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Multimodal Measurement of Parchment Using a Custom 3D Scanner

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Abstract

A multimodal optomechatronics system is presented for measuring and monitoring change in cultural heritage objects exposed to environmental condition fluctuations or conservation treatments. It combines structured light, 3D colour digital image correlation and multispectral imaging, delivering information about an object's 3D shape, displacements, strains and reflectivity. The high functionality and applicability of the system are presented with the example of historical parchment subjected to changes in relative humidity.

Motivation

The influence of environmental conditions on Cultural Heritage Objects (CHOs) usually results in changes to their physical and mechanical properties. The heritage science community is conducting extensive research to understand, document and monitor the slightest changes occurring in CHOs, and use the information towards archiving and preventive conservation [1]–[4]. Full-field optical measurement methods, which are non-destructive, and non-contact monitoring tools, are a common strategy for documenting and assessing changes in CHOs. Their advantages also include the capability to provide shape and displacement data with different sensitivities, measurement ranges, and spatial, spectral, and temporal resolutions depending on the application needs, while they can often be used in situ. Such optical methods include coherent light (holographic and speckle interferometry, grating interferometry) [2], [4] and noncoherent light methods (photogrammetry [5], [6], moiré fringe methods [3], structured light methods (SL) [7], [8], digital image correlation (DIC) [9], multispectral (MS) and hyperspectral imaging [10]–[12].

In particular, incoherent light approaches have been included in the daily practices of conservators and museum professionals throughout the last decades. This can be attributed to the lower hardware requirements, complexity, and expense compared to coherent light approaches. Furthermore, the adjustable acquisition parameters, minimal operational hazards, and the possibility of being operated by non-specialized personnel make them ideal everyday tools for conservation scientists.

However, extracting accurate conclusions regarding an object's surface condition typically requires combining multiple pieces of information from more than one imaging modality. This task can be rather complex, involving the development of instrumentation which combines multiple modalities into a unique measurement system[13] followed by multimodal and multiscale data fusion through post-processing algorithms [14].

The work presented in this paper follows the latter approach, the combination of multiple imaging modalities originating from a single system for a multimodal imaging approach. Despite the numerous references and existing research for individual modalities in the field of Cultural Heritage [15], multimodal solutions originating from single setups are scarce and require special attention devoted to merging all measured data into a common coordinate system. Keeping these in mind, the primary scientific objective of this work is to present a multimodal approach in both the acquisition and processing of the collected data. To achieve this, multiple imaging modalities have been selected to be combined into a relatively low-cost device that can be used in situ. The modalities selected for the multimodal system described in this work are SL, 3D colour DIC (cDIC) [16] and multispectral imaging. Using the selected modalities, we can monitor in situ and in a non-destructive way the:

- shape (P(x,y,z)
- reflectivity information ($P(\lambda_1,\ldots\lambda_i)$)
- full-field displacements, both in-plane U(x,y) and V(x,y) and out of plane W(x,y)

while offering the option for strains estimation through derivatives calculations [9].

The functionality and applicability of the proposed system are presented using the example of a historical parchment exposed to changes in relative humidity (RH). Parchment is a complex biological material and an important carrier of written cultural heritage in the form of manuscripts, books, and scrolls. As a result, many research investigations are being conducted to document, monitor, and comprehend the physical features of parchment as well as the causes of its degradation.

Experimental Apparatus

We have developed a custom-made scanner (dimensions ~60x10x16cm, weight <7kg) capable of recording multimodal information using three incoherent light methods, presented in Fig. 1: structured light, 3D cDIC and multispectral imaging. It is a compact system comprised of two colour cameras (Basler ace acA4112-8gc) in a stereo configuration, equipped with 16mm lenses, an image projector (DLP 3010 EMV-lc, with synchronization board) and white LED illumination sources, with two colour temperature options (approx.. 5600K and 3200K) (Akurat LL2120hp), mounted on a tripod. Data capturing and processing have been realized using Python and MATLAB, while DIC analysis is performed using VIC – 3D7 software from Correlated Solutions.

