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Extended framework for Multispectral RTI

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Abstract

Reflectance transformation imaging (RTI) is a widespread technique for studying and documenting cultural heritage artifacts encompassing textural information. The principle is capturing an object from a static camera position by changing the direction of the incident light in each image. The coupling of this approach with multispectral imaging (Multispectral RTI) has shown promising results in the recent years. Considering this approach, we propose an expanded framework for the investigation and documentation of the visual appearance of surfaces, targeted to cultural heritage artifacts. In this work, we study the integrated representation of the angular and spectral components of reflectance, as well as the contributions of exploration by independent wavelengths.

Introduction

The accurate description of the visual appearance of a surface is essential when documenting a cultural heritage (CH) artifact. As a result of breakthroughs in computer sciences and digital photography, acquisition techniques that allow digitization and tracking the object's condition based on visual appearance changes, have arisen in recent years. This includes Multilight Image Collections (MLICs) approaches, which enable the analysis and documentation of an object's surface using images taken at various lighting angles. Under this category Reflectance Transformation Imaging (RTI), since its introduction in the 2000s, is gaining ground as a tool for the digitalization, study, and documentation of object's surface, particularly in the field of CH. RTI requires photographing a surface, from a fixed position, with a stationary camera while varying the angular position of the light source at each shot. From acquired MLICs and using a relighting approach ([1], [2], [3]), It is possible to recreate the visual characteristics of the surface interactively and dynamically, as well as its microgeometry, by estimating normal maps and their derived maps (slopes, curvatures). In parallel, Multispectral Imaging (MSI) technology has proven to be an important tool for studying and documenting CH artifacts or architectural surfaces. MSI consists in capturing the surface at multiple wavelengths, even beyond the visible spectrum, resulting in a broader viewpoint for surface analysis and documentation. The research presented here, focuses on the combination of RTI and MSI.

RTI acquisition approaches can be divided into two main categories: the Dome-based [1] and the Free-form [14, 15] methods. A third group, which we refer to as alternative systems. The Dome-based devices can be sub-divided in two categories. The first one consists of light sources at fixed positions that are homogeneously distributed over the surface of the dome and a camera at fixed position on the hemisphere. In the second one, a more dynamic configuration is achieved by using a single spotlight held by an arch that can be freely positioned in any desired angular position. The Free-form as it can be inferred by its name does not have a defined structure. It can be implemented depending on the acquisitions needs. The most important characteristic of this kind of setups is the use of a single light source whose current position is manually moved to illuminate the surface from any desired point, often intuitively following a hemispherical shape. Thus, in the Free-form setup, the light source is often positioned by hand, which implies that the light position is not known. It is necessary to use references, like shiny spheres to estimate the direction of the incoming light by detecting the produced highlight. This technique is referred as Highlight-RTI (H-RTI) [15, 4]. Although the two types of RTI systems described above account for the great majority of RTI acquisition devices, new options are emerging with the goal of meeting varied demands. Particularly, two new alternative acquisition approaches, have gained importance in recent years: The robotic arm-based [12] and the drone-based [13] acquisition setups.

Background

The use of different wavelengths for the documentation and monitoring of CH artifacts or conservation treatments is currently routinely used in the field. To this extent numerous contributions have been proposed concerning the application of multispectral analysis for the study of CH artifacts, demonstrating the technique's usefulness in the domain. Investigations, such as those presented in [5], employing MSI to investigate historical manuscripts, prove its benefits for revealing masked or erased information and isolating required elements based on the selection of the appropriate wavelength. Furthermore, MSI highly useful in detecting under-drawings or over-paintings. It has also been used to document and enhance the interpretation of ancient inscriptions, as well as to identify and discriminate materials [5, 6, 7]. Following this trend, some researchers have already prepared the road for RTI and multispectral coupling. Important contributions on the development of Multispectral RTI (MS-RTI) were presented in [8, 9, 10]. More recently, *Ono et al* [11] demonstrated the feasibility and potential of multispectral
RTI for the investigation of varnish cleaning of painting. The acquisition of MS-RTI also requires adapting the acquisition devices and the subsequent data processing. Regarding this *Ciortan et al* [16], have proposed a multispectral LED dome and an associated processing workflow.

