The Codex 4D project: a novel method for the virtual exploration of ancient books

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ABSTRACT
In this paper, an innovative method for the digital representation of ancient books is proposed. Specifically, this approach consists of the reconstruction of the book three-dimensional geometry through photogrammetric images obtained from different viewpoints using Structure from Motion. In addition, both reflectograms in the mid-wave infrared spectral range and thermograms, recorded by pulse thermography, have been adopted since they enable a depth-resolved characterization of the manuscript. The final result is a 4D digital model of the codex, which allows both the visualization of the geometry of the book and stratigraphic exploration of the features buried beneath the surface. Data obtained from humanistic studies and diagnostic surveys have been also mapped onto this model in the form of semantic annotations. Finally, several outputs were developed, including a 3DWeb platform and a holographic showcase designed for museums, with the goal of creating an interdisciplinary experience with the ancient codex.

1. INTRODUCTION

In recent years, several actions have been proposed for the dissemination of cultural heritage (CH), many of them aimed at improving the accessibility for both the scholars and the general public. Accordingly, increasing attention has been paid to the development of procedures for the digital representation of ancient manuscripts [1], [2]. However, these procedures are limited to only providing a two-dimensional (2D) representation of the visible elements on the surface, thus excluding those that can be hidden below it. For instance, some hidden elements can be found within the bookbinding, as in the case of recycled written fragments used to reinforce the structure between the board and the spine or inserted between the cover and endpapers [3], [4]. In addition, ancient books were often decorated with illuminations, which may conceal underdrawings and pentimenti beneath the pictorial layer [5], [6]. Illuminations may also be affected by damage, such as detachments of the gildings, and other subsurface defects. Such elements constitute the so-called fourth dimension (4D) of the book which can be only detected by means of non-destructive imaging techniques, such as Infrared Thermography (IRT) [7], [8]. However, IRT does not enable gathering information concerning the shape of the object under investigation due to its intrinsic 2D character. Owing to this reason, to overcome such limitations, various three-dimensional (3D) reconstruction techniques, combining geometric and thermographic data, have recently been proposed [9], [10].

This paper presents an innovative method for generating 3D thermographic models enabling also the stratigraphic exploration of CH. Such a method was developed in the framework of the Codex 4D project, and its main objective is the creation of an interdisciplinary experience with the ancient codex, both from an art/historical as well as a diagnostic and conservation perspective. To pursue this goal, a 4D model of the codex, allowing the depth-resolved exploration of the 3D model, was produced. To generate such a 4D model, photogrammetric techniques, which use RGB images to obtain

the shape of the object, and infrared (IR) imaging techniques, which allow the depth-resolved investigation of subsurface features, have been integrated [11]. In addition, chemical, microbiological, and physical analyses have been also carried out on both elements and leaves of interest in the manuscripts. Such investigations were aimed at detecting the material degradation products, traces of biodeteriogens in the present or past life of the manuscript, and to identifying pictorial materials. The results of both cultural studies and scientific analyses were then mapped onto the 4D model as interactive annotations. To facilitate the virtual browsing of the model to the general public, several outputs were developed, including a 3DWeb platform for the real-time scientific visualisation of the codex and its stratigraphic exploration, which is available on the Codex website. Finally, a holographic showcase was specifically designed for museums to enable an engaging interaction with its content through an emotional narrative.

2. MATERIALS AND METHODS

2.1 The books of the Angelica Library in Rome

The investigated manuscripts were selected based on the following requirements: i) book size, considering the distances imposed by both the field of view and depth of field of the IR camera and the space available for the digitization in the library's room; ii) good state of preservation of the book; iii) rigid or semi-flexible binding so as to allow a stable positioning during the acquisition; iv) content suitable for the narration (storytelling); v) presence of elements of interest buried beneath the visible surface , i.e. pentimenti, gold leaf detachments, etc.

Based on the criteria mentioned above, the following three books were selected. The first book is a 15th century manuscript, Book of Hours (MS. 459), written in French Gothic minuscule. The manuscript is on parchment with dimensions of 235 x 160 mm, and it is richly illustrated with 15 full-page miniatures. The second book is the manuscript De Balneis Puteolanis (MS. 1474) by Pietro da Eboli [12]. It is on parchment, its size is 184x130 mm, and its production date is probably between 1258 and 1266. Finally, the third codex is Dante Alighieri's Divine Comedy (MS. 1102), dated around 1340. The manuscript, measuring 345 x 240 mm, is on parchment, and it has several illuminations with abrasions and censorship, such as those on the nudity of demons [13].

