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Estimation and Correction of Geometric Distortion in Pushbroom Hyperspectral System for Imaging Art Paintings

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Abstract

Spectral imaging has been proved as a promising technology to perform scientific documentation and analysis of cultural heritage objects. Imaging systems used for this purpose varies in different forms and complexity. Most of the spectral devices are designed not specifically for cultural heritage imaging, but for other application domains like remote sensing, satellite imaging etc. While these imaging systems used for cultural heritage scanning, the same processing workflow may not be adequate to meet the required image quality. In this paper, we investigate one of the several quality parameters, geometrical distortions in a spectral image caused by the translation stage of the camera. For this study, we used a hyperspectral image dataset derived from a pushbroom hyperspectral imaging system attached in a rotational translator. Using geometrical model, we have estimated the distortion, which is function of the scanning angle and distance. Image correction has been proposed and tested over a number of images acquired at the laboratory and in a museum environment.

Introduction

Spectral imaging becomes an attractive tool to document and study the cultural heritage (CH) objects as it provides valuable scientific knowledge related to the materials and techniques employed by the artist [1, 2, 3]. Documenting every minor details in the object is particularly important to understand the deformations over time. Geometric distortion generated during the image scanning affects the study of such deformations and mapping. In order to achieve the accuracy in imaging and analysis, the imaging systems used to capture the details has to be distortion free and correctable.

Compared to conventional 3-channel imaging, spectral imaging record scene over more number of bands samples in the wavelength spectrum. There are different techniques to do this and there has been lot of developments in the spectral imaging devices over the years [4, 5]. Snapshot and sequential imaging systems, which use different technologies for the acquisition of spectral and spatial information has developed and adopted from other fields of applications. Spectral and spatial resolution, accuracy, speed, complexity, image quality etc. are some of the key parameters, which decide the choice of these systems for CH imaging [4, 6]. Push broom hyperspectral systems found to be interesting due to several reasons such as, spectral resolution, number of spectral bands and easy to adopt from the remote sensing domain. Though push broom based hyperspectral systems has the above-mentioned advantages, the captured images are likely to undergo distortions in certain configurations.

Push broom hyperspectral scanner has developed for remote sensing applications where the scanner is attached to translator in the airborne platform and sweep across the ground to record the spectral data. As the movements are controlled by several parameters and undergo several forms of distortions (roll, pitch, yaw, tangent) based on the altitude variations, sweeping angles, sensor orientation etc. This motivated the research to develop correction algorithms for such applications [7, 8].

The most common configuration in which the line scanner used in CH is in a linear translator stage and the movement is synchornised with the other imaging parameters. Due to practical reasons push broom scanners in some cases used in rotational translator stages. For instance, the difficulty of taking out a painting from a museum wall, scanning paintings of larger sizes, documenting wall paintings etc. This paper discuss the distortions arises when the line scanning based hyperspectral imaging system acquire data while the movement is driven in a rotational translator. In case of single shot camera where the optical elements is the source of distortions of different forms such as barrel distortion, pincushion distortion etc. In the present paper, we discuss the distortions derived from a line scanner based hyperspectral system. The quality of image generated from a line scanner depends on the direction from which the scanner points to the object. With a linear translator, the movement of the sensor is always perpendicular to the object plane and resulting image will be distorted the least. On the other hand, in several cases, due to practical reasons the sensor may not follow a perfectly linear way and this creates distortion in the resulting image.

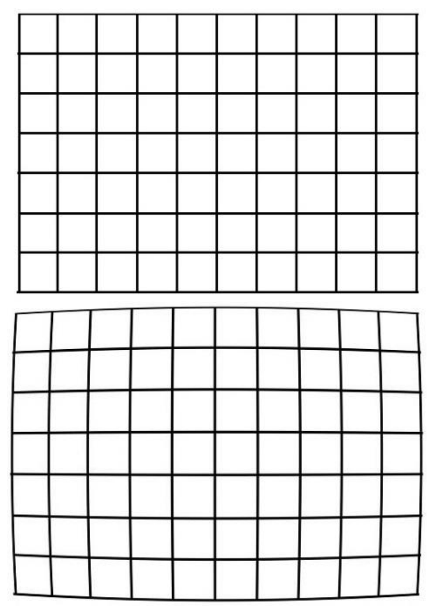

Figure 1. Illustration of distortion caused by the line scanner in a rotational stage. Original (top) distorted (bottom).

