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2D and 3D optical techniques for manuscript analysis: diagnostics based on data integration

Nicole de Manincor[1*], Sara Mazzocato[1], Dumitru Scutelnic[1], Claudia Daffara[1]

[1] *Department of Computer Science, University of Verona, Strada le Grazie 15, 37134 Verona, Italy*
[*] *Correspondence: claudia.daffara@univr.it;*

***Abstract* – Nothing like an ancient manuscript, passed from hand to hand over the centuries, better represents the legacy of history. Researchers are called to advance the techniques that allow the interpretation of this ancient heritage. This work sets out the methodology for performing comprehensive data analysis through the integration of 2D and 3D optical techniques. The approach involves the use of traditional UV-VIS-NIR imaging, combined with SWIR imaging, and the recent Thermal Quasi-Reflectography technique. In addition to examining the spectral signature, the investigation also employs a microsurface perspective, *i.e.*, the imaging is integrated with surface topography.**

I. INTRODUCTION

Studying ancient manuscripts is essential for understanding our rich historical heritage and unravelling the mysteries of these witnesses to the past. The fragility of these artefacts places a significant responsibility on researchers to preserve their delicate nature and to decode their contents. Optical techniques play an important role allowing non-contact measurement of the artifact in a multimodal approach that is effective for material inspections, restoration monitoring, and historical study [1, 2, 3, 4].

The prevailing noninvasive approach for manuscripts investigation involves multispectral imaging in the UV-VIS-NIR range in conjunction with pointwise spectroscopic analyses [5, 6, 7]. Recently, the SWIR band has been shown to be promising [8, 9, 10]. The present research seeks to make a contribution to the advancement of the diagnostic protocol for manuscripts analysis. The work demonstrates the potential for expanding the spectral range of imaging to the SWIR and MWIR regions and for combining the imaging response with microsurface analysis.

The proof of concept of the integrated diagnostic based on 2D and 3D optical techniques is given, as exemplary case study, on a single leaf of a 16th-century choir book on parchment containing instrumental and vocal music. Notes and text are written in black ink, some significant letters are marked in red. Blue and red pen-flourished initials, ornamented, embellish the manuscript (Fig. 1a).

II. 2D IMAGING TECHNIQUES

The diagnostic imaging campaign was conducted using techniques operating in different, yet complementary, spectral bands, including VIS-NIR photography, VIS-NIR multispectral imaging, IR Reflectography (IRR, SWIR range), with the added value of the recent Thermal Quasi-Reflectography (TQR, MWIR range) [11], developed by the authors.

Since its introduction, TQR technique was mostly employed on wall paintings [11], coupled also with thermal analysis [12]. Recently, it was integrated into the workflow for manuscript diagnostics as a tool to investigate the condition of the artifact and previous conservation treatments [4, 13]. In the present study, in-band TQR analysis in the MWIR range is shown to provide further significant information about the materials.

The multimodal image stack was spatially registered using an OpenCV-based algorithm that combines Scale-Invariant Feature Transform (SIFT) for extracting distinctive, scale- and rotation-invariant local features, Fast Library for Approximate Nearest Neighbours (FLANN) for efficient and reliable descriptor matching, and Random Sample Consensus (RANSAC) for robust outlier rejection [14]. The method proceeds by detecting and describing local features in each image, matching corresponding descriptors across modalities, filtering unreliable correspondences using RANSAC, and estimating a homography that geometrically aligns the images. The resulting registration maintains structural consistency across the image stack, facilitating downstream analyses that rely on precise spatial correspondence.

Data integration demonstrated the potential of the multimodal and multiband workflow, which combines established imaging techniques with TQR, for discrimination and qualitative characterisation of materials in ancient manuscripts. For further confirmation of the imaging results, a spectrometry analysis in the VIS-NIR range (FORS, $360\,\mathrm{nm} - 2150\,\mathrm{nm}$) was carried out using the Zeiss MCS600 spectrometer. The FORS spectra are compared with reference literature [15], [7] and public databases (CRN-IFAC, FORS database).

A. MULTISPECTRAL IMAGING IN THE VIS, NIR, SWIR RANGE

For VIS-NIR photography, a CCD camera with extended sensitivity in the 400 nm to 1100 nm range was employed. Hoya R72 high-pass filter selects the IR range 720 nm to 1100 nm. VIS and NIR images were fused by IR False Colour (IRFC) method.