There are two fundamental strategies to obtain multispectral images: passive and active methods [17]. The passive methods incorporate filter elements in the optic path. They usually use light sources of broad spectrum, as well as spectral filters coupled to the image sensor. On the other hand, active systems perform spectral sampling by controlling the illumination. Instead of using a wide-spectrum light source, active systems use different light sources of narrow spectrum.

Although evolutions of multispectral cameras constitute a great progress in the field of photography, these cameras, implement filters arrays, which when placed in front of the photosensitive cells of a CDD or CMOS sensor, provide a multispectral image. These filter arrays are called Multispectral filter arrays (MSFA). However, because of the nature of these filters, the image generated is the result of interpolation, thanks to demosaicing techniques. In a typical MSFA, as illustrated in Figure 1, the quantity of pixels per color channel varies depending on the pattern of the filter array. A multispectral camera thus results in a loss of information. In contrast, combining a monochromatic sensor with a multi-wavelength light source does not result in such loss since 100% of the photosensitive cells of the sensor are active at all wavelengths. For example, in the case of a color image, 100% of the pixels are red, green, and blue.

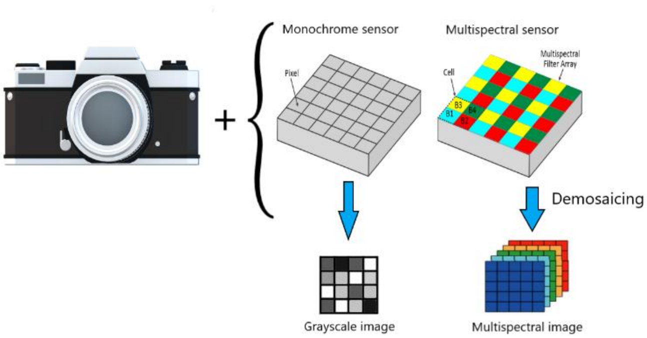


***Figure 1**. Monochrome camera and MSFA.*

Furthermore, multispectral cameras are frequently used in conjunction with broad-spectrum illumination sources (white or halogen). Although this method of obtaining color and multispectral images has proven to be very useful and provide visual information of great quality, we consider for the purposes of this study that an active type solution is more appropriate for the evaluation of surface properties. Thus, data presented in this paper was acquired using an in-house Dome-based RTI system that features a 12.4-megapixels monochrome camera, and light sources of six different wavelengths: 365nm, 395nm, 505nm, 530nm, 625nm and 850nm.

Proposed Approach

To obtain a joint reconstruction of the surface's angular and spectral reflectance, we proposed an image-based spline interpolation. The approach is summarized in Figure 2. Considering classical RTI data processing, the first step is to reconstruct the relightable images for a chosen light direction for all wavelengths, using a fitting model. This results in a stack of images for all input wavelengths. Therefore, for a given input series of RTI images in six different wavelengths we obtain six reconstructed images. Then, a final image is calculated as an interpolation of images in this stack. This study three models are employed: Polynomial Texture Maps (PTM), Hemispherical Harmonics (HSH), and Discrete Modal Decomposition (DMD). The exploration of the surface features has been carried out with a custom-made processing and visualization tool dedicated to multispectral-RTI (Figure 3).

