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COST EFFECTIVE ADAPTABLE HYPERSPECTRAL IMAGING OF MANUSCRIPTS: MAPPING SURFACE TOPOLOGY VARIATION

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ABSTRACT

Ancient and medieval parchments were frequently reused as covers and binding material bindings for early printed texts due to their durability and the availability of manuscripts considered obsolete. This has persevered texts that may otherwise have been lost at the cost of significant wear and damage which reduces legibility. Additionally, transport of these fragments, especially those still *in situ*, risks damage and so photographs are all that is generally available without visiting the libraries and repositories where they are preserved. Non-contact imaging techniques are critical to recovering the text from these fragments without causing further damage. We utilize a PyrOptik Chromamapper, a portable, low-cost hyperspectral imaging system for the retrieval of ancient and medieval texts due to the enhanced processing that can be done on such datasets. We also demonstrate a technique to construct 3D surfaces of the fragments utilizing hyperspectral datacubes which enables a digital version of the object to be studied as if it were physically present but without the risk of harm to the fragile samples.

Index Terms— Hyperspectral imaging, low-cost, 3D, codicology, fragmentology

1. INTRODUCTION

Manuscript fragment analysis, not unlike working with codices, poses unique challenges due to fragility, priceless value owing to the uniqueness of the materials and their sparsity. Imaging techniques such as UV fluorescence photography [1, 2] and multispectral imaging [3, 4] allow the damaged texts to be better analyzed, preserved and studied but required samples to be brought out of safe storage for the application of each technique, exposing them to light, moisture and increased risk of damage.

In this work, a PyrOptik Chromamapper system (CM-IR-256-v1) was applied to the field of fragmentology; the datasets were used to recreate 3D surface scans of the texts which could then be digitally handled remotely with no additional risk to the delicate measurands. The Chromamapper produces datacubes with 2000 by 1000 pixel resolution with 260 spectral channels with a spectral resolution of 10 nm.



Figure 1. A 3D render of the PyrOptik Chromamapper.

The fragments that were imaged as part of this work were from the Cardiff Special Collection housed in the Arts and Social Studies Library at the University of Cardiff.

Two fragments were used for the test. The first is a bifolium from a thirteenth century codex of Horace probably produced in Italy, transmitting *Epodes* 1.6-7. This bifolium was reused as a wrapper to protect the cover of an early printed book of the *Sermones de tempore et de sanctis et quadragesimalis* by Jacobus de Voragine (Lyon, 1499, now at the Cardiff Special Collections, shelfmark: incunabulum 187).

The other fragment is an offset fragment, partly visible on the board of Incunabulum 168; the actual flyleaf is lost but it must have come from a choir book probably produced in England during the thirteenth or the fourteenth century.

The aim of this work was to demonstrate that low-cost hyperspectral imaging techniques can improve the quality of manuscript fragments. It is also shown that a handheld instrument can produce usable data for the field of fragmentology and 3D surfaces can be produced from the hyperspectral datasets that by controlling the illumination.

2. METHODOLOGY

Two scanning approaches were performed in this work. Samples that could be laid flat were imaged on a translation stage. Handheld scans were carried out to demonstrate the

flexibility of the system, where fragments are not convenient to be placed on a translation stage. A spatial reference card was laid beside or on top of the fragments which allowed the variation in scan speed and direction to be accounted for and removed as per the methodology demonstrated by Davies et.al [5].



Figure 2. A spatial reference card is placed onto a sample that cannot be scanned on a translation stage due to its size and the restriction on the opening angle.

The scans performed on the translation stage were illuminated by a Thorlabs stabilized halogen lamp [SLS302] at a fixed angle of 80° to the imaging view shown in Figure 3. The scan duration on the translation stage was ten seconds where the Chromamapper system was stationary, and the sample moved through its field of view (FOV). The illumination could then be aligned to the Chromamapper's FOV, reducing the exposure of the bright lamp onto the samples' surfaces.