The MSX prototype camera was used for VIS-NIR multispectral measurements [16]. The device has monochrome and RGB CMOS sensors, with a filter wheel that holds eleven narrow-band filters.

IRR was performed with the Apollo camera by Opus Instruments, equipped with a 128×128 InGaAs array with sampling grid up to 5100×5100 pixels, and sensitivity in the NIR-SWIR range 900 nm to 1700 nm. The lens has 150 mm focal length with selectable lens f/number to optimize the depth of field. A filter set allows to select three broad bands: 900 nm to 1250 nm, 1250 nm to 1510 nm, and 1510 nm to 1700 nm. Two 150 W halogen lamps were used as IR sources, in reflection geometry.

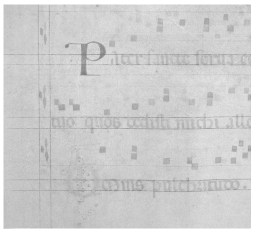
IRR analysis was useful to reveal a thin outline in dry medium, probably a draft the artist carefully followed and covered, when he painted the initials. This can be clearly observed when the filters are applied. Specifically, with the 900 nm – 1250 nm filter, the transparency of the red pigment increases, revealing the outline in the O initial, while the blue pigment of the P initial is absorbent, appearing dark colored (Fig. 1d). Conversely, when using the 1510 nm – 1700 nm filter, the blue pigment of the P initial is more transparent and the outline can be unveiled, while the red pigment of the O initial is highly reflective, hiding the draft (Fig. 1e). The dark blue appearance of the blue P initial and the yellow-orangish colour of the red letters (O initial and lowercase red letters) obtained in the IRFC image qualitatively suggested the use of, respectively, azurite and vermilion (Fig. 1b).

FORS spectra confirmed the pigments identified by IRFC method. In the interpretation of the FORS data, it must be underlined that from about 1100 nm all the FORS spectra are dominated by broad absorption features attributable to the parchment support [17]. The azurite spectrum has a peak reflectance at 465 nm, with a subsequent rise from 900 nm and a characteristic narrow absorption feature at 1497 nm. A modest increase in reflectance in the 750 nm to 900 nm range could be indicative of the presence of a small amount of lead white mixed with azurite. The S-shaped vermilion spectra show a sharp transition between 602 nm and 604 nm. The red spectra only differ in the level of brightness and the intensity of the absorption features associated with the parchment support, as the O initial shows higher reflectance and less intense absorption bands. This might be explained by suggesting the presence of a further layer underneath, perhaps a white reflecting ground layer, that partially attenuates the absorption from the parchment. The difference in reflectance can also be perceived in the 1510 nm reflectogram, where the O initial is brighter than the lowercase red letters (Fig. 1e).

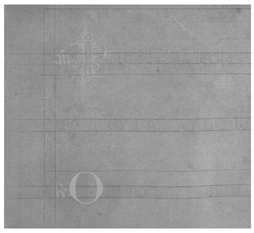
(a) VIS

(b) IRFC

(c) VIS-NIR multispectral imaging - 470 nm



(d) IRR - 1250 nm



(e) IRR - 1510 nm

Fig. 1. Imaging in the VIS and IR bands.

B. THERMAL QUASI-REFLECTOGRAPHY IN THE MWIR RANGE

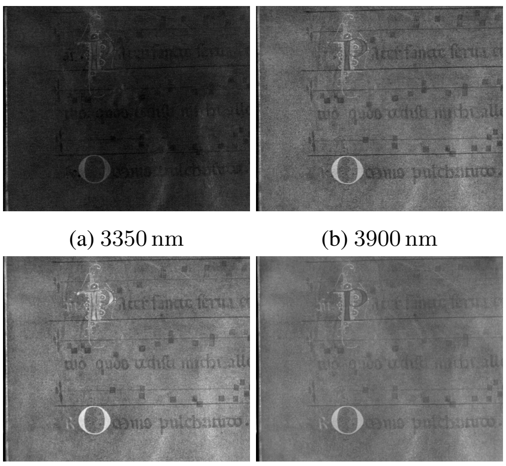
The TQR set-up consists of a MWIR (InSb) camera, with sensitivity from 1 µm to 5.5 µm, coupled to non-heating sources matched to the sensor, and reference standards. Following the measurement procedure detailed in Ref. [18], the result is a calibrated reflectance map in the MWIR region. An internal filter wheel allows for selecting the bands to tailor imaging to the materials response.