2.2. Methods

The research project was created with the aim to accomplish the following outcomes:

1) innovation of the digitisation and documentation processes through the integration of different disciplines, methodologies, and techniques. In this regard, one of the initial results of the project was the development of an efficient methodology for digital data acquisition and their post-processing for their integration into a single multidimensional model allowing its real time exploration;

2) improvement of the methods for the content transmission and representation through a detailed study of user needs, advanced digital application tools and storytelling.

In our opinion, the obtained results may be considered helpful in broadening the accessibility of these valuable items, which indeed are quite often difficult to appreciate. To pursue this aim specific tools have been implemented in the 3DWeb

App allowing the user to explore specific papers or manuscript configurations and open or create annotations related to the information corresponding to specific points of interest. Virtual reality is thus a useful tool for the integration of data, which can be updated over time by the scientific community. While the virtual model refers to specific configurations of the manuscript and provides punctual information about their contents, the Codex 4D website provides a broader presentation of the Codex 4D main results, such as the ones concerning the previous restorations or the state of preservation.

The holographic showcase displays the same set of research data but with a poetic-emotional style. A narrative character, who lives in the illuminations where he plays with the research data, has been created. While moving on the pages, he reveals several information about the illuminations such as the adopted realisation process, the materials and the painted characters. In addition, by means of such a showcase it is also possible to directly interact with the 4D model through hand gestures, in a simple and funny way to zoom in on details and activate annotations.

The adopted methodological workflow can be summarised as shown in Figure 1. The work packages of the project were 1 - Selection and characterization of artefacts, 3D data acquisition, diagnostic investigations; 2 - Creation of multidimensional artefact models, metadata mapping and 3D annotations; 3 - Creation of the access platform and user experience scenarios; 4 - Dissemination of the research model.

2.2.1 Preliminary activities

In the initial phase, a preliminary examination of the selected manuscripts was done by ordinary visual inspection and by thermographic surveys to identify any hidden elements of interest. Three configurations for each manuscript were identified: (a) De Balneis Puetolanis: cc. 9v-10r, 12v-13r,19v-20r; (b) Book of Hours: closed, cc. 21v-22r, 67v-68r; (c) Divine Comedy: cc. 4v-5r, 55v-56r. The selected poses of the manuscripts were then studied by codicologists, paleographers, and art historians. At the same time, benchmarking was carried out, to contextualise and create added value for the Codex 4D project, with respect to state of the art, especially in relation to digitization strategies, and usage scenarios. The following tools were sought and analysed: (a) Websites and platforms; (b) Multimedia applications, VR and AR; (c) Implemented features, tools, services and interfaces; (d) Scientific articles; (e) RGB and IR integration models; (f) 3D thermographic models that can be explored stratigraphically. In a nutshell, the benchmarking results highlighted (a) poor dialogue between humanities and diagnostic sciences; (b) prevalence of 2D content digitization; (c) lack of information on materials, state of preservation, and restorations; (d) diffusion of standard and interoperable formats (standard FITS, IIIF framework); (e) lack of 3D representations of manuscripts; (f) poor information on invisible and stratigraphic elements; (g) absence of 4D annotations; (h) lack of attention to the value of the manuscript as material evidence; (i) difficulties in the manuscripts dissemination in museums due to their cognitive and physical inaccessibility) [14].

