PRISMS: remote high resolution in situ multispectral imaging of wall paintings

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Abstract

The non-invasive monitoring and examination of wall paintings in grotto sites, tombs and buildings is particularly important since these paintings are often extremely vulnerable. Traditionally, inspection of wall paintings at high resolution (i.e. sub-millimetre resolution) requires either scaffolding or some heavy and cumbersome mechanical structure to lift a person or camera to the upper parts of a wall or ceiling. We have developed a proto-type portable remote imaging multi-spectral camera that operates at ground level for in situ high-resolution colour and spectral imaging of wall paintings. We present here the latest developments for the instrument and examples of how the instrument can be used for diagnosis of wall paintings.

Résumé

La surveillance et l'étude non invasives des peintures murales sur les sites des grottes, tombes et constructions sont particulièrement importantes puisque ces peintures sont souvent extrêmement vulnérables. Habituellement, l'examen à haute résolution (c-à-d. une résolution submillimétrique) des peintures murales nécessite soit la pose d'un échafaudage soit une structure mécanique lourde et encombrante afin d'élever une personne ou une caméra au niveau des parties les plus hautes du mur ou du plafond. Nous avons développé un prototype de caméra portable d'images multi-spectrales à distance qui fonctionne au niveau du sol pour les couleurs à haute résolution in situ et pour les images spectrales sur les peintures murales. Nous présentons ici les derniers développements de cet instrument et les exemples de son utilisation pour le diagnostic des peintures murales.

Synopsis

La supervisión y análisis no invasivos de las pinturas de pared en grutas, tumbas y construcciones resulta especialmente importante, ya que estas pinturas son a menudo muy vulnerables. Tradicionalmente, la inspección de las pinturas de pared a alta resolución (es decir, resolución submilimétrica) requiere andamios o algún tipo de estructura mecánica pesada y voluminosa para ascender a una persona o cámara a las partes superiores de una pared o techo. Hemos creado una cámara prototipo multiespectral de representación óptica remota portátil que funciona a nivel del suelo, para una representación óptica

Keywords

wall paintings' conservation, multispectral imaging, hyperspectral imaging, infrared reflectography

Introduction

Wall paintings in grotto sites, tombs and buildings are particularly vulnerable because of the remoteness of some sites and the difficulty in controlling their environment, since the paintings are part of the structure (e.g. walls of a building or cave). Consequently, the problems related to the conservation of wall paintings are much more difficult when compared with easel paintings kept in museums and galleries. There is an urgency in monitoring their condition for conservation purposes.

Large format portable cameras such as the MARC for colour imaging (Saunders et al. 2002) are limited to painting sizes less than 2 m if sub-millimetre resolutions are required. Traditionally, detailed examinations of wall paintings are only possible with scaffolding or cherry pickers which are cumbersome, time-consuming, expensive and sometimes dangerous. For example, annual inspections of the Baroque ceiling paintings at Hampton Court Palace are conducted by lifting a conservator up in a cherry picker. A recent Mellon Foundation funded pilot project to photograph paintings in 40 of the painted caves at the Mogao grottos on the ancient Silk Road, took four years to complete using colour digital photography taken from scaffold towers (Wallach 2004). A minimum of 6 people were needed on site, and the post-processing, including mosaicing (stitching) of the images, was achieved manually with ADOBE Photoshop, which was extremely time-consuming. A similar method was used for the imaging of a large modern painting (Lange 1996). In the recently completed EU 5th Framework VITRA project, which was dedicated to the digital three-colour imaging of stained glass in churches, efforts were made to design a flexible system that can operate without the need for scaffolding, using a colour digital camera mounted on a robotic arm extending to heights of 15 m (Macdonald 2006). While the VITRA project achieved its aims of creating high resolution, colour accurate images of stained glass, the robotic arm system weighing over 300 kg makes it less than practical for transportation to remote sites and potentially damaging to mosaic floors. A portable, light weight, automatic imaging system installed and operated from ground level is needed even for simple tasks such as colour imaging at sub-millimetre resolution for large paintings and wall paintings in lofty buildings.

in situ a color de alta resolución y espectral, de pinturas de pared. Presentamos aquí los últimos avances para el instrumento y ejemplos de cómo este instrumento puede utilizarse en diagnósticos de pinturas de pared.