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The procedure may be helpful in imaging in the CH domain, for instance while performing accurate documentation of the object where minor deformations in the object has to be determined to understand the aging process.

Image acquisition and distortion

To study the distortion derived from the line scanner in a rotating stage, the image acquisition has done with the following settings. Hyperspectral data was obtained using the HySpex line scanning spectrometer VNIR-1600 [9], manufactured by Norsk Elektro Optikk. This camera covers the visible and near infrared spectral range 400 to 1000 nm with 160 spectral bands. The VNIR-1600 has a spectral sampling of 3.7 nm and captures 1600 spatial pixels across the field of view. The image is acquired line by line during the scanning process with each line being one pixel wide. The camera was attached to a rotating translator and the object (painting) to be scanned was placed in a fixed stand. At the mean position, the camera was at a distance of 91cm from the painting. The camera software synchronizes the speed of the translator with the camera frame rate. Light from a halogen source was used for illuminating the object and was illuminated uniformly over the area under scan. Angle and height of the light sources were adjusted to get maximum signal in the sensor. The equalization filter has used in front of the focusing lens to reduce the radiation in the bands having the highest sensor sensitivity and most intense illumination, allowing for correct exposure at the wavelength edges. This arrangement improves the noise levels in the blue region as well as the NIR region. In addition, to reduce the noise in the dataset, every line is captured several times and the values averaged before moving to the following line. Spectralon reference was also acquired along with the images and this has been used later to normalize the images.

Radiometric calibration of the data has been performed using the camera post processing software HySpex RAD. This converts the raw images to the sensor absolute radiance values. It also corrects the non-uniformity and dark current factors during this stage. Test images for this research has acquired at laboratory conditions as well as in a museum environment.

Distortion modeling and correction

In this section, we discuss the imaging geometry, distortion model and correction algorithm. Unlike in snap shot camera where the distortion is mostly comes from the lens geometry, in line scanner imaging, the role of lens is less prominent in the image distortion. Snapshot image corrections has been studied well over the past few decades and there exist several well established correction algorithms [10, 11, 12]. In case of pushbroom camera, the image is formed by combining the lines of pixels scanned from the object. Line scanner in a linear translator move perpendicular to the object and the lines of pixels always have the same geometry. In a rotational translator, each lines captured at a different axis and this has to be estimated and corrected to get the undistorted image at the end. With no distortion, all the lines in the image has the same magnification of the object. Figure below shows a mesh image undergone line distortion. As the scanner rotates, the instantaneous field of view changes as this affect the magnification. As a result, the center part becomes more stretched outwards (Figure 1). Line distortion is similar to positive radial distortion. At certain point, depends on the focus depth of the lens used, the image becomes completely out of focus and in an irreversible form. Distortion in an acquired image has been represented in a geometric model below (Figure 2).

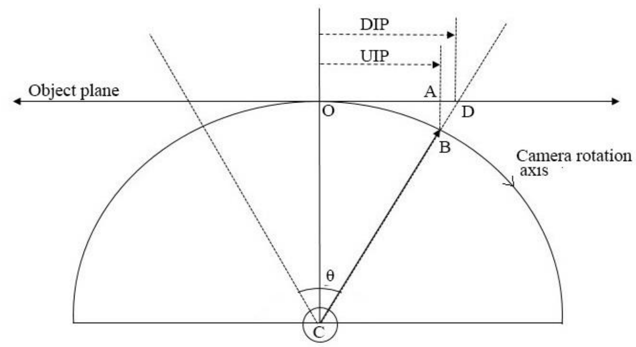

Figure 2. Geometrical model which represent the line scanner in a rotational translator.

As represented in the figure, CO is the camera to object distance. In the present case the focal length of the camera is fixed (CO = 100cm) and the focus depth is 10cm. The camera rotates in the axis as shown in the diagram. At the mean position line scanner, camera is perpendicular to the object plane (painting) and recorded line of pixels are undistorted. As the rotational stage advances its position after scanning each lines, the distance between the camera and object changes. In addition to this, the angle at which the camera see the object also changes and this makes the magnification different for every lines recorded. Based on the sensor orientation and optics design, each line scanner has its instantaneous field of view (IFOV) and this determines the area of object, which capture in every pixel. However, this can be different when the camera is at an angle with respect to the principle axis. Here UIP represents the undistorted image point as if the camera scans the image at right angle to the object and DIP is the distorted image point. By solving the trignometrical relationship in the triangles formed by OCD and ABD, it is possible to find the displacement of DIP and UIP. To describe the radial distortion caused by the line scanner, the relationship between the physical coordinates of the distorted image points to the actual points has to be mapped.