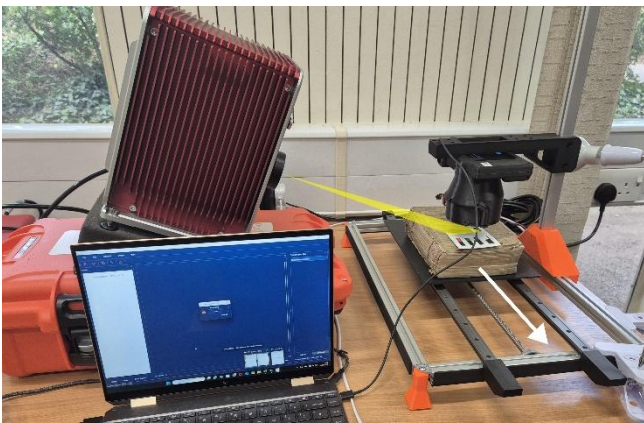


Figure 3. A photo of the experimental setup. The Chromamapper system is mounted facing down at the sample on the right. The sample rests on a platform attached to a linear translation stage; a white arrow indicates the direction of travel of the scan. The sample is illuminated by the Thorlabs light source on the left.

The controlled illumination during the translation stage scans meant that shadows cast due to the creases in the parchments could be related to local surface orientation. The brightness in a 2D image slice from the datacube was assumed to be proportional to the dot product of the light direction to the local surface normal meaning a depth map could be produced. However, brightness in the 2D slices also varied because of the text or marks on the parchment itself. This was accounted for by selecting slices at wavelengths where the text was not visible either due to transparency or equal reflectivity to the paper.

The variation in brightness of these slices can be interpreted as variation in the slope of the surface. This relationship is linearized under the assumption that the variations are small which holds for creased parchment. The resulting field of partial derivatives corresponding to the local change in height in x and y as per Equation 1:

$$p(x, y) \approx \frac{\partial z}{\partial x}, q(x, y) \approx \frac{\partial z}{\partial y}$$

Equation 1

This can then be reformed as a Poisson equation as per Equation 2:

$$\nabla^2 z = \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y}$$

Equation 2

The Fourier transform can then be taken of both sides which replaces the Laplacian operator with a simple multiplicative term and the equation simplifies to:

$$\hat{z}(k_x, k_y) = -\frac{ik_x \hat{p} + ik_y \hat{q}}{k_x^2 + k_y^2}$$

Equation 3

The inverse Fourier transform can then be taken to solve for z. In practice this was done numerically using Python. The result was a grey scale image with the same pixel resolution as the original 2D datacube slice, where the intensity of the pixel corresponded to depth.

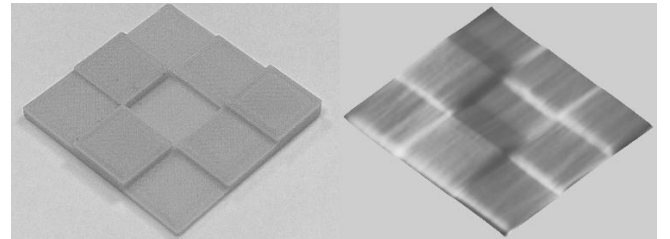


Figure 4. (left) A photograph of a 3D printed height reference used for calibration; (right) A digital model of the

3D calibrated reference reconstructed from the calculated depth map.

An object of calibrated height was imagined using an identical setup (shown in Figure 5) to calibrate for the true height since the initial depth maps were of arbitrary scale. This was due to the slice brightness being normalized to account for its less than one hundred percent reflectance, and the arbitrary selection of a pixel value in the slice that corresponded to the maximum height. The depth maps of the measured fragments could then be calculated by keeping these steps consistent during the calibration stage.