Multispectral imaging

Multispectral imaging is a non-invasive imaging technique capable of recording the spectral reflectance per pixel of a painting with accuracy comparable to a spectrometer but with the added advantage of being able to capture the spectral reflectance of millions of points simultaneously (e.g. Liang et al. 2005). The images obtained can be used for non-invasive monitoring of deterioration and conservation treatment, examination of past intervention, pigment identification and accurate colour rendering in any given illumination.

Multispectral imaging of paintings was first developed to increase the colour fidelity of the images. In the past 15 years, a number of EU projects have been dedicated to the design and implementation of high colour fidelity, high resolution scanning systems for the recording of museum paintings and other objects of art (e.g. Burmester et al. 1992, Saunders and Cupitt 1993). Multispectral imaging enables rendering of colour accurate images of paintings under any lighting conditions, unlike a normal tri-colour image, which can only capture an accurate colour image under the specific illumination used at the time. The full potential of multispectral imaging was later explored by extracting the reflectance spectra for pigment identification and by comparison of the images through different spectral bands (e.g. Baronti et al. 1998, Balas et al. 2003, Liang et al. 2005, Delaney et al. 2005). Brusco et al. (2006) imaged fresco paintings using a multispectral camera at low spatial resolution (<5 mm per pixel) and by combining with a laser range finder, a 3D colour accurate texture rendering of the whole painting was achieved.

In the last five years, hyperspectral imaging using Liquid Crystal Tunable Filters (LCTF) has been explored in the 400 nm–700 nm range (Hardeberg et al. 2002, Balas et al. 2003, Berns et al. 2005) and the 650 nm–1040 nm range (Mansfield et al. 2002). One of the disadvantages of the LCTF is the low blue response. Since the reflectance spectra of pigments in the 400 nm to 1000 nm range is fairly smooth, the increased spectral resolution of a hyperspectral system at the expense of decreased signal-to-noise did not provide much additional information.

Over the last 20 years, a number of projects have been devoted to the multispectral and hyperspectral imaging of paintings (see Fischer and Kakoulli 2006 for a review), but none has been able to image large and inaccessible paintings remotely at high resolution from the ground level.

PRISMS – a portable remote imaging system for multi-spectral scanning

PRISMS (Portable Remote Imaging System for Multi-spectral Scanning) is a multi-spectral/hyperspectral imaging system designed to operate remotely from the ground level, both in the visible and the near infrared (0.4 μm – 1.7 μm) with 40 nm bandwidth in the visible. The current proto-type operating in the wavelength range between 400 nm and 880 nm, consists of a filter system with a digital camera mounted on a small telescope which enables high resolution remote imaging without the need to bring the camera close to the painting (Liang et al. 2007). Figure 1 shows the system mounted on a tripod. The system is automatically controlled by a laptop to change filters, to focus, to move the pointing direction of the telescope and to capture images. For imaging at a distance greater than 3.5 m, a Meade EXT-90AT telescope with 90 mm aperture and focal length 1250 mm is used. Resolutions of at least 200 μm per pixel can be achieved for working distance of 25 m, 30 μm per pixel for close range imaging at ~4 m and sub-millimetre resolution for distances up to 100 m. For working distances less than 3.5 m, a Schneider Componon-S 5.6/150 lens is used which gives a spatial resolution of 40 μm per pixel at a 1 m distance. The filter system consists of a filter wheel and a set of 10 interference filters between 400 nm and 880 nm. The first nine filters have bandwidth of 40nm and are evenly spaced at 50 nm