The correction algorithm aim to map the distorted image points back to the original point and keep the actual magnification at the image. The change in magnification with an off axis at an angle θ is ΔM. At point D where the DIP = UIP + Δr, the magnification is lower that at point O. i.e, $\frac{\Delta M}{\Delta r} < 0$.

The undistortion function here is the UD(θ) which is based on angle variant factor Δr. Any such distortion can be approximated with its Taylor expansion

$$s = r + K_1 r^3 + K_2 r^5 + \cdots.$$

Where, K_i is the radial distortion coefficients and s is the distortion level. In the present case, this is depended on the line scanner. This infinite series has approximated to get decent quality based on experiments and is in the form[13].

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$$s = r + K_1 r^3 = r(1 + K_1 r^2)$$

In the case of a line scanner, the rotation angle and focal length are known and this allows to choose the right distortion factor. For a larger rotation angle, the degree of distortion to the image is more and the also distortion factor will be. The proposed correction has been applied over a number of hyperspectral images of art paintings captured using the scanner in rotational translator. Figure below shows the captured images as well as the corrected. Each of these images with lens with focal length 10 cm and the angle of rotation is different.

Actual and distorted pixel points in the image are derived from the geometrical model. Cartesian coordinates are used to transform the image into real world coordinates while the undistortion has been described and performed in the polar coordinate system. To map the distorted pixels /lines to its corrected position, cubic interpolation has been applied in the present case.

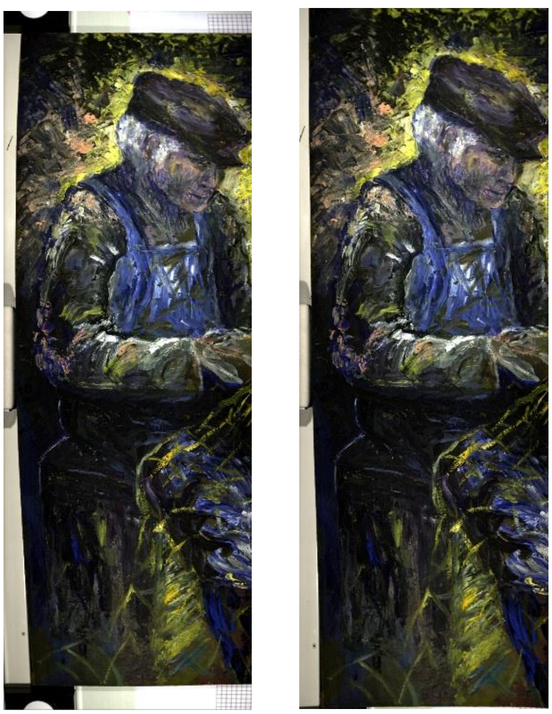

Figure 3. (a) Image of the painting captured with the scanner rotation of 51 degrees. (b) Corrected image

Images of the two paintings in Figure 3 and Figure 4 were captured in a laboratory condition where the paintings were placed in a supporting stand along with a mesh image and reference targets. The degree of distortion is related to the rotation angle the scanner makes and in the present case, image in Figure 3 has rotated at an angle of 42 degrees and image in Figure 4 at an angle of 51 degrees during acquisition. This in fact related to the size of the object. Image in Figure 3 has 4635 lines of pixels and in Figure 4 has 3841 lines of pixels. Reference targets in Figure 4 also allows to find the change in spectral values before and after the correction has performed. Frames of the painting can be considered as the geometrical reference for visual comparison and it is quite visible from the images (rotated view), that the images are distorted.

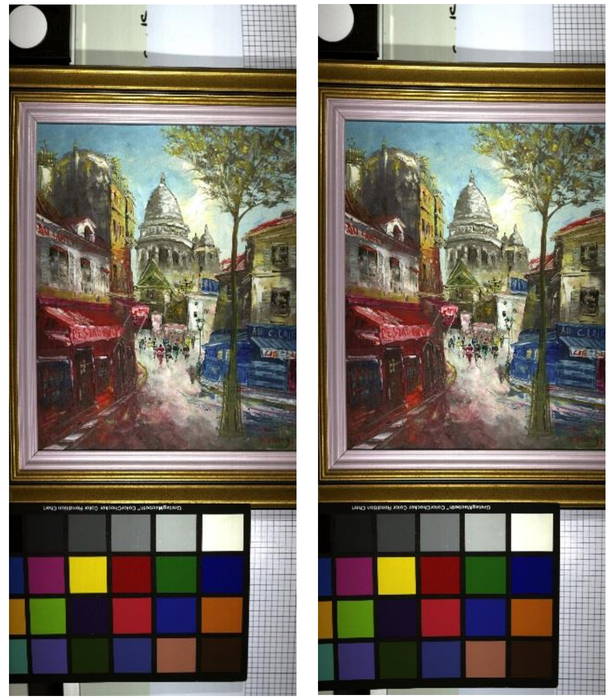

Figure 4. (a) Image of the painting captured with the scanner rotation of 42 degrees. (b) Corrected image

