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Original article

A method for the registration of spectral images of paintings and its evaluation

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ABSTRACT

This work concerns the automatic registration of spectral images of paintings upon planar, or approximately planar, surfaces. An approach that capitalizes upon this planarity is proposed, which estimates homography transforms that register the spectral images into an aligned spectral cube. Homography estimation methods are comparatively evaluated for this purpose. A non-linear, robust estimation method that is based on keypoint features is adopted, as the most accurate. A marker-based, quantitative evaluation method is proposed for the measurement of multispectral image registration accuracy and, in turn, utilized for the comparison of the proposed registration method to the state of the art. For the same purpose, characteristic for this application domain, benchmark datasets that are annotated with correctly corresponding points have been compiled and are publicly availed.

1. Introduction

Multispectral imaging (MSI) is a non-destructive diagnostic technique, combining digital imaging with spectroscopic analysis, to recover spatial and spectral information about a surface or an object. MSI is applied in medicine, agriculture, remote sensing, food industry, and cultural heritage sciences, including art conservation, archeology, and art history [1,2].

In MSI, a monochromator, i.e. a series of bandpass filters, is placed in front of the illumination system or the imaging sensor. This sensor then acquires a sequence of quasi-monochromatic images at consecutive narrow spectral bands, mainly in the visible spectrum but often extending to the infrared (IR) and/or the ultraviolet (UV). The acquired grayscale images are called *spectral images* and their sequence a *spectral cube*.

Analysis of the spectral cube provides information related to stratigraphy of a painting, that is the paint layers that comprise it. The intensity values along a column of the spectral cube form the extracted reflectance spectrum, at the column location. This spectrum is informative about the imaged materials and used in pigment studies [3–5]. Revealing the pigments used in artworks, assists the conservation process as well as studies in art history [2,6]. In some cases only traces of the material are present, casting the spatial accuracy of measurements crucial.

The filter wheel approach to MSI is widely used and allows portability [7,5]. As different wavelengths follow different optical paths inside optics [8], focus readjustments are needed between acquisition of spectral images. This refocusing changes focal length and the Field of View (FOV). In addition, portability implies low-weight instrumentation as well as flexible and modular supports, which are sensitive to vibrations. Both of these factors lead to misalignment between the acquired spectral images. Registration of these spectral images is required before spectrum extraction, so that a physical point is imaged at the same coordinates in all images of the spectral cube.

In the review paper [9], registration methods are respectively identified as local or global, depending on if the matched features are points or entire image areas. In the domain of cultural heritage, image registration has been employed in the alignment of spectral images for the creation of spectral cubes.

Concerning global MSI registration methods that have been used to create aligned spectral cubes, correlation based registration has

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been used in [10–12]. In [8,13], aberrations due to filters are compensated based on Mutual Information (MI), but registration errors due to vibrations are not considered. In [14], registration is based on the Fourier–Mellin transform.

Local MSI registration methods require point correspondences between the images to be registered. These correspondences are established by 1-1 matching of keypoint features, between image pairs. In [15,16], cross correlation of keypoint neighborhoods is used to find matches. In [17,18], the Scale Invariant Feature Transform (SIFT) features are utilized to find matches and spurious matches are reduced using the Random Sample Consensus (RANSAC) [19]. In [20,21], local features are utilized to register images in a piecemeal fashion, by tessellating images into patches. However, to avoid textureless patches, which are poor in keypoint features, tessellation is supervised [21].

Quantitative accuracy evaluation enables comparative assessment of registration methods. In the aforementioned works, evaluation is conducted qualitatively rather than quantitatively. An exception is [21], which utilizes a line grid for this purpose. However, line thickness introduces uncertainty. In addition, the grid is visible in a subset of the spectrum, thus hindering evaluation in some bands.

Contributions of this work are the following: (i) a local multispectral image registration method for planar surfaces that estimates homography transformations between images, (ii) a marker-based approach for the quantitative evaluation of multispectral registration methods, (iii) five publicly available benchmark datasets for the evaluation of registration accuracy of MSI of paintings that cover characteristic application scenarios, and (iv) a comparative experimental evaluation, of the proposed method against pertinent state of the art methods.

This work is motivated by the acquisition of spectral cubes from planar surfaces that belong to cultural heritage objects. Focus is placed upon the most dominant and representative type of such surfaces, which are paintings, e.g. panel paintings, easel paintings, or wall paintings. We believe that more types of planar surfaces such as, for instance, manuscripts, printed matter, textiles, or tapestries can also be treated in the same way. We, thus, warrant the continuation of pertinent experimental studies, in future work.

