Thermal texturing for ancient codices 4D exploration

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Abstract – **In this work the main results obtained in the framework of the "Codex 4D" project have been presented and discussed. In particular, pulsed thermography (PT) and RGB photogrammetry have been combined to obtain a 4D virtual representation of some ancient codices. The aim is to facilitate the end-user experience, giving the possibility to explore subsurface elements, detected by PT, in a 3D virtual model.**

I. INTRODUCTION

In the field of book and archival heritage, digitization activities, carried out by means of standard 2D scanning and photography techniques [1], focus mainly on the content of codices. However, from both historical and codicological perspectives, the structural features of a book, such as the binding, the book block and the decorative elements are also of fundamental importance. It is worth mentioning that part of this valuable information is not accessible because it often lies within the bookbinding or it is buried beneath the pictorial layer of the illuminations [2-3]. Moreover, the elements buried inside the bookbinding may also contain hidden texts, on fragments obtained from waste materials, of interest from scholars. In fact, since the 16th century it became very common to use earlier library material for the making of new bookbindings due to the increase of the production of books caused by the invention of printing [4]. In particular, printed or manuscript sheets were either used for supporting the structure between the board and the spine or inserted between the cover and the end papers [5]. The use of earlier library material ended in the 20th century when the safeguard of the library heritage began to be taken into greater consideration.

The decorative apparatus of the book may also consist of the illuminations, which may conceal underdrawings and *pentimenti* hidden under the pictorial layer [6-7]. Moreover, illuminations can be affected by structural defects, such as detachments of the gildings, and other subsurface features. All these elements constitute the so called 4th dimension of the book and they can be investigated through infrared (IR) imaging techniques, like the so called pulsed thermography (PT). PT is a non-destructive technique which enables the depth-resolved investigation of different kind of features. However, such a technique gives the results as maps of the temperature distribution (thermograms) which may be unclear to a non-expert audience [8-9]. For this reason, the end-user experience could be facilitated by including the hidden elements detected by PT in a 3D virtual representation of the book. In this work, some of the results obtained in the framework of the "Codex 4D" project will be presented and discussed. In particular, PT is applied in combination with 3D image-based techniques (RGB photogrammetry) in order to obtain a 4D virtual representation of the subsurface features buried in ancient codices.

II. AIMS

The main goal of the "Codex 4D" project, which started in April 2021 and is scheduled to be completed in December 2023, is to create an interdisciplinary experience with the ancient codex, both from an art-historical as well as a diagnostic and conservation perspective. In order to integrate and contextualize in a coherent space all the information related to the visible elements (shape and color), with that related to the elements hidden in the underlying material levels, a model of the codex is elaborated in 4D. The model is explorable and analyzable in its three dimensions and in the different levels of its stratigraphic depth. To do this, it is necessary to integrate photogrammetry techniques, which employ RGB images to obtain the volumetric model, and IR imaging techniques, which allow the acquisition of images at various depth levels. The instruments on the field are very different in terms of optical characteristics and operating modes [2,10]. For this reason, the first goal of the project was to develop an efficient methodology for data acquisition and post-processing. The results of cultural studies and scientific analyses increase the knowledge of the artefact and they are mapped onto the 4D model in the form of interactive semantic annotations. A web 3D platform is developed for real-time scientific visualization of the codex and for its multilevel exploration, using a series of tools. The platform, based on the ATON framework developed by CNR ISPC, (http://osiris.itabc.cnr.it/aton/), consists of a back end through which editors can deploy contents over the time, and a front end accessible to the wide public.

The contents will also be translated within a holographic showcase for museums, in a more metaphorical and poetic form. Here the codex will be narrated and represented in a dramaturgical style, with the hope of making it more comprehensible to the public and enhancing it as a depositary of so much knowledge and history that normally remains inaccessible [11].

III. ACQUISITION OF THERMOGRAMS

The procedure used for generating the thermal texturing [10] makes use of a texture mapping algorithm. PT was used to record thermograms of the analysed manuscripts from different viewpoints. In addition, to perform a consistent orientation between the thermographic and RGB images, homologous images, obtained by shooting the same checkerboard, were used. The image coordinates of such markers play a crucial role in the thermal texturing of the model.

A) Pulsed thermography

PT is based on the monitoring of the time dependence of the IR radiation emitted in the mid-wave IR (MWIR) spectral range following the sample heating induced by the absorption of a short visible light pulse. The emitted radiation is then recorded during the cooling stage by means of an IR camera, which provides a sequence of images, called thermograms, each corresponding to a different delay time with respect to the onset of the heating pulse, that gives information on the evolution of the temperature distribution at the sample surface. In particular, the possible presence of buried elements is detected through their influence on the local heat diffusion that gives rise to contrasted features in the recorded thermograms [12]. Information about possible subsurface features, such as their size or position within the sample volume, can also be evaluated [13].