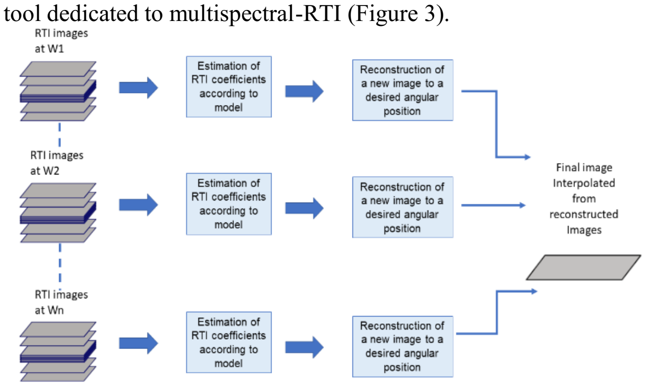


***Figure 2**. Summary of the proposed methodology for joint reconstruction of reflectance angular and spectral components*

As a result of the proposed strategy:

- It is possible to visualize the continuous representation of the angular reflectance of the set of images of each spectral band independently.
- Using the proposed integration approach, it is possible to synthesize the information extracted from all the bands in a single image.
- It is possible to interpolate in the wavelength space. Thus, analogously to the RTI conventional reconstruction for virtual light angles, it is possible through a linear or a spline interpolation to visualize non-acquired wavelengths renderings.

These features are included in the visualization tool designed to analyze MS-RTI data. The visualization application is presented here below.

Visualization tool for MS-RTI

A Matlab-based interface was designed to allow the viewing and extraction of information from multispectral-RTI data. Here, we include a brief overview of the application's most significant features. Using buttons "Load Images" and "Load LP" the images and the lighting positions file (LP file) can be loaded. After loading the images and the LP file, the acquisition's angular positions can be viewed in panel "LP file display", and the images corresponding to each wavelength can be observed in panel "Independent wavelength input images display". "Image slider" allows one to scroll through the sequence of input images and display them in the panel "Independent wavelength input images display". One can choose between the two proposed interpolation modes, images or coefficients, using the drop menu "Method selection". From drop menu "Model selection", one may choose among three relighting models available for the reflectance reconstruction: PTM, HSH, and DMD. By pressing button "Build", an image will be reconstructed at the angular position given by sliders 2 and 3 (azimuth angle and collateral angle respectively), which correspond to theta and phi, respectively. The "wavelength slider" allows the user to get a visualization of interpolated wavelength estimated through linear or polynomial interpolation. The relighted image can be then observed in "Relighted image display". An additional feature is included for the DMD modeling approach. For this method a pop-up menu will allow the user to input the desired number of modes to perform the modal reconstruction.

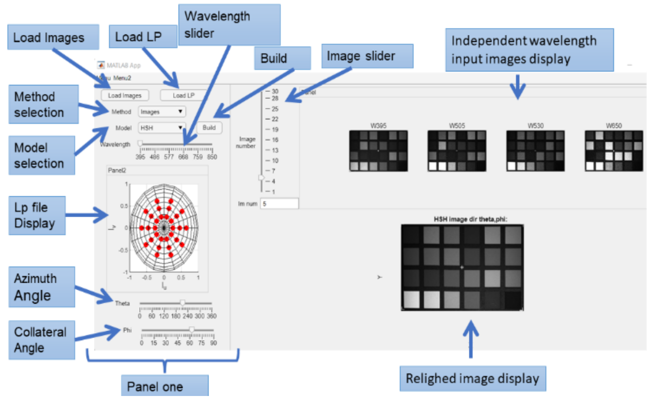


***Figure 3**. Custom-made visualization tool*

Results and discussion

The methodology was validated using a color checker. Then methodology is applied on two cultural heritage case studies: a Swiss artisanal gouache painting made with natural pigments on paper (signed David, depicting Yverdon) and a limited series tin box from the early 20th c. of the company "Suprême Pernot" from Dijon, with color printed on the surface. The analyzed samples are presented in Figure 4.