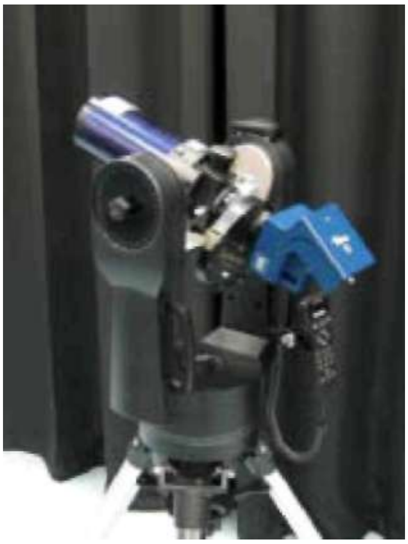

Figure 1. The proto-type remote multispectral imaging system PRISMS

Figure 2. Colour digital images captured with PRISMS from the 12th C wall painting in Plumpton Church, Sussex showing a crack and the surface of the wall. The image is of a region ~1.5 cm × 1.5 cm taken from a distance of 6 m

Figure 3. Qualitative remote imaging to inspect the ceiling of the Queen's staircase at Hampton Court Palace using PRISMS.

intervals; the last filter at 880 nm has a bandwidth of 70 nm. The 14 bit monochrome digital camera, Jenoptik ProgRes MF^{cool} with peltier cooling and 5 frames per second download speed (low noise, slow readout mode) has 1360 by 1024 pixels. A Tungsten-Halogen source is used for illumination, since a smooth spectrum source is desirable for accurate spectral imaging.

A colour digital camera can also be used with the telescope for quick remote high resolution colour imaging. The whole system stays at ground level during operation. The imaging system can be packed in a suitcase and weighs 25 kg with the maximum weight of each component being less than 10 kg. The portability of the system means that it can be taken to remote sites to image large paintings in situ at ground level.

Spectral calibration is achieved by imaging a spectral standard (e.g. a Labsphere Spectralon white standard) through all the filter channels. A Tungsten-Halogen slide projector was used as a test source and a calibration procedure specific to remote imaging was developed (Liang et al. 2007). A light source specific for remote imaging is currently being tested.

To use the system in situ during daylight hours, means the lighting level can change significantly as clouds go past. For a worst-case scenario, we tested the system in the gallery of the Nottingham Castle Museum during opening hours on a sunny but cloudy day. The gallery is lit by a mixture of artificial and natural light, the latter of which is let through the glass roof. The imaging system was set up such that it images a painting 6 m away. An image was taken of the painting with both projector light on and projector light blocked, both at the same exposure time such that the daylight contribution can be subtracted. The measured spectra of a set of colour patches compared with those measured with a spectrometer demonstrated that the system is capable of measuring the spectral reflectance at an accuracy of a few percent.

Applications to wall paintings

We present case studies of the application of PRISMS at various sites for different purposes to demonstrate how the instrument can be used to help conservation in these cases.

Plumpton Church

The system was brought to the Plumpton Church on the south east coast of England to examine a 12th C wall painting, one of the oldest in the country. Since it was a qualitative inspection, a colour digital camera was used with the telescope and normal church lighting for illumination. The small cracks and the sandy surface of the wall are clearly discernable in Figure 2. One of the other tasks was to produce a high-resolution image of the letters above Christ for art historical studies. A number of images were mosaiced together to show the area with letters.

Historic royal palaces – Hampton Court Palace

The Historic Royal Palaces (HRP) in the UK is responsible for the care of over 26 royal decorative painted interiors dating from the 14th century through to the 19th century. Many of the palace's interiors are over 12 m in height and are only accessible for examination using scaffold or mobile elevated platforms. Since all the sites are open every day, this makes regular examination of the artworks for condition checking extremely difficult, costly, and disruptive to site operations.

