,26]. It was also recognised that full diagnostic potential of HSI may be improved by implementation of robust data processing algorithms [28].

It is clear that HSI technology combined with advanced signal processing techniques have already found various application in the art world. However, to date these have focused on supporting various aspects of conservation and have allowed researchers to better understand paintings by allowing them to observe materials below the surface of the completed work. In this paper, we illustrate a novel combination of near- and mid-infrared hyperspectral imaging with state-of-the-art signal processing algorithms and background information from experts in the field of art analysis to provide HSI data based classification of paints and artwork for the purposes of authentication. As long as near infrared range was reached with widely known HSI technology, access to the mid-IR region was granted by the novel application of an active, laser-based mid-IR Imager. Although similar wavelength range was already explored with a passive system [35], to the authors' knowledge, our work presents the first ever application of this active device for the artwork analysis. This text demonstrates hyperspectral imaging empowered by automated paint classification techniques as a non-invasive method supporting the identification of counterfeit paintings. Our work was divided into two parts: (1) algorithms were developed using bespoke paintings which were created for this study and imaged in a well-controlled environment under laboratory conditions and (2) the techniques developed were applied to hyperspectral images of paintings held by the Berlin Landeskriminalamt which of comprised known and suspected forgeries, including, for the first time analysed with HSI, paintings from the infamous Beltracchi case [36–40]. This paper maintains this dual structure and focuses initially on describing system development and testing before providing details and the results achieved during this work. Some aspects of this study were also described in [41] however that text focuses on the difficulties of data acquisition and methods for overcoming these problems. Here, the focus is on the data analysis and processing as well as the application.

2. Materials and methods

2.1. Hyperspectral equipment

Applications of HSI systems operating in the visible–near-infrared (Vis–NIR) spectrum (400–1000 nm) have already been presented in the literature and tend to focus on performing and supporting various tasks including spectral characterisation of pigments [17,18,20,23,26–28]. InGaAs detector based hyperspectral imagers are also reaching further into near-infrared region (900–1700 nm, and in some cases extended up to 2500 nm) and these also have found application in the study of artworks [16–18,25]. However, relevant literature describing the use of sensors operating in longer wavelengths, approaching up to 4000 nm, which are known to contain rich spectral information and useful chemometric descriptors is not so readily available. In this paper, we therefore use two hyperspectral imaging systems operating in different (but overlapping) regions of the infrared portion of the electromagnetic spectrum. The choice of these two systems allowed us to study the impact of the image acquisition techniques and illumination methods [41] on the performance of our proposed signal and image processing techniques designed to automatically analyse the near- and mid-infrared range data. This work is driven by the motivation that in addition to the colour information contained in the visible spectrum, often sufficient to identify various pigments, a range of paint types (including pigments, binders and solvents) also have spectral features in the longer wavelengths. Hence this study is focussed on exploring these for the accurate discrimination of paints. It should be noted however, that while the intention of this study is to explore the usefulness of these longer wavelengths, many pigments can be discriminated using the Vis–NIR region and this could be beneficial for the final application of this technology by art scientists. As such, we discuss this topic further in Section 4.1.

The hyperspectral imaging systems which were employed during this study were: an active, laser based, mid-infrared hyperspectral imager (Firefly IR Imager, M Squared Lasers – see Fig. 1a) and a passive hyperspectral camera operating in the near-infrared wavelength range (Red Eye 1.7, inno-spec GmbH – see Fig. 1b).

While the near-IR range covered by the passive system (from 900 nm up to 1700 nm) is becoming more common and can be captured by various systems, devices operating in the infrared bandwidth beyond 3000 nm are still quite rare. The Firefly IR Imager is based on Optical Parametric Oscillator (OPO) technology that, with its inherent narrow spectral linewidth and wavelength tunability makes a foundation for a new class of hyperspectral imaging technology that is able to sense radiation beyond 3000 nm. It achieves this by converting radiation from a fixed frequency near-infrared laser source (1064 nm) into broadly tunable radiation in the mid-IR portion of the spectrum (2500–3750 nm) where compounds contained in paints exhibit distinct optical absorption.