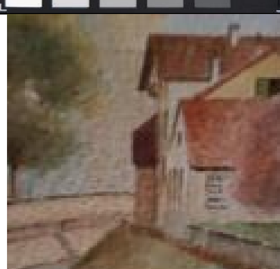
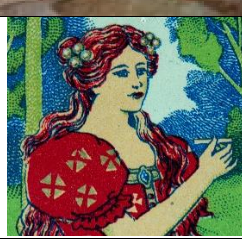
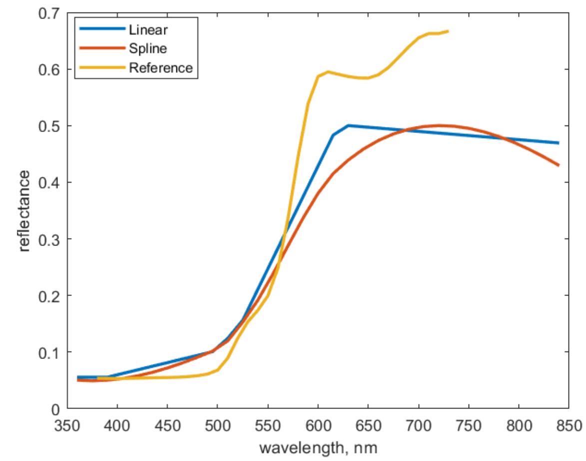
	RGB photo
Color checker	
Case study 1	
Case study 2	

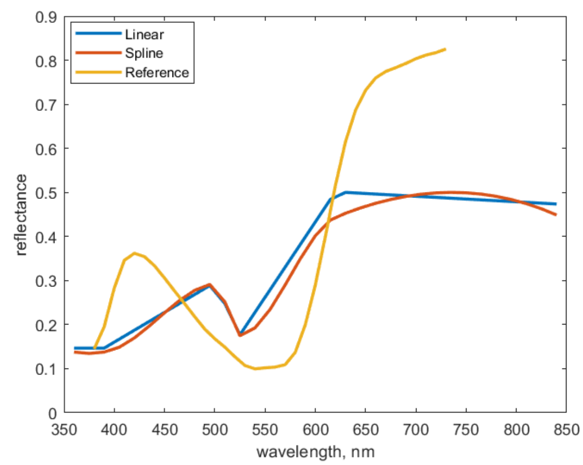
***Figure 4**. Studied samples.*

The color checker target was used to assess the accuracy of the proposed method. Using a spectroradiometer the reflectance is estimated for each color patch. These data were used as ground truth to compare the reflectance reconstruction obtained for each patch from the proposed method.

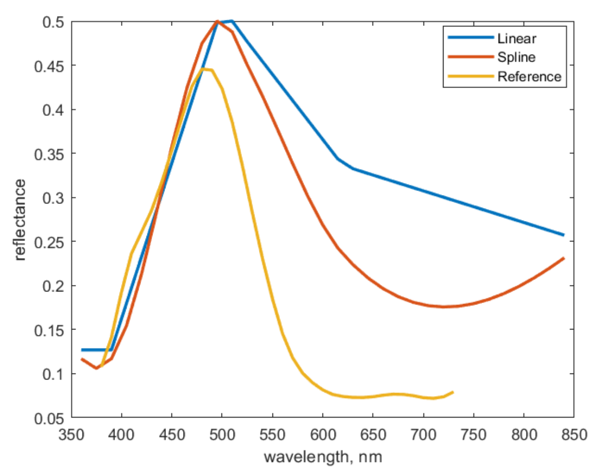
The method was tested using two approaches, linear and spline interpolation. Results are presented below in Figure 5.



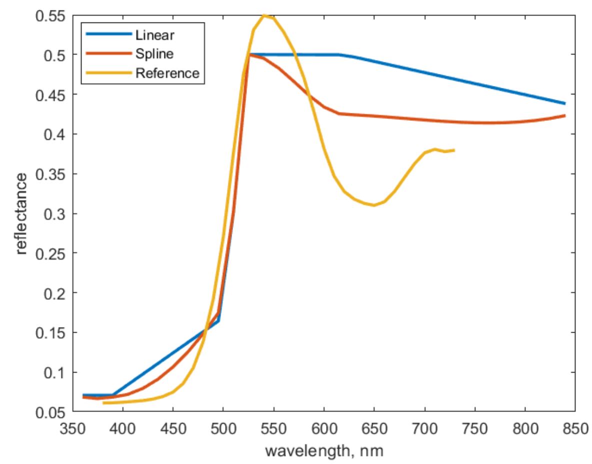
Patch 7 Orange reference and interpolated (Linear & Spline)