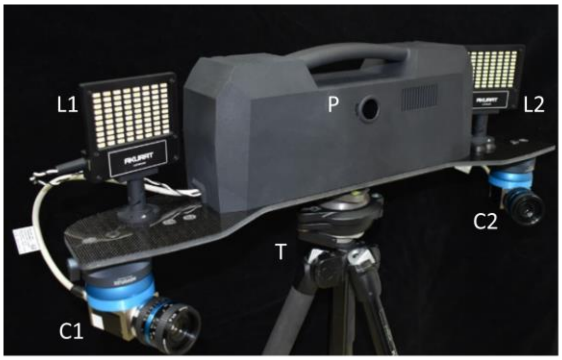

Figure 1: *The photo of the prototype of the system: C1,C2 – cameras, P – digital projector, L1, L2 – light sources, T- tripod.*

For each modality, sets of images are recorded with different illumination schemes. The 3D cDIC data are recorded using the white light illumination, and preprocessing of the data involves demosaicing, followed by calculating the displacement maps. 3D DIC is a method essentially tracking the position of unique intensity pattern across subsequent images, though correlation criteria, for the calculation of displacements and strains. To optimize the result for natural texture objects, we followed the approach described in [16] by generating merged displacement and strain maps from the individual colour channels based on the optimum correlation for each pixel. The structured light method is achieved by capturing images of the object under varying illumination patterns projected onto the object. Finally, the spectral reflectance content is recorded within the visible region of the spectrum utilizing the RGB camera channels and the LED illumination of the projector. In an approach similar to the one described in [17], [18] the camera sensitivity functions, and the projector LEDs' spectral power distributions (SPD) have been experimentally measured (Fig.2). The final spectral bands result from combining the projector illumination with the camera's sensitivity functions. The result is a five-band multispectral system, two arising from the combination of the red and blue projector SPD with the respective camera channels and three more from the green camera channel and its combination with the projector SPD for each LED. Therefore, the reflectance modality consists of 5 spectral bands, with varying bandwidths distributed within the visible part of the spectrum (Fig. 3).

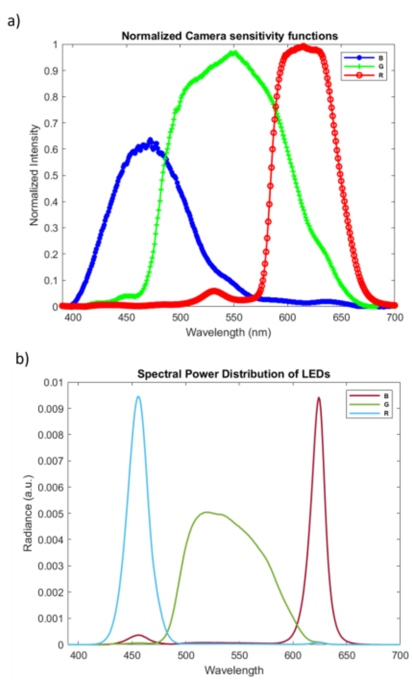

Figure 2*: Experimentally determined a) normalized camera sensitivity functions and b) spectral* power *distribution of projector primary LEDs.*

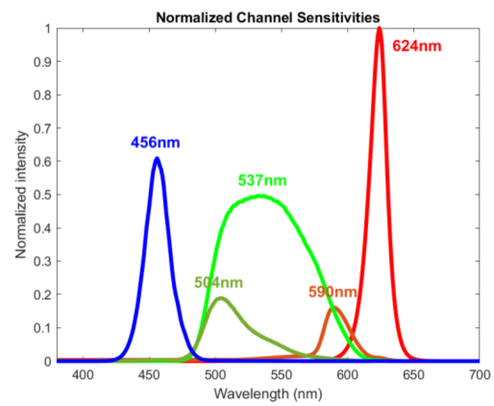

Figure 3*: Multispectral bands as they were experimentally determined from the combination of camera sensitivity functions and the LED spectral power distribution.*

Proper geometric, colourimetric and spectral calibration protocols are performed before each measurement. Then, results are extracted for each technique, in terms of the shape, displacements, and reflectance factor for each spectral band. Finally, the individual modality outcomes are merged into a single dataset which is represented by points with multiple information (shape (x,y,z), reflectance (λ_1,..,λ_5), and displacements (U, V, W)), as shown in Fig. 4.