2.2.2 Digitisation process

The digitization of ancient codices employed an accurate methodology integrating cutting-edge technologies such as Structure from Motion (SfM) photogrammetry, infrared (IR) imaging and advanced computer graphics techniques. Such an approach was aimed at creating highly detailed 3D models
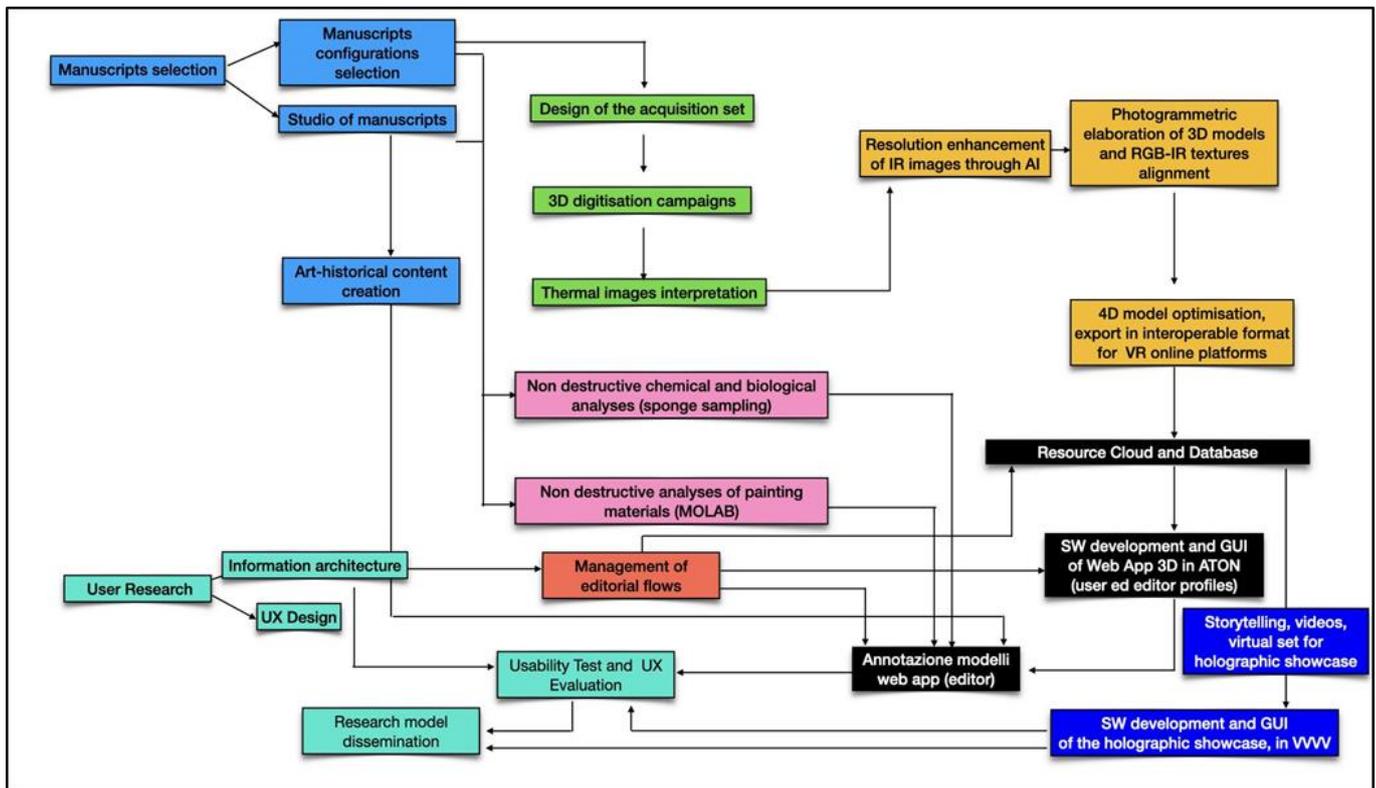
Figure 1. Methodological workflow of the Codex 4D project.

representing both visible and buried features embedded within the manuscripts. The adopted process encompasses three main stages: acquisition, processing, and post-processing. On-site acquisition involved the use of both photographic and thermographic instruments. The acquisitions were carried out on the same days by means of two separate set-ups hosted in the same room.

To obtain the thermographic images the pulsed thermography (PT) configuration has been used. PT is based on monitoring 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. In particular, the recorded thermograms are maps of the temperature distribution at the surface, where it is possible to detect the presence of buried elements. This is due to the fact that the presence of subsurface elements influences the local heat diffusion and, as a consequence, it gives rise to contrasted features in the recorded thermograms [7]. Quantitative information about subsurface features, such as their size or position within the sample volume, can also be evaluated. 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 characterised by a Noise Equivalent Temperature Difference (NETD) < 25 mK at 30 °C (320 × 240 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 [7]. The impact of the method on the investigated manuscripts depends only on the type of the excitation source. In the case of PT and photogrammetry, the perturbation is induced by VIS light lamps, in which the damaging UV component is filtered out through specific filters. Moreover, the duration of the pulse in the case of PT is about 3 ms thus inducing a temperature rise of a few degrees. In the case of MWIR reflectography the illumination of the manuscript is obtained by means of an IR sources. Special care was taken to minimize the exposure time (~ 0.1 s) and the power of the incident IR radiation to reduce the sample heating and, consequently, the mid-wave IR radiation thermally emitted by the sample [15].