In the present study, the thermal stimulus has been induced by two flash lamps (Bowens Estime 3000, maximum power 650 W) delivering 2,5 ms long light pulses. The lamps have been positioned at a distance of 0.4 m with respect to the investigated codex with their axes at 45°. Thermographic sequences were recorded by a Cedip JADE camera characterized by a Noise Equivalent Temperature Difference (NETD) < 25 mK at 30 °C (320x240 pixel, InSb focal plane array, 30 μm pitch, 3.6-5.1 μm wavelength range) for 1s in full frame mode with a frame rate of 150 Hz and, thereafter, processed by the Altair 5.50 software. To evaluate the time dependent change of the thermographic signal for all the image pixels, the corresponding signal levels pertaining to the frame obtained just before the flash pulse was subtracted from each pixel in all the recorded thermograms. This procedure gave the possibility to display the induced changes in the thermograms with a larger dynamic range [14].

B) Photogrammetry

Considering how photogrammetry as documentation's paradigm for Cultural Heritage morphological and colorimetric data has extensive and qualified literature [15-18], it does not seem useful proposing another report related to such tool. What actually deserves some critical analysis is the measurement campaign's simulation carried out, as shown in Fig. 1, in order to facilitate camera location for IR poses, considering their low resolution (320 x 240 pixels), limited depth of field, absence of exit data and optical difference than those used for volumes morphometric description.

Following the analysis of the surveying context, we opted for the implementation of a full frame sensor (Canon 6D) with normal focus optics (50 mm), operated with a remote, installed on a stand. The shots were taken along the perimeter of a circumference of 2.9 m of radius, taking an image every 15 degrees. Shot positions have been materialized on the floor so that they can be repeated easily also with the IR sensor. In order to facilitate cameras orientation a particular calibrator has been created, as illustrated in Fig. 1, useful both for scaling models in real world units and in order to have a pattern, even with automatic targets recognition, facilitating of the camera location calculation for IR shots.

IV. DATA PROCESSING

Photogrammetric restitution process was carried out using two SfM procedures, Agisoft Metashape® and Capturing Reality®. These products have robust history of case studies and results validation [19], in both cases the alignment made use of the target self-recognition system, targets were also used as a reference for scaling the models. Models generation followed the classic path of photogrammetric data processing (alignment, dense cloud and surface generation, texturing), however, before finalizing the model, the IR poses were aligned in the project as described in the next paragraph.

A) *Thermal texturing*

Thermal texturing in order to obtain image geometries that can be used within SfM, generally makes use of approaches requiring GAN (Generative Adversarial Network) implementation [20]. The experimentation conducted as part of the "Codex 4D" project led to the development of at least two solutions that can, with good reason, be considered more expeditious and full of possible development, namely: i) texturing in computer graphics; ii) implementation of AI software to increase IR images resolution.

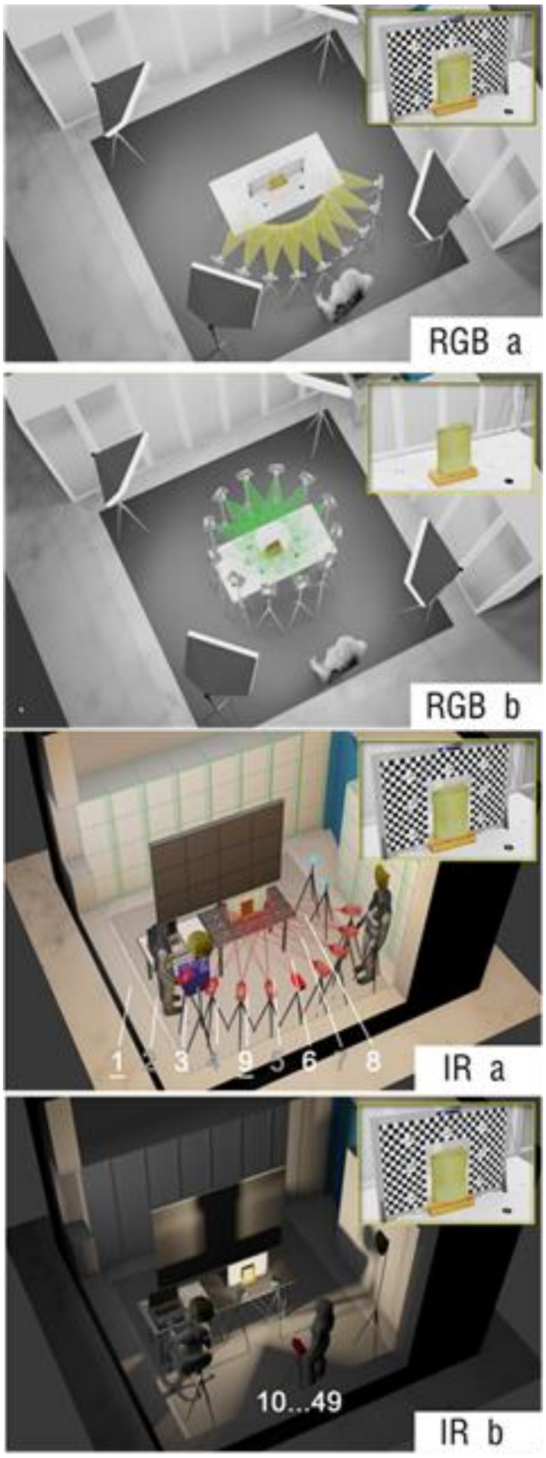

Fig. 1 -Virtual simulation of the acquisition set, useful for both RGB images and thermograms. The calibrator has been created to have a pattern for the automatic targets recognition.

