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Original article

4D thermo-reflectography of cultural heritage. The Codex 4D project: From data acquisition to the implementation in innovative virtual and mixed reality platforms

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ABSTRACT

In an effort to try and improve the dissemination of cultural heritage, in this paper a novel method for the four-dimensional (4D) digitization of artefacts, based on images recorded in the mid-wave infrared spectral range, is presented. Such a method is here applied to ancient manuscripts in the frame of the "Codex 4D: journey in four dimensions into the manuscript" project. In the proposed approach, the three-dimensional geometry of the manuscript is reconstructed by processing the reflectographic images, obtained from different points of view with respect to the artefact, through Structure from Motion techniques. Thermograms obtained by means of Pulsed Thermography are also recorded since they provide a depth-resolved characterization of the artefact that is also integrated into the digital reconstruction along the orthogonal direction to the surface, hereafter referred to as the fourth dimension. The results gathered from humanities and scientific studies, are also mapped onto the 4D model in the form of interactive semantic annotations. The goal of such a reconstruction is to allow users to browse the subsurface elements into the 4D model, thus facilitating the study and the exploration of the manuscripts through the inclusion of information about their literary and art-historical contents, materials, execution techniques, and state of conservation. In addition, virtual and mixed reality environments have been developed for different kind of audience such as expert users and museum public. Despite the experimentation presented here was carried out exclusively on manuscripts, in our opinion the methodology can be successfully applied to other types of artefacts.

1. Introduction

1.1. The Codex 4D: a multi-dimensional and multi-disciplinary approach to the manuscript

The methods typically employed for the generation of the three-dimensional (3D) thermographic reconstruction are based on the integration of two-dimensional (2D) thermograms into a 3D geometric model of the investigated object that can be obtained by means of laser scanners [21,24] or photogrammetry employing red-green-blue (RGB) cameras [2,5,7,20,30]. In order to avoid the procedure of merging images from different techniques, in the proposed method the 3D shape is reconstructed through the reflectographic images collected by means of the same infrared (IR) camera employed for the thermographic acquisitions. The effectiveness of such a method has been tested by carrying out 3D depth resolved investigations of ancient manuscripts in the frame of the "Codex 4D" project. In particular, four books, dating from the 13th to the 15th centuries, have been selected from the collections of the *Casanatense* and *Angelica* Libraries in Rome. More in general, the program of the project consists of the following main methodological streams:

1) development of 4D digitization techniques aimed at detecting visible and invisible/subsurface features in manuscripts, which are then mapped on a 4D virtual model, annotated and semantically enriched;

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2) design of the user experience with 4D manuscripts. Based on the detected image dataset, different digital environments to facilitate the dissemination of 4D manuscripts amongst different types of audiences have been designed, such as a website, a web app, and a holographic showcase.

The project intends to establish a link between humanities and diagnostic sciences, which are two research domains with a still poor connection, particularly in the field of manuscripts [16]. In such a field, digitization is still mainly 2D [3,6,9,23,26,31], and most of the efforts are focused on written and painted contents, which do not allow for a complete appreciation of the manuscript's value. In fact, very little has been done to complement the contents of the book with a material representation in its three-dimensional structure, integrating information on multiple levels including those ones invisible under the surface, useful to understand the history of the object, its making technique, provenance, and its conservation history [17,18]. The few 3D models of manuscripts available online, shared on sites such as Sketchfab do not provide tools to explore hidden elements or to access the outcomes of chemical, physical and biological analyses. In a very few cases, advanced tools for immersive virtual exploration of annotated 3D models have been implemented on individual manuscripts, such as in the project "Using Virtual Reality to Explore 15th Century Illuminated Manuscripts" carried out by an interdisciplinary group of experts in history, art history, photogrammetry, 3D modelling, and game design, from the South University of California[1] [39]. Finally, it is worth noting that manuscripts cannot be fully appreciated in museum environments, because of their scant accessibility, dim lighting, difficult-to-read handwriting and outdated language, and the inability to leaf through the pages.