With the 3350 nm, for example, the lowercase red letters are absorbing, while the O initial is reflective (Fig. 2a). With the 4350 nm filter, instead, all the red letters appear reflecting (Fig. 2c). The extracted reflectance spectra from the O initial and the lowercase R letter have the same spectral shapes, but slightly differ in intensities. A comparison of both the extracted spectra with the FTIR dataset matches well with vermilion in egg tempera, suggesting that an egg-based medium was employed in all the red letters. According to the literature, egg white was one of the most employed binding media for illuminated manuscripts

([19]), and was found as the binder in vermilion and azurite pen-flourished initials [5]. To explain the difference in MWIR reflectance, therefore, it seems plausible that the red O initial was painted above a light ground layer, further supporting the hypothesis previously suggested.

The in-band TQR images of the blue P initial appear reflecting with a peak at 4350 nm (Fig. 2c), and absorbing at 3900 nm (Fig. 2b) and 5220 nm (Fig. 2d). The extracted spectrum is consistent with the egg tempera azurite spectrum obtained through the FTIR dataset. All the in-band TQR images of the P letter also show a dark bold outline, which can as well be observed in the monochrome 470 nm image acquired through the MSX camera (Fig. 1c). This outline, which covers the dry medium underdrawing and was probably made to further guide the artist while painting, seems to be applied by a liquid medium. To explain its very low reflectivity, it might be suggested that a different binder was employed. Arabic gum, which was the exclusive medium in writing inks [19], could be a good match, as the FTIR spectrum has very low reflectance in the entire 3 µm to 5 µm range.

The hypotheses proposed here need further investigation and discussion, however, in-band TQR imaging proved to be a useful tool for preliminary discrimination of materials to be included in the imaging workflow on manuscripts. An ad hoc pigments checker prepared on parchment with a collection of pigments (applied alone, or mixed, or layered) dispersed in different binding media (*e.g.*, Arabic gum, egg glair, egg yolk) could provide significant support to test imaging techniques on manuscripts.



(a) 3350 nm (b) 3900 nm

(c) 4350 nm (d) 5220 nm

Fig. 2. TQR imaging in the MWIR band.

III. 3D TECHNIQUES: MICROPROFILOMETRY

In the course of investigating the potential techniques for the analysis of ancient manuscripts, the present group has dedicated significant research efforts to the development of a reliable quantitative surface analysis from the data obtained by the prototype of an optical microprofilometer [20]. The instrument operates on the basis of the conoscopic holography principle, thereby enabling the acquisition of a height map of the document with micrometer accuracy. As demonstrated by the authors in [21] and [22], the analysis of the micromorphology of the surface can provide valuable insights into routine diagnostics.

The focus of the microsurface analysis was placed on the capital letters P and O of the manuscript investigated in the previous sections. The acquisitions were performed with the 50mm lens, a scan step of 50 µm and a scan velocity of 10 mm/s. Fig. 3 shows the height map of the R letter and a part of the O capital letter. It is possible to observe the concavity of the letter R, probably indicative of the manner in which the pigment has been applied. By comparison, the surface structure of the O letter exhibits a convex shape.

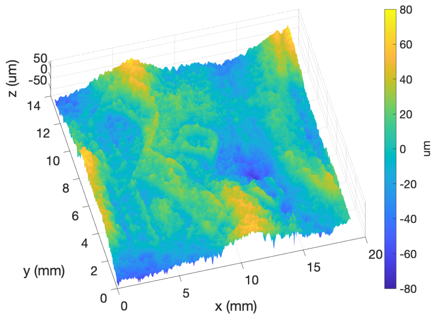


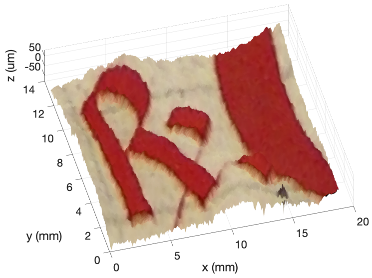
Fig. 3. Height map of the R and a part of the O capital letter.