For the scanner used in the present study, the lens is required to change for various distance of image acquisition. Painting in Figure 5 was captured in a museum environment where the scanner to object distance was 3 meters. Though the spatial resolution decreases as the distance to the object changes, the angle of rotation that the scanner has to make to capture the painting reduces with distance. This makes less distortion in the resulting images. Figure 5 is an example for such an experiment where the undistortion results shows that by the radial distortion caused by the line scanner at different distance of acquisition can be corrected by the proposed method.

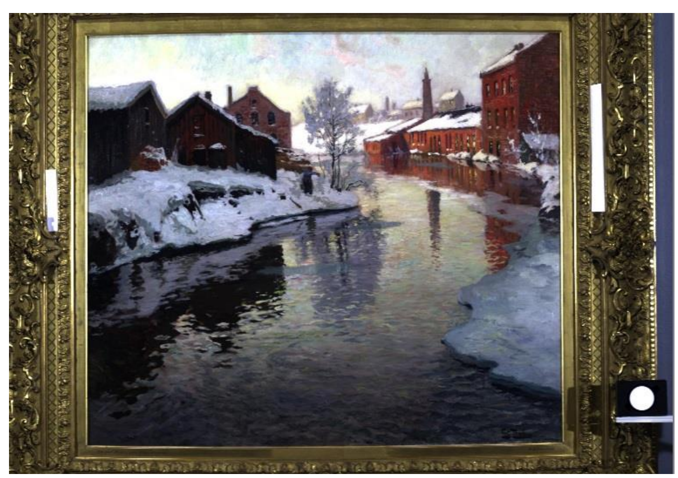

Figure 5. (a) Image of the painting 'The Old Factory, Akerselva (1901) / Den Gamle Fabrikk, Akerselva (1901)' by Frits Thaulow captured in a museum environment.

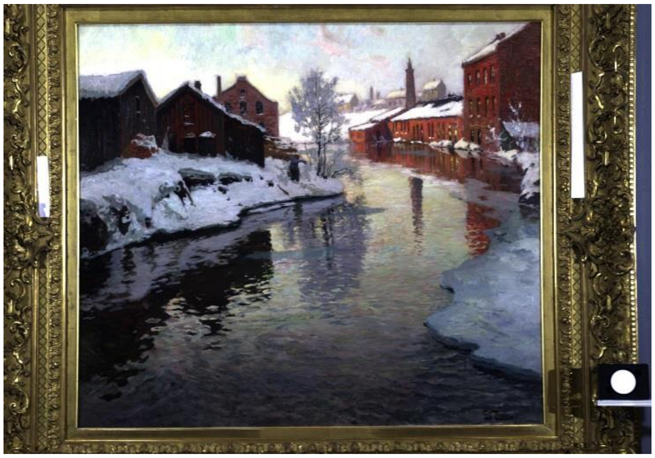

Figure 5. (b) Corrected image of the painting 'The Old Factory, Akerselva (1901) / Den Gamle Fabrikk, Akerselva (1901)' by Frits Thaulow recorded at a distance of 3 meter.

Conclusion and future research

The paper discussed the geometrical distortions in a push broom hyperspectral system attached in a rotational translation stage. Image distortion has corrected based on the geometrical model fitting for the current imaging system. Results shows that the proposed method corrects the distortions which mostly introduced by the radial motion of the line scanner.

Future research will focus on quantifying the distortion based on measurements from standard test images. It is also important to consider the geometrical distortions across the spectral bands. Studies will aim to develop model that fit for different lenses too by conducting experiment at different distances and angles. Another aspect to be studied is the spectral accuracy at the image before and after the correction. Since the imaging geometry is different for every lines of pixels, geometrical correction in spectral images also need to take this into account.

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Paintings reproduced in this paper are from private collections and also from Lillehammer Art Museum, Norway.

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