2.2.3 Creation of the 4D virtual model

In the processing stage, the photogrammetric models were created by generating a point cloud with spatial information including XYZ coordinates and RGB colour values. Post-processing involved also the extraction of a polygonal solid model and the creation of photographic textures to achieve photorealistic rendering.

The incorporation of infrared (IR) images into the RGB workflow enabled the mapping of the 3D model with both visible colour and thermal data. Integrating the RGB and IR datasets into a unified model required their alignment within the same reference system. Due to differing resolutions between datasets (e.g., IR images were characterised by a resolution of 320 × 240 pixels), such an alignment was carried out in different steps. A panel with grid patterns and auto-recognition targets was specifically designed and imaged by means of the IR and

RGB techniques simultaneously to the manuscript. Such a panel has been proven to be useful for aligning the datasets and ensuring accurate camera positioning. Additionally, resolution enhancement algorithms were employed to improve the automatic recognition of both targets and control points on IR images, thus enabling precise orientation in 3D space aligned with RGB mapping. Following such a digitization procedure, computerised graphics software enhanced the aesthetic rendering of 3D models, optimised mesh topology, UV mapping and managed different layers of atlas texture (both RGB and IR). The polygonal solid models were optimised for seamless integration into the VR, MR and Web3D platform, thus facilitating their accessibility. In conclusion, this combined approach facilitated the creation of accurate and visually appealing 3D models, incorporating both visible and not visible layers to enhance the fruition of the investigated books. Furthermore, specific experimentation was carried out to obtain a digital reconstruction of three-dimensional codex geometry directly from infrared images.

2.2.4 Diagnostic surveys

As mentioned before several chemical and microbiological analyses of the manuscripts were also carried out at the libraries hosting the investigated manuscripts. In particular, High Performance Liquid Chromatography (HPLC) was carried out to assess the state of chemical-molecular deterioration of the cellulosic components [16], particularly of the support materials (parchment), bindings and covers, and collations. Similarly, Fourier-Transform Infrared (FTIR) spectroscopy was carried out to gather information on the chemical composition of the artefact component parts such as parchment, fillers, glues, and inks of organic nature [17]. Microbiological analysis such as Sanger Sequencing and Next Generation Sequencing (NGS) were employed to assess both the presence and the typology of biodeteriogens on manuscripts to prevent and, hence, counteract the effects of biodeterioration [18], [19]. Finally, X-ray fluorescence analysis, Vis-NIR and Raman reflectance spectroscopy [20], multi-spectral imaging techniques such as UV fluorescence [21] were carried out on c.13r of De Balneis Puteolanis, to identify the pictorial materials of the illuminations and the gilding preparations (Figure 2). The results were compared and supplemented with the observations from art-historical study and the prescriptions reported on some ancient treatises dealing with the production and use of pigments in the illuminations manufacture.

2.2.5 User studies and editorial management

In the initial phase of the project, the study was focused on defining the user needs and synthesising them with typical profiles (Personas). Data were collected through interviews and were then analysed by Grounded Theory [22], [23], (through the Designer Italia's Personas kit [24]). The people interviewed were

Figure 2. Biological and XRF analysis carried out on manuscripts in Angelica Library.

Table 1. Categories and subcategories used to organise the collected information in the frame of the Codex 4D project.

Categories	Subcategories	
Iconography and Iconology	Description Dating and Attribution Style Visual Comparisons Ornamental Elements	Characters and Symbols Ideological Message Sources and Traditions Reconsiderations Subsequent Modifications
Materials and Execution Techniques	Particularities of Materials	Particularities of Execution Techniques
Structure	Size Binding Layout	Re-use of Elements
Conservation and Restoration	Restoration Biological Evidence Chemical Evidence	Physical Evidence Theft and Subtraction Damage
Text and Writing	Transcription Particularities of Writing Subsequent Amendments	Translation Notes
Censorship	Text Censures	Damage Censures
Musical Annotation		

both internal to the project group, (b), and external to the project, being some of them without familiarity with the ancient codex field. The identified users lead to the definition of categories and subcategories (Table 1), to model the contents. Categorisation was necessary to obtain a rigorous and coherent editorial structure allowing both editors and users to reach the information of their interest easily. To enable the project team to work efficiently, the creation of a shared drive with a structured repository was necessary, as well as the management the editorial flows. Templates were prepared for each type of content to enter information and data and then to integrate them into the various applications.