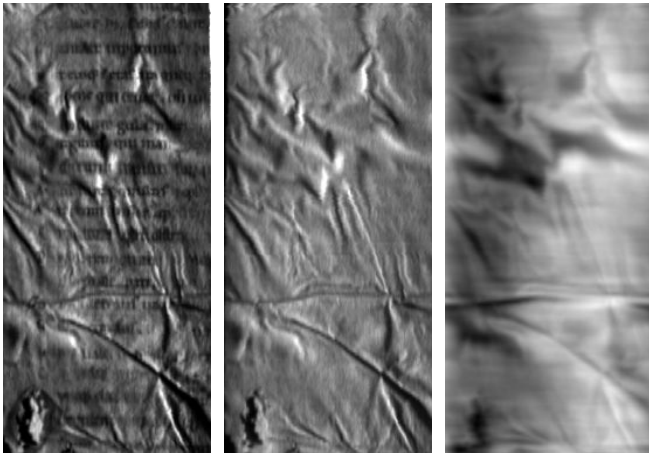


Figure 5. (left) A 2D datacube slice at 450 nm. The text is high contrast with the parchment, but creases and shadows are present; (center) A 2D datacube slice at 850 nm. The text is not visible, but shadows are present; (right) A depth map calculated from the NIR image.

Figure 5 shows two image slices and a depth map produced from the text-less slice. In this work, the shadows were removed as a post-processing step using the text-less datacube slice as a shadow map which was value inverted. Each other datacube slice was then added to the inverted shadow map to remove the shadows from the datacube. True spectral reflectance was not a concern in this work and so the impact of this step on this parameter was not considered.

Additional imaging with uniform illumination could have been performed to provide a datacube without shadows that could then be overlayed onto the depth map, but this was beyond the scope of this work.

Figure 6 shows the inputs to the shadow removal and the result. Both the 450 nm slice and the 850 nm slice have the same light and dark regions due to the lighting and defects in the parchment and so these can be removed through image processing techniques previously discussed. This also means that in addition to removing non-uniformity due to the illumination, other marks and non-spectrally dependent defects are removed/reduced.

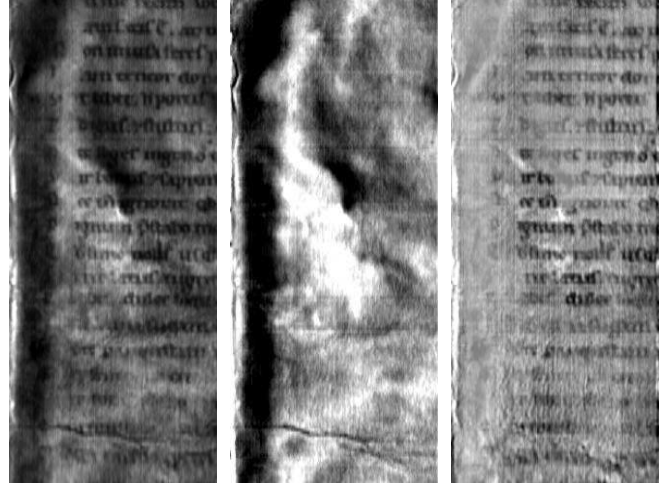


Figure 6. (left) A 2D datacube slice corresponding to 450 nm; (center) a 2D datacube slice corresponding to 850 nm; (right) The result of the image processing to remove the shadows introduced by the directional illumination.

3. RESULTS AND DISCUSSION

A key advantage of a system that can be operated as a handheld scanner is that awkward geometries or targets can be imaged in place without the need for a tailored mount to translate the system along a specific path. Some samples were attached to large books that had to be handled with extreme care and would not be convenient to image with a push-broom scanner on an off-the-shelf linear stage.

The Chromamapper can be operated as a handheld instrument by placing a spatial reference card in the scene.

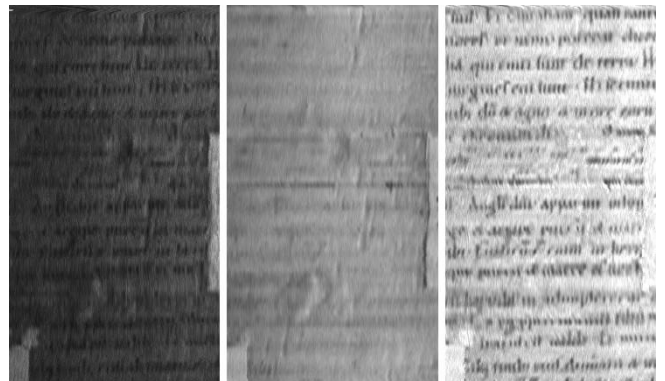


Figure 7. (left) A 2D slice of a handheld hyperspectral scan corresponding to 450 nm; (center) A 2D slice corresponding to 900 nm; (right) A high contrast reconstruction from the combination of the two image slices.