2. The proposed approach

2.1. Preliminaries

The proposed approach is illustrated in Fig. 1. A multispectral camera with a filter wheel images a planar surface. Imaging distance is assumed sufficiently large so that deviations of surface shape from planarity and penetration of wavelengths within the surface are both assumed negligible.

In an ideal setup, Fig. 1(a), the scene is imaged by a static camera and light travels the same optical path length through any of the interchangeable filters and camera lens. Consequently, impact is the same for all filters and switching between them would not affect focus. Images of a spectral sequence I_i, $i \in [1, N]$, are simply stacked to obtain an aligned spectral cube $\mathcal{S}$.

In practice, the optical path length is not the same for all wavelengths and switching between filters affects focus [8,14]. Focus is then readjusted, affecting FOV and, thus, image scaling. Refocusing and accidental vibrations between image acquisitions result in minute changes of camera pose. The combined effect of both factors results in a sequence of misaligned images Fig. 1(b). We assume an optical lens of narrow FOV and negligible lens distortion. We acknowledge that lens distortion compensation would improve results and plan this for future work.

A homography is a perspective transformation between two images of the same planar surface, which predicts the effects due to changes in camera pose and image scaling. Its number of Degrees of Freedom (DOF) is 8 and it is represented by a 3×3 matrix $\mathbf{H}$. A homogeneous 2D point upon the *transformed* image, $\mathbf{p} = [\,x \quad y \quad 1\,]^T$, is *transferred* to the corresponding location $\mathbf{q}$ in the *reference* image as $\mathbf{q} = \mathbf{H} \cdot \mathbf{p}$, where $\cdot$ denotes matrix multiplication. Finding point correspondences between the two images, enables the estimation of homography $\mathbf{H}$ which warps the transformed image upon the reference, Fig. 1(c). The homography between images I_i and I_j is denoted as $\mathbf{H}_{i,j}$. Using the estimated transformations, all images are registered to a reference image in the sequence, yielding the aligned spectral cube $\mathcal{S}$, Fig. 1(d).

MSI practice requires the camera axis to be oriented perpendicularly to the imaged painting. It ought to be noted that homography estimation and, hence, the proposed approach, do

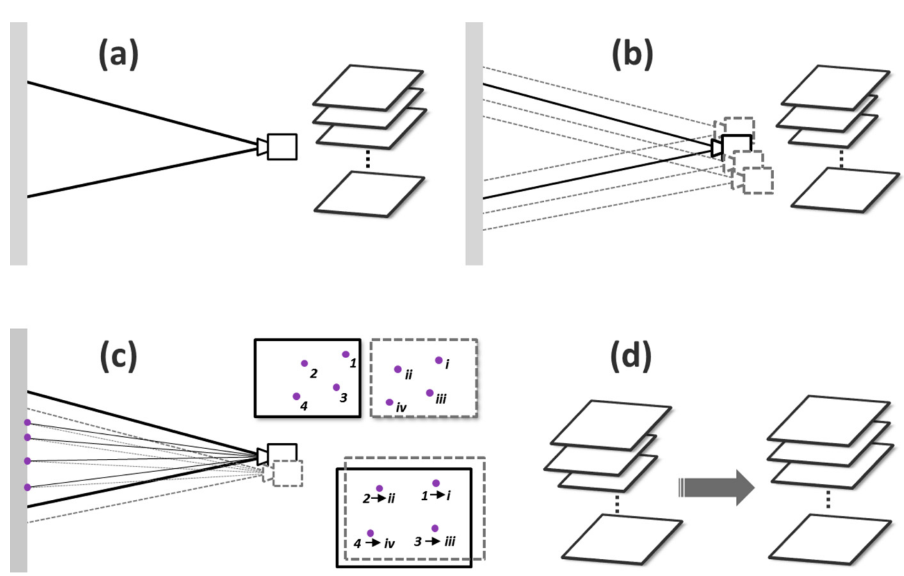

Fig. 1. Method overview. Geometry of (a) ideal and (b) realistic spectral cube acquisition; (c) feature point matches between two spectral images are used to estimate the homography transformation that registers them; (d) sequential registration of all images provides an aligned spectral cube.

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