The first solution proposed using manual camera mapping within 3D modelling software for IR shots, however, it only bypassed the problem, without therefore obtaining a solution for IR camera alignment. This first approach also had the limits of shots number and non- complex geometry implementation. This approach was therefore discarded. The second solution involved the use of Gigapixel AI software, used to pre-process IR images, multiplying their original resolution, 320 x 240 pixels, by four times. This made it possible to obtain a robust orientation also for the IR camera within the Capturing Reality® procedure.

B) 3D model optimization workflow

Books digitized using photogrammetric process (PP) were further processed within computer graphics software (CG) for the purposes in the bulleted list:

- edit the polygonal model and improve aesthetic rendering of the 3D models
- optimize UV mapping of models to exploit and manage textures (RGB and IR) more efficiently:
- optimize mesh (number of polygons and topology) for future implementation within the “ATON” [20], a web3D application to navigate and query semantic models.

First, the photogrammetric model was imported into Blender software. Here the topology was optimised using editing and sculpting tools to correct and modify sub-object levels of the selected object (vertices, edges, and faces). For example, small holes, caused by under sampling during acquisition were filled in and some disturbing elements such as elements used to stop pages were digitally removed. Then by means of remeshing tools the surface of the model was simplified and the triangular faces turned into quadrangular to make it cleaner and easier to edit for the subsequent UV Mapping (Fig. 2). This latter is the process of projecting a 2D image (texture) to a 3D model's surface to attribute colour and make it photorealistic.

In photogrammetry, this process is automatically computed by PP software in three steps: 1) calculation of the UV (or texture) coordinates for each vertex in the mesh; 2) generate texture from mixing different pictures of the dataset; 3) apply the texture to the respective faces of the mesh. Indeed, the first step was the most important for our purposes because it control how the texture is applied onto the mesh models, so we decided to manually control it using unwrapping tools in CG. In this way it was possible to weigh the detail in pixels of the colour assigned to the various parts of the model, giving higher priority to the areas of greatest interest (those with text and images) over others (Fig. 3).

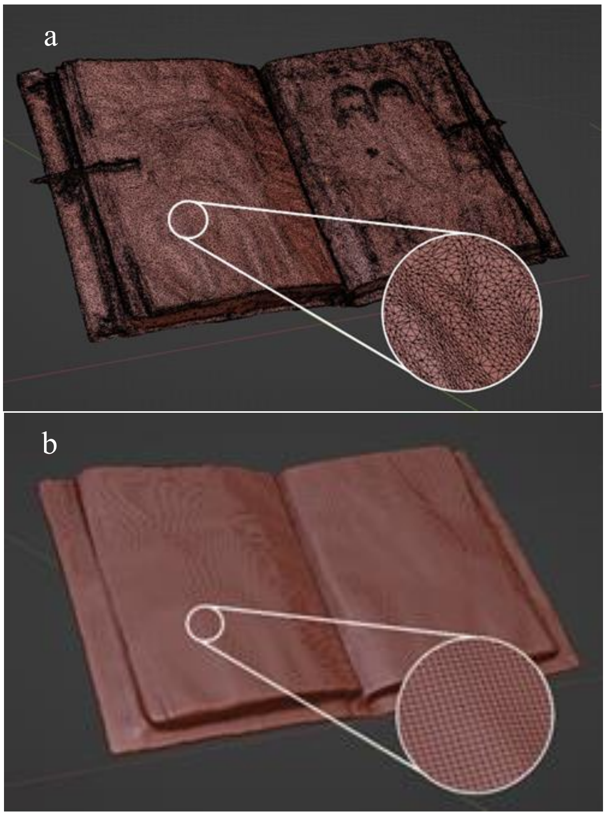

Fig. 2 -a) triangulated mesh generated by photogrammetry processing; b) quadrangular mesh created with remeshing filters.

Fig. 3 - Atlas texture created in photogrammetry software using texture building algorithms. Left) texture built using automatically generated texture coordinates; right) texture built using manually created texture coordinates. In the image in the right side the detail was weighted by prioritizing the pages.

The authors underline that this manual process in no way affects the accuracy of the mapping. Finally, the model was imported back into the photogrammetry software to generate and apply the final atlas textures (RGB and IR) and to obtain the real color effect (Fig. 4).

Fig. 4 - Final models of a book textured with RGB and IR images.

V. OUTCOMES

The final result consists of a 3D thermographic texturing showing features lying at different depths allowing to display the book from different angles. Finally, the 3D representations should go beyond current levels of visual depictions, support information integration, shape-related analysis and provide the necessary semantic information for in-depth studies.

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