Figure 3 shows an image of the ceiling of the Queen's staircase at Hampton Court Palace. The system was installed on the 1st floor landing 12 m from the centre of the ceiling. The paint loss, cracks and the thickness of the paint can be seen at high resolution in Figure 4.

Figure 4. Detailed image of paint loss on the ceiling (shown in Figure 3) imaged from a distance of 12 m (the image corresponds to an area ~6 cm wide)

Figure 5. A normal low resolution digital camera image of the right side of the painting in the Byward Tower depicting Saint Michael (capital letters A, B, C and D refer to the imaged regions)

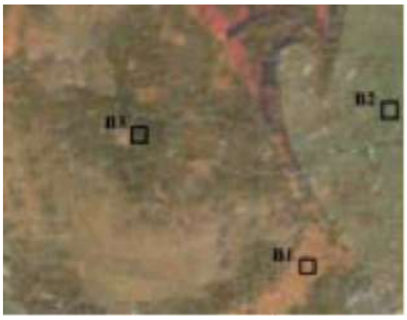

Figure 6. Colour image (~2.5 cm by 2 cm) derived from the multispectral images captured with PRISMS of part of the parakeet (region B in Figure 5)

Historic royal palaces – Byward Tower

The Byward Tower of the Tower of London has a 14th C wall painting, Crucifixion with flanking saints, 1.7 m above ground level and 1.9 m in height (Figure 5). Some samples had been taken in the past from the painting to identify the pigments and paint layers. This painting offers a perfect case study of how remote multispectral imaging can help in material identification and conservation diagnostics.

Four regions of the painting were imaged (labelled region A, B, C and D on Figure 5) with PRISMS, each with a field of view of ~2.5 × 2 cm^2. The high resolution multispectral images captured by PRISMS were then converted to colour images which show clear details of the paint surface (Figure 6). It was suspected that there might be underdrawings beneath the surface of this painting. A near infrared image at 880 nm (corresponding to the spectral range of infrared photography) of the left eye of Saint Michael (region A) did not reveal any underdrawings. This does not necessarily mean that there is no underdrawing, even though the same system has been used successfully on 15th C easel paintings to reveal underdrawings. We intend to image the painting again using a digital infrared camera operating in the spectral range corresponding to infrared reflectography (wavelength range 0.9–1.7 μm) with the telescope, as most paints are more transparent at longer wavelength.

For accurate absolute recording of the spectral reflectance or precise colour imaging, it is important to follow the precise flatfield calibration procedure for remote imaging (Liang et al. 2007). However, for relative measurements such as monitoring change over time, it is sufficient to record the precise position of the instrument and the precise instrument performance such as intensity and spatial distribution of illumination each time. Similarly, for the purpose of pigment identification, it is not necessary to follow the precise flatfield calibration procedure, especially when a light source of relatively uniform spatial distribution is used. The most important calibration for pigment identification is spectral correction.

Figure 7 shows that the yellow neck region of the parakeet (region B1 in Figure 6) was best identified with yellow ochre. Similarly, the brown robe of Saint Michael (region C in Figure 5) is best identified with natural raw sienna. The spectra were the result of averaging 25 by 25 pixels which corresponds to a 0.5 mm by 0.5 mm area.

Figure 8 shows the spectra of all the green regions imaged along with the reference spectra of verdigris in linseed oil and verdigris mixed with lead white. While verdigris appeared to be the closest match compared with other reference green spectra, the match is not perfect indicating that there may be other components present in the green paint. However, the spectra of the various green areas imaged are found to have similar spectral shape showing that all the green areas were painted with the same material. Microscope examinations of cross-sections of samples taken from the green background showed it to be verdigris mixed with lead white with possibly a layer of copper resinate/oleate glaze on top. This shows how the current technique can assist in identifying precise material content over the entire painting by using a sampled area as a reference. While destructive analytical techniques can often offer more information on the material content, the current non-invasive method offers the possibility of pigment identification over the entire painting rather than just the tiny region sampled.