2.2.6 Content integration on platforms

In parallel with other project activities, the customised user platforms, tools, and GUI (graphic user interface) were also implemented in the Codex 4D 3D Web App, including generic and expert/editor user profiles. It is based on the open-source (GPL v3) ATON framework [25], developed by CNR ISPC. This framework made it possible to nimbly create the Web App by ensuring its access from common web browsers installed on any possible device.

Conversely, the Codex 4D holographic showcase is based on VVVV [26], a visual programming platform known especially in the field of digital art. Finally, scripts and storytelling were elaborated for the application running in the holographic showcase. Video shooting in a virtual set, chroma key and compositing techniques were also necessary to integrate the virtual character in the visual storytelling.

2.2.7 Evaluation and dissemination of the research model

In the later stages of project development, user experience tests and evaluations were carried out to verify the effectiveness and educational ability of the applications under development. Thanks to the obtained results, only minor improvements to the interaction interface of the applications were necessary to meet the target audience requirements.

Finally, the research model and its results were presented through a web site (https://codex4d.it), exhibitions, workshops and scientific publications.

To sum up the considerations reported before, the innovative value of the Codex 4D project consists in interconnecting several disciplinary fields. Such a multidisciplinary methodology was made possible by the

cooperation of different skills that make up the working group. The cooperation among partners implied co-design sessions, aimed at defining the expectations and needs of everyone. The outcomes of the co-design activity led to the creation of the Codex 4D information architecture and the semantic relations among contents. The final digital ecosystem should enable the dissemination of the illuminated manuscripts' knowledge in their extraordinary complexity.

2.2.8 3D thermo-reflectography

The method described in the previous section is based on the integration of photogrammetric and thermographic techniques However, such an integration has been proven to be rather challenging. However, a recently proposed patent by some authors of this paper [27] offers an innovative approach to create 3D thermographic reconstructions directly from thermograms. This method aims at addressing the limitations originated from the SFM and PT image integration, although it also faces issues such as low image resolution and the loss of reference points regarding the book's shape and geometry. To address these challenges, our method starts with the MWIR reflectograms recording by illuminating the artefact with an IR source, thus ensuring sufficiently contrasted IR images. Subsequently, PT sequences are recorded using the same IR camera to guarantee precise correspondence between PT and reflectographic images. Furthermore, IR image resolution was enhanced by means of specific software tools based on artificial intelligence. This resolution enhancement is of crucial importance for the orientation process, as it allows the photogrammetric software to find sufficient corresponding points between pairs of images (the original images failed to produce accurate results due to their low resolution). Once the geometry is reconstructed, the original images are then used to build and apply texture to the 3D model.

The proposed method aims at overcoming the limitations of commonly used procedures for 3D thermography, where thermograms are combined with 3D spatial data obtained from images recorded in a different spectral range using devices other than the IR camera. By means of MWIR reflectograms a PT sequence recorded in succession, a more accurate 3D thermographic reconstruction of the artefact can be created.

3. RESULTS

3.1. Virtual exploration of invisible features in the 4D model

As mentioned above, the proposed method is aimed at producing 4D digital models which enable the virtual exploration of the manuscripts. Figure 3, for instance, shows two different views of the 4D model obtained on the manuscript MS. 459 by processing the images recorded in the MWIR spectral range. It is worth noticing that the data obtained by means of PT are inserted in the model, thus allowing its in-depth resolved exploration and, hence, the detection of the elements lying at different depths within the book. As an example, in Figure 4 some of the results obtained on the manuscript MS 1102 are reported. In particular, Figure 4a displays the 4D model of carta 4 verso-5 recto and Figure 4b shows the photographic magnification and the corresponding thermogram of the area highlighted by the dashed rectangle.