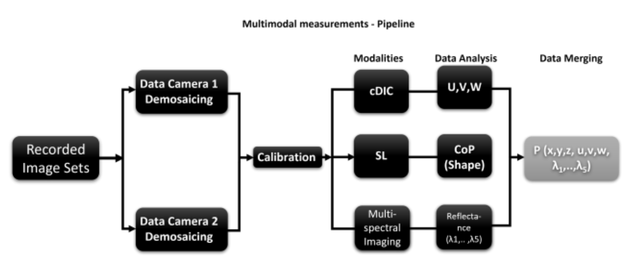

Figure 4*: The pipeline of multimodal measurement acquisition and processing of multimodal data*

Experimental Scenario

A historical parchment sample has been chosen for the multimodal measurement. It is a handwritten manuscript from the fourteenth century with an unknown provenance (Fig. 5). The parchment was discovered within a book cover serving as a supporting spine strap. The historical material has been mounted using a system with elastic hinges as described in [19], [20] and its response to naturally varying humidity levels, ranging from 35%-55%, during a day was monitored.

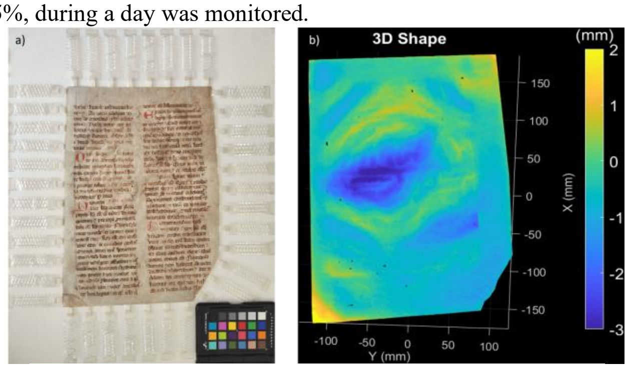

***Figure 5**: a) Parchment manuscript and mounting system, along with b) the corresponding shape from SL.*

The measurements were performed using two different protocols:

- Capturing data at the beginning and the end of the RH changes using three modalities while the object is in static conditions. The static conditions correspond to RH=35% at the beginning of the experiment and RH=55% at the end. In both cases, the environment was stable for approximately 30mins before the data recording.
- Capturing data during the RH changes with one modality, 3D cDIC, to monitor the sample's response.

The recording protocols followed for this experiment are not restrictive and can be modified based on the application requirements. It is possible to perform a monitoring session with recording at consistent time intervals based on the expected response time of the object to the external loading. The recorded data are image files in *bmp* and *png* format, while the output data are in *bmp*, *mat* and *ply* format. The input and output data format is not restrictive to these categories and can be modified.

Results

Through multimodal measurement, we recorded information regarding multiple quantities of the object. The recorded datasets can be visualized in multiple ways, depending on the application's purposes. For example, in Fig. 6a-e, we present details from the multispectral data of the sample for RH=35%. An area of the sample corresponding to the letter "O" of the manuscript, which is red, fades for the spectral bands of 590nm and 624nm (marked with red in Figs. 6a-e). The reflectance factor and spectral reconstruction of that area correspond to the plot in Fig. 6f. The reflectance factor is calculated after flat field correction and dark current removal, for each multispectral band at the peak wavelength (Fig. 3).

In addition to the shape and reflectivity, the in (U, V) and out (W) of plane displacements and strains (ε_{xx}, ε_{yy}, $\varepsilon_{xy.}$) of the parchment, as a response to the relative humidity fluctuation are also recorded. Representative results from displacement and strains analysis are shown in Fig.7, where the W displacement map (Fig. 7a) along with U and V in plane displacements (Fig. 7b, c) and strains (Fig. 7d-f) of the historical manuscript are presented for the