Wall paintings in a Tang dynasty tomb

The ShaanXi History Museum has over 1000 square meters of wall paintings in their collection, mostly from tombs of Tang aristocrats (7th to 9th century) and some from the Han dynasty (2nd century BC to 3rd century). On average, about three to four tombs with wall paintings per year are excavated in the area (~50 square meters of paintings). In recent years the number of

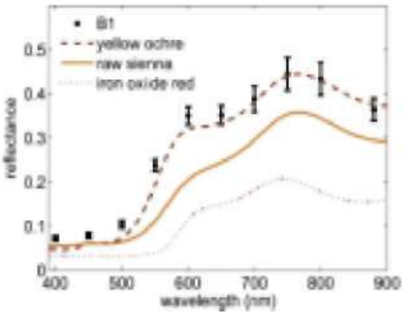

Figure 7. Measured spectral reflectance of the yellow neck area (B1) (dots with error bars) compared with various reference spectra of pigments in linseed oil. The spectrum was obtained by averaging 25 × 25 pixels which corresponds to an area 0.5 mm by 0.5 mm

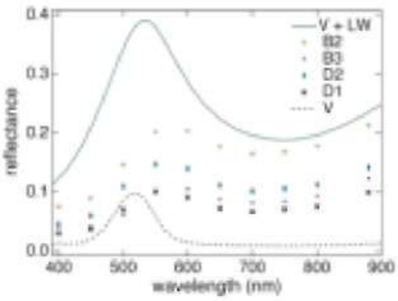

Figure 8. Spectral reflectance of various green region in Figure 5 measured with PRISMS (discrete data points measured through the 10 filters) compared with the reference spectra of verdigris in linseed oil (dashed curve) and verdigris mixed with lead white (solid curve). Spectra were obtained by averaging a region 25 × 25 pixels which corresponds to an area 0.5 mm by 0.5 mm

tombs excavated has more than doubled because of the increased rate of housing construction. It is particularly important to record accurately the paintings in their original setting before they are detached since once construction begins the tombs are destroyed forever. In the case where a tomb is preserved, it is important to monitor the deterioration as the speed of change can be significant over a rather short period of time.

Recently, a preliminary test run was conducted with PRISMS to image wall paintings in a Tang dynasty tomb in Xi'an China. This was the first time the instrument had been taken on a plane journey and it was taken from Nottingham to Xi'an by one person alone demonstrating the robustness and portability of the instrument. In situ imaging was conducted in the tomb of the crown prince Zhanghuai (654–684 AD), which was excavated in 1971 and is currently open to the public. Most of the wall paintings were detached and kept in the collection of the ShaanXi History Museum, however, original paintings in the coffin chamber and the corridor just before it were left intact in the tomb. The tallest part of the tomb was ~7 m high, but the narrowest part of the corridor was ~1 m wide with paintings from ceiling to wall; hence both the lens and the telescope were necessary. In the future, we intend to both monitor the paintings in the tomb and compare them to the conditions of the paintings from the same tomb kept in the museum.

Conclusion

This is the first instrument to be able to image paintings at inaccessible heights in situ from ground level at high resolution to produce not only colour but multi-spectral images. Compared to colour laser scanning, this system has less emphasis on 3D modelling, but has the advantage of high spectral resolution imaging and is 5–10 times less expensive. The portable multi-spectral system will enable in situ spectral imaging of paintings either in tombs, buildings and caves or museums. The possibility of in situ spectral imaging without the need for cherry pickers or scaffolding means long term savings and increased ease/frequency of monitoring. The portability of the system (suitcase size and about 25 kg) means flexibility and easy transportation such that it can be taken to remote sites to image large paintings in situ from ground level. In museums, this means the possibility of imaging at high-resolution very large paintings. The remote high-resolution spectral imaging system provides conservators with an invaluable tool for examining and monitoring the condition of paintings.

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