Patch 17 Magenta reference and interpolated (Linear & Spline)



Patch 18 Cyan reference and interpolated (Linear & Spline)



Patch 11 Yellow green reference and interpolated (Linear & Spline)

***Figure 5**. Reflectance comparison of color checker patches.*

The reference wavelength was mensurated between 380nm and 780nm, which explains why the reconstruction curves extended further, between 365 and 850, the range of used multispectral-RTI system. The differences in the curves can be attributed to three factors. The first one is that the reference is measured at regular intervals of 10nm, but our system provides peaks at six specific wavelengths with non-regular interval.

The second reason is related to the interpolations, first in angular space (at 90°phi), and then in spectral space of the resulting images for each wavelength after applying the RTI model, for this experiment, the HSH model. The third one, is that calibration is only done for intensity of lighting sources for each wavelength, but the camera response is not considered in this calibration process.

Case study 1 Gouache painting on paper.

For this first study case, we show resulting images obtained through linear interpolation, in the wavelengths space. This feature allows one to generate an image that is the product of interpolation of output images at all wavelengths, after the model fitting is applied (Figure 6). In this case, a light direction is set first, then an interpolated image is produced at the specific wavelength.

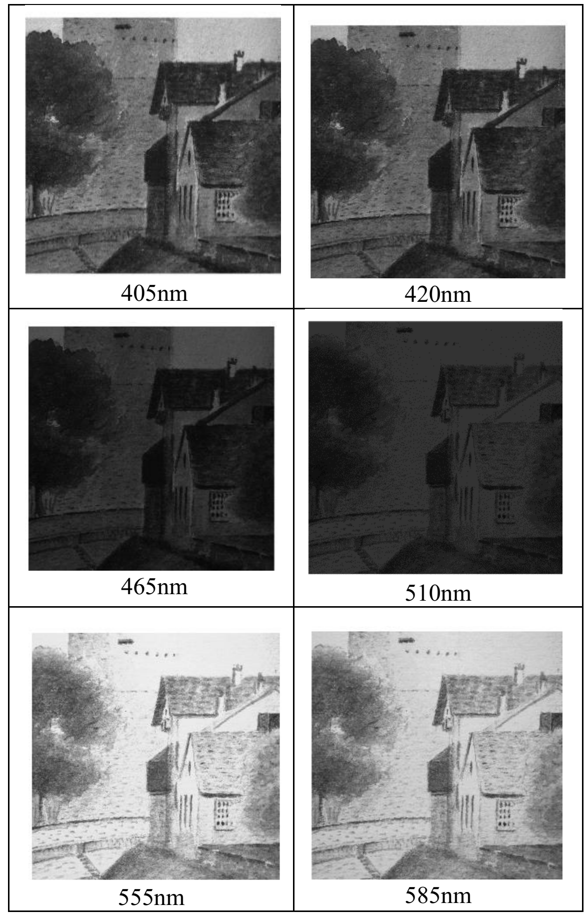
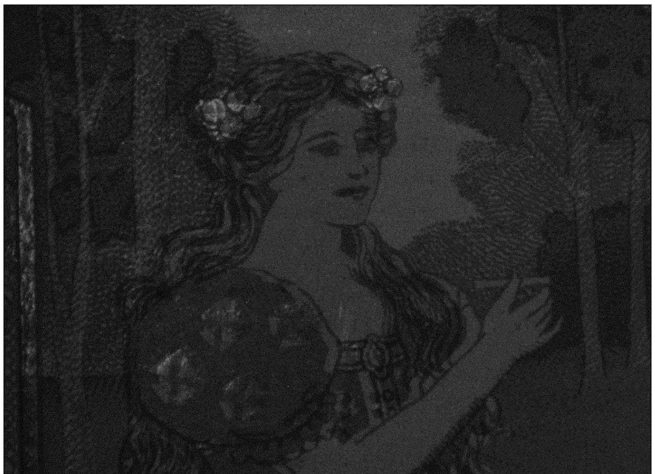