Figure 7 shows data from a handheld scan. The lighting used for the handheld scans was uniform so no depth maps were produced, but in principle the same lighting set up as the stage scans could be used.

Figure 8 demonstrates the utility of hyperspectral imaging for codicological and textual analysis. The text on the right of the images is much clearer in the image from the deep red portion of the spectrum (700 nm) than in the blue (430 nm), where the underlying text becomes clearer.

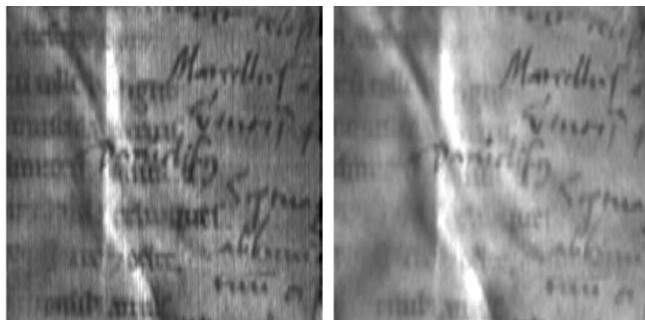


Figure 8. (left) A cropped slice of a datacube corresponding to 430 nm; (right) The same spatial region of the datacube at 700 nm.

Figure 9 shows a 3D depth map with the hi-resolution photograph overlaid as a texture.

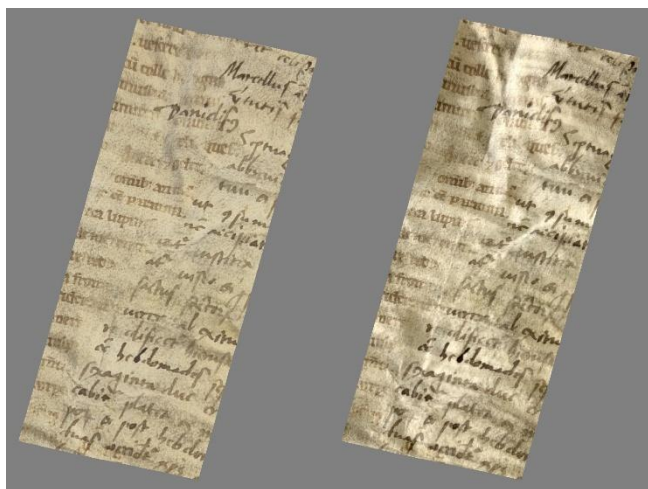


Figure 9. (left) A computer model of a hi-resolution photograph imposed on the depth map produced by the hyperspectral imaging; (right) The same model with simulated lighting to emphasize depth.

Additional scans with differently orientated lighting would improve the quality and accuracy of the scan, but the aim of this work was to demonstrate what could be produced with the imaging setup as it would be for a standard hyperspectral scan.

4. CONCLUSION

This work has shown significant potential of a PyrOptik Chromamapper for the imaging of parchment manuscripts. Wavelength selection allows for enhanced contrast of text, which could be improved with enhanced illumination at shorter wavelengths, potentially retrieving otherwise illegible text. Removal of defects and brightness fluctuations in the samples is also reported. Scans could be performed in less than 30 seconds and processed data was available in 5 minutes. Handheld scans were used where samples were not appropriate for translation on a linear stage due to fragility or geometry with such scans producing legible images.

Controlled illumination allowed for 3D surface reconstruction utilizing wavelength slices where text was not visible. These 3D scans were calibrated using a known reference and provide digital twins that can be manipulated remotely on a computer removing the need for travel to, or transport of delicate artifacts or prolonged exposure to different light sources

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