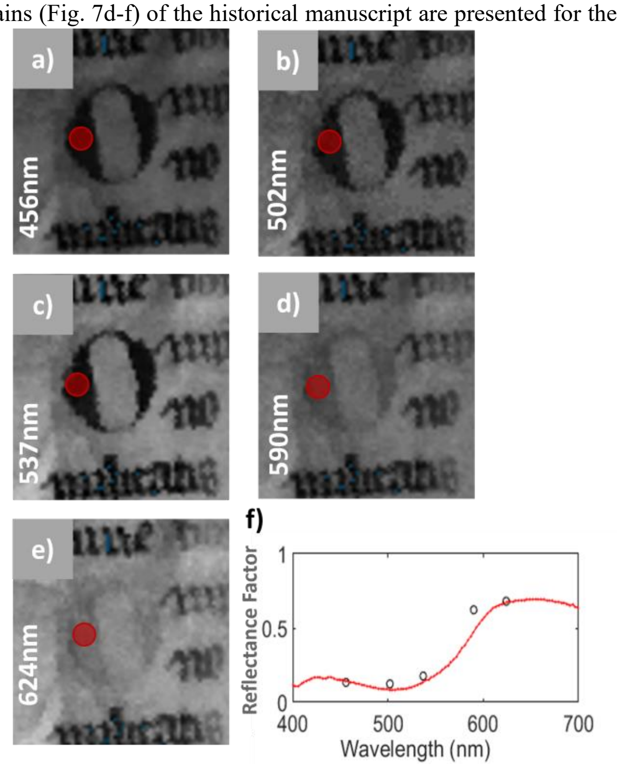

***Figure 6**: Detail from multispectral dataset of the historical manuscript (the wavelength indicates the peak of the band) (a-e), along with the reflectance factor of one exemplary point and its spectral reconstruction (f). The origin point on the sample is denoted with red colour.*

maximum humidity percentage of the experiment (RH=55%). The out-of-plane displacement (W, Fig.7a) is low [19] due to the presence of the mounting system (Fig. 5a), which prevents the sample from significant deformation. At the same time, the in-plane displacements (U, V) show the effect of the fixture with almost linear terms and peak-to-valley values in the range of 0.3mm (Figs. 7b and c respectively). The higher strain values are located around the edge of the sample and close to the mounting, where while lower values are observed in the middle (Figs. 7d-f).

Conclusions

We have designed and built a portable, relatively low-cost measurement system that enables multimodal data acquisition and processing sufficient for archiving, documentation, and structural monitoring of various CHOs, under variable external conditions. The system, for the first time, offers for each measurement point the results, which include shape (x,y,z), reflectance spectra ($\lambda 1,...,\lambda 5$), displacements (u,v,w) and strains (ε_{xx}, ε_{yy}, $\varepsilon_{xy.}$) of the object under investigation within a common coordinate system. The functionality of the apparatus is illustrated through the example measurement session of a historical parchment exposed to RH changes. We successfully recorded this parchment's geometrical features, displacements, strains, and reflectance content in a noninvasive way.

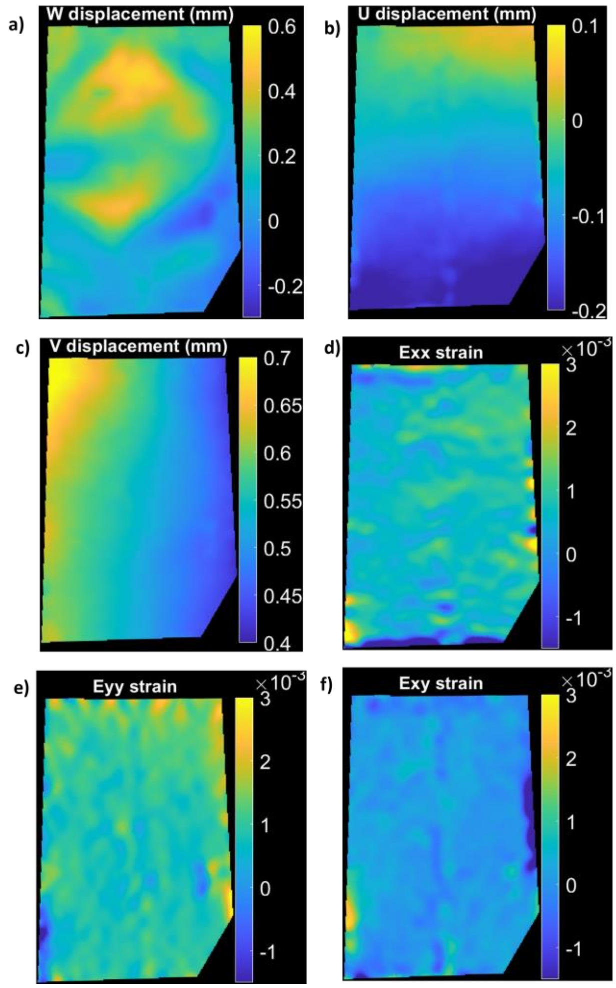

***Figure 7**: a) Out of plane displacement (W), along with (b, c) in plane displacement maps (U, V), and strains (e-f) for RH=55%.*

The same apparatus can be used also to monitor other CHOs and materials sensitive to environmental conditions or undergoing conservation treatments. It is additionally possible to analyze changes in the 3D shape, reflectance and displacements occurring during storage or display to allow conservators to effectively assess the condition of the sample and prevent future degradation. Depending on the measurement objective, the modalities can be used selectively, or combined as proposed herein.

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