Another example is shown in Figure 5 where the images of the 4D model corresponding to carta 9 verso and carta 10 recto of De Balneis Puteolaneis are depicted. In particular, Figure 5a has been obtained from the thermogram recorded right after the
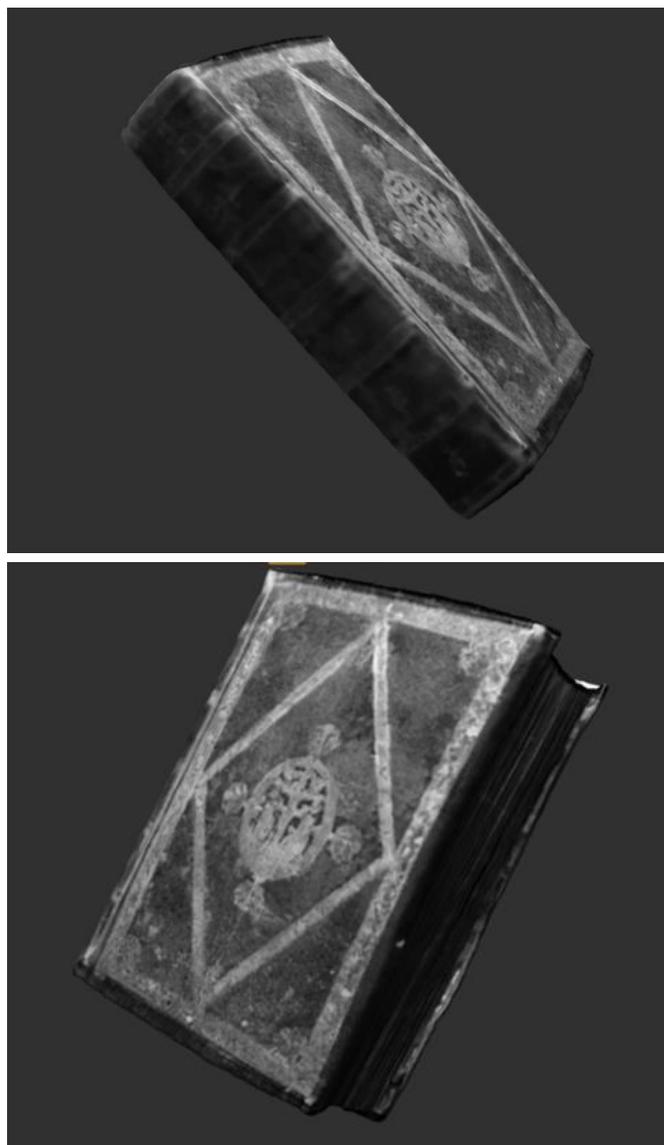

Figure 3. Different views of the 4D digital model of the MS 459 (Biblioteca Angelica in Rome).

Figure 4. MS1102, Biblioteca Angelica in Rome . a) 4D digital model of carta 4 verso and 5 recto; b) photographic magnification and corresponding thermogram of the area marked by the dashed rectangle in a).

onset of the heating pulse and, consequently, it enables the visualisation of shallow features. The magnification of the area highlighted by the dashed rectangle in Figure 5a is depicted in Figure 5b where the corresponding thermogram of Figure 5c reveals a jellyfish which is not visible in the photograph.

Figure 5. De Balneis Puteolaneis, Biblioteca Angelica in Rome. a) 4D digital model of carta 9 verso and 10 recto; b) photographic magnification and corresponding thermogram of the area marked by the dashed rectangle in a)

3.2. Outputs of the project

3.2.1. Web App

A Web3D environment, addressed to an expert audience, is dedicated to the interactive visualisation and exploration of manuscripts, and to the querying of contextualised annotations in the four dimensions (Figure 6). (A movie demo can be seen at: https://tube.rsi.cnr.it/w/jZi6XWdHcqMBeYZo52SKTf). As mentioned in section 2.2, alongside the public user profile, the Codex4D WebApp also provides an editor profile, via authentication. Both profiles have been designed to allow real time exploration of the acquired configurations of the manuscript. It is possible to use measurement tools, display or hide annotations entered on the model, move lights in the scene to better highlight specific details. It is also possible to use, on the 4D model, the IR interactive detector lens, that allows deep analysis through the different layers of the manuscript, thus switching from surface RGB to IR images (Figure 7). An interesting feature of the editor profile is given by the possibility to create new semantic annotations, or to edit and delete any previous annotations. Changes will be visible in real time by the users. For both profiles, semantic annotations can be selected depending on the category.
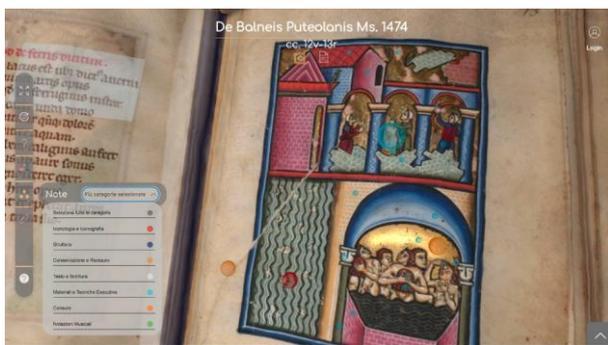