***Figure 6**. Case study 1 results.*

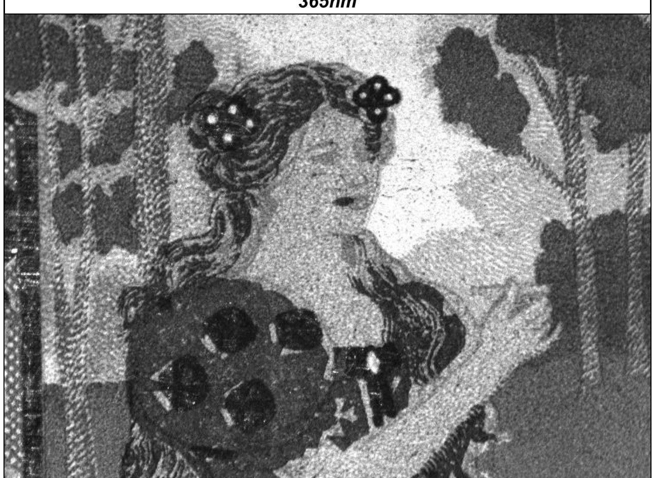
Thanks to the interpolation in the spectral space, we obtain an estimation of the visual characteristics of the object, in wavelengths different from those that were acquired. This allows one to have a more complete representation of the appearance of the object's surface. This estimation is dependent on the input wavelengths; in our case, we only have two base bands between 625nm and 850nm, thus the interpolation in this range is less variable than between 365nm and 600nm, where we have four input wavelengths.

Case study 2 tin box

We present images corresponding to the objects in the obtained wavelengths (Figure 7) and analyze various elements of the object that are visible depending on the examined wavelength. In the case of the tin box, the manufacturing details of the surface as a result of the color absorption at different wavelengths are revealed. Examining an object at multiple wavelengths and angles of light reveals interesting aspects of its appearance. In this section, we present photos from Case Study number 2 acquired at 260°θ and 45°φ at four distinct wavelengths. The object contains different level of information that become clearer at different wavelengths. To better explain the technological aspects of this case study it is better to first examine the wavelengths closer to red and NIR (625-850nm). The red colors are absorbed whereas the blue lines of the design of the woman figure are well visible. When examining the green range (530nm) the red and blue colors are more prominent, and respectively in 505nm the blue colors are highly absorbed. Through this examination it is also possible to observer that the color printing does not create a homogeneous layer on the surface. From this examination the technological defect becomes more prominent since it is clearly depicted that, when printed, the red color has an important shift in comparison to the drawing. Furthermore, by combing RTI data we can get additional surface information. In this example it is possible to detect the metallic parts of the surface at certain raking angles.



365nm



505nm

530nm

625nm

850nm

Figure 7 *. Case study 2 results.*

Conclusion

In this paper, we provided an approach that allows us to investigate the visual characteristics of an object's appearance in a dynamic way by combining a multilight method (RTI) with multispectral imaging, producing a Multispectral-RTI approach. Combining angular and spectral reflectance along with the associated visualization tool, provides the ability not only to relight the surface in a desired angular direction, but also to observe the variations produced at each wavelength. We observed that this process allows us to study the object in both illumination and spectral space, interpolating the multiple wavelengths acquired to generate a dynamic representation. We show that even if the reflectance reconstruction is not perfect, is not completely far from the reference. This method then required more investigation to obtain more accurate results. We observed that studying objects at different wavelengths can reveal details that are not easily noticeable in an RGB image.

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