The imaging data cannot be separated from the surface topography, which affects the scattering. In light of these considerations, the scientific analysis of ancient manuscripts can be performed by combining the imaging and the quantitative microsurface perspectives. By way of example, Fig. 4a shows the 3D map fused with the visible image, while Fig. 4b shows the 3D map fused with IR imaging (900 nm to 1250 nm).

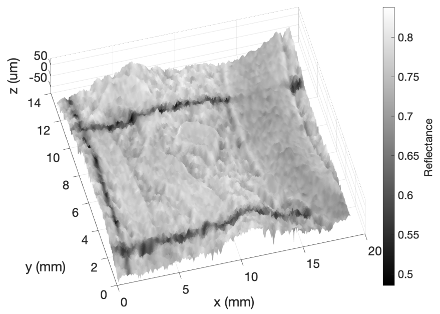
The P capital letter offers the possibility to appreciate the different marks left on the parchment during the preparation of the document. Three different subROIs, highlighted in Fig. 5, were selected.

Fig. 6a (green subROI) emphasizes a detail of the hollowed-out edge to create the border of the P letters.

Fig. 6b (yellow subROI) and Fig. 6c (gray subROI) show the different traces engraved in the parchment when the squaring lines were drawn. It is evident that the tool employed for delineating the yellow line (Fig. 6b) engraved the parchment with threefold lines, while the gray line (Fig. 6c) appears as a single line. These observations can guide the understanding of the different utensils used for



(a) VIS



(b) IR

Fig. 4. VIS and IR (1250 nm) images mapped and fused with the height map.

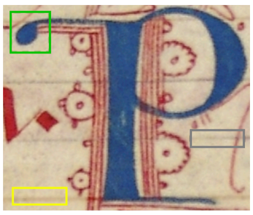
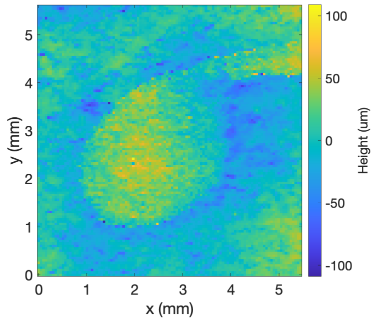


Fig. 5. VIS image of the P capital letter with the subROIs highlighted.

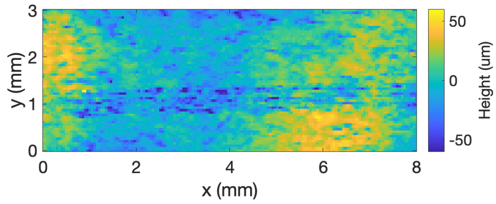
manuscript preparation.

IV. CONCLUSION: DIAGNOSTIC POTENTIAL OF DATA INTEGRATION

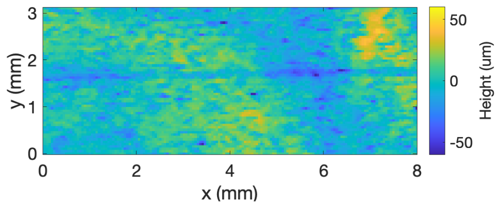
This work aims to establish a foundation for a more comprehensive and significant analysis of ancient manuscripts, integrating diverse perspectives, namely imaging and quantitative morphological inspection. Utilising an ancient parchment from a 16th-century choir book as a case study, the research demonstrates the potential for advancing the conventional practice of acquiring imaging stacks in the UV-VIS-NIR range. Indeed, the imaging stack is extended to include the SWIR and the MWIR ranges, and it is demonstrated how complementary pieces of information can be retrieved. Furthermore, the paper demonstrates how the spectral imaging response can be mapped and fused with the microsurface, thus enabling in-



(a) Green subROI



(b) Yellow subROI



(c) Gray subROI

Fig. 6. Height map of the green, yellow, and gray subROIs of Fig. 5.

depth and comprehensive full-field analysis.

V. ACKNOWLEDGEMENT

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VI. *

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