Figure 6. Interface to filter annotations in the Web App. Different colours refer to different categories.

Figure 7. Interactive detector lens tool for unseen information discovery in the infrared (IR) layer. Example of annotation in the IR level.

3.2.2. Holographic showcase

The 4D models and their contents that emerged from the investigations are translated within a holographic museum showcase, based on the Pepper's Ghost technique. Here the manuscripts, their significant elements and the tools needed to investigate them, are represented in a dramaturgical style.

The holographic showcase is conceived as a small theatre, equipped with lights, and directing software that offers the possibility of activating multimedia events within it. The goal is to narrate, through an "augmented" experience, the museum object that is generally contained within it [28], [29].

The user can interact directly using hand gestures, without the mediation of other devices or controllers. Thanks to a Leap Motion sensor, hand movements (left or right indifferently) are tracked and translated into input in the virtual scene. In fact, by moving the hand horizontally or vertically in the interaction space, it is possible to explore the 3D model along the depth axis (RGB and three IR levels) and activate contextualised annotations on the model (Figure 8).

The choice of manuscripts, configurations and related narrative videos, is made through a totem equipped with buttons located in the front of the showcase.

The showcase introduces a dramaturgical storytelling: a narrator character, played by an actress filmed in green screen, lives in the miniatures and performs actions on the manuscript. It narrates that world from the inside, is as small as the illuminated figures, and performs actions or activates tools to enhance reading and understanding of the codex (Figure 9). In this way, the Codex 4D project not only aims to increase scientific knowledge of the manuscript, but also to push the languages of scientific communication into new experimental terrain to attract and intrigue new audiences.

3.2.3. Web site

The Codex 4D website (https://codex4d.it) has educational as well as scholarly value. It offers a wide variety of sections that allow users to embark on a narrative and multimedia journey, and it is addressed to a broad audience interested in learning about the context of ancient manuscripts. The main sections of the site are:

1) Project - Objectives, survey and documentation technologies used in the project are explained with a special focus on integration methods. The project team and the involved skills are also presented;

2) Collection - The manuscripts are introduced and contextualised, with the possibility, for each one, to directly access the complete description structured consistently with the

Figure 8. The Codex 4D holographic showcase exhibited to the public in the Angelica Library in Rome, from the 10th of November to the 8th of February.

Figure 9. Codex 4D holographics showcase based on the Pepper's Ghost technique and integrating dramaturgical storytelling.

information architecture of the project, and the complete photo-gallery documenting all the pages. For each codex, it is also possible to directly access the Web App;

3) Narrated Glossary - It differs from the usual list of definitions in alphabetical order, and introduces a narrative approach, focusing on the materials and stages of codex making;

4) Results - It includes the contents that constitute the project results, scientific publications, reporting (templates and deliverables), and news.

4. CONCLUSIONS

In this article, an overview of the main results obtained in the framework of the Codex 4D project were presented. An innovative method for obtaining a digital representation of the ancient codex that can be explored stratigraphically was discussed. The result is a digital model of the book appearance, obtained by photogrammetric techniques, but at the same time allowing in-depth exploration of invisible elements detected by infrared thermography. In addition, the results of various chemical and biological analyses were mapped onto the model in the form of interactive annotations.

The project also included several outcomes for virtual exploration of the model namely the 3D WebApp, the holographic showcase and the web site. Each outcome addresses a different type of audience and enables different levels of understanding of the content. The aim is to create a multidisciplinary experience of the ancient codex that will enhance it and promote its fruition.

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