The innovative value of the Codex 4D project consists of interconnecting multiple disciplinary fields under a comprehensive methodology that aims to increase the knowledge of the ancient manuscripts, taking into account their tangible and intangible values [27,34]. In order to integrate the information related to the visible elements with that related to the elements hidden in the underlying layers, a model of the ancient codex in 4D has been created, that can be browsed in both the three canonical dimensions and in the successive levels of stratigraphic depth. The results of chemical, biological and physical analyses, as well as those of palaeographic, codicological and art-historical studies, are also mapped onto the 4D model in the form of interactive semantic annotations and visualized in a web platform, useful for researchers and conservators, but that can be also easily used by the public. Annotations are associated to the surface and sub-surface layers, and they are organized in thematic categories and subcategories, which can be chosen and filtered by the users in the visualization according to their specific interests.

1.2. 4D thermo-reflectography of cultural heritage

In the dissemination of Cultural Heritage (CH), digital representation of artefacts is traditionally limited to the documentation of the features lying on the surface even if the non-visible elements hidden in the underlying layers are also of the highest importance. Such an improvement is nowadays made possible by the increasing number of suitable techniques that are available for the in-situ inspection of the CH interior structure [12]. Amongst others, Pulsed Thermography (PT) is nowadays considered as a well-established technique for the non-destructive diagnostic of CH items since it enables an in-depth description of the features beneath the visible surface [4,19]. However, conventional PT does not allow to gather information about the shape of the investigated object due to its intrinsic 2D character. In order to overcome such limitations, several 3D reconstruction techniques combining both geometrical and thermographic data have been recently proposed and applied in different fields [5,11,37].

In the "Codex 4D" project an innovative method for the generation of 3D thermographic models has been experimented, which, amongst others, enables also the depth-resolved exploration of artefacts. The model, which can be then considered as a 4D one, is obtained using Structure from motion (SfM) approach which in this study has been applied to reconstruct the 3D surface of the investigated item from 2D images recorded by means of both PT and mid-wave infrared (MWIR) Reflectography, being to the best of our knowledge such an approach never been used before.

2. Research aim

The project has multiple objectives. The first goal is to increase documentation and knowledge of manuscripts, which are considered as complex artefacts, by taking into account their shape and structure, contents, materials and state of conservation. The second one is to integrate both visible surface elements and the ones hidden under the surface, in a single multidimensional virtual model, thanks to the combined use of Photogrammetry, Pulsed Thermography, and MWIR Reflectography. In addition, further diagnostic investigations have been carried out on manuscripts, such as chemical, microbiological, and physical analysis to identify the materials, to assess their degree of degradation and, hence, to establish its possible origin. Finally, the third objective of the project is to enhance the perception of manuscripts in Virtual Reality (VR) and Mixed Reality (MR) environments. In this regard, new approaches to scientific visualization and storytelling inside museums have been specifically developed to stimulate the public interest towards the manuscript.

3. Materials and methods

3.1. Integration of pulsed thermography and MWIR reflectography

In the adopted PT configuration, the sample is heated through the absorption of visible light pulses and the subsequent induced variation in the emitted IR radiation is detected by an IR camera. Such a camera provides a sequence of images, in the following referred to as thermograms, each corresponding to a different delay time with respect to the onset of the heating pulse. One of the peculiar abilities granted by PT is given by the possibility to distinguish between features located at different depths into the sample. In fact, a temperature rise is initially produced at the sample surface which, with the increase of the time delay, diffuses over a growing depth into the sample volume. The possible presence of subsurface heterogeneities can locally affect the heat diffusion rate to a level that may lead to a variation in the time dependence of the local surface temperature, and therefore of the PT signal, in comparison to the surrounding ones. This gives rise to contrasted features that show up in the recorded thermograms at increasing time delay as the depth position of the observed feature increases [22]. Conversely, MWIR Reflectography relies on illuminating an object with an IR source and then on detecting the reflected component of the IR radiation. Such a technique is particularly sensitive to the features located in the shallow sample layer whose possible different local optical properties in the IR spectral range may give rise to the contrast in the recorded images [25]. In the proposed method, MWIR Reflectography is employed to obtain the 3D shape of the artefact. Thereafter, the thermographic PT sequences are subsequently recorded on the same sample area under

[1] Using Virtual Reality to Explore 15th Century Illuminated Manuscripts: https://dornsife.usc.edu/xrlab/neh-vr-exploration-of-illuminated-manuscripts/ (accessed on 2 of December 2023).

Fig. 1. left: original IR image with a resolution of 320×240 px; right: Ai interpolated image with a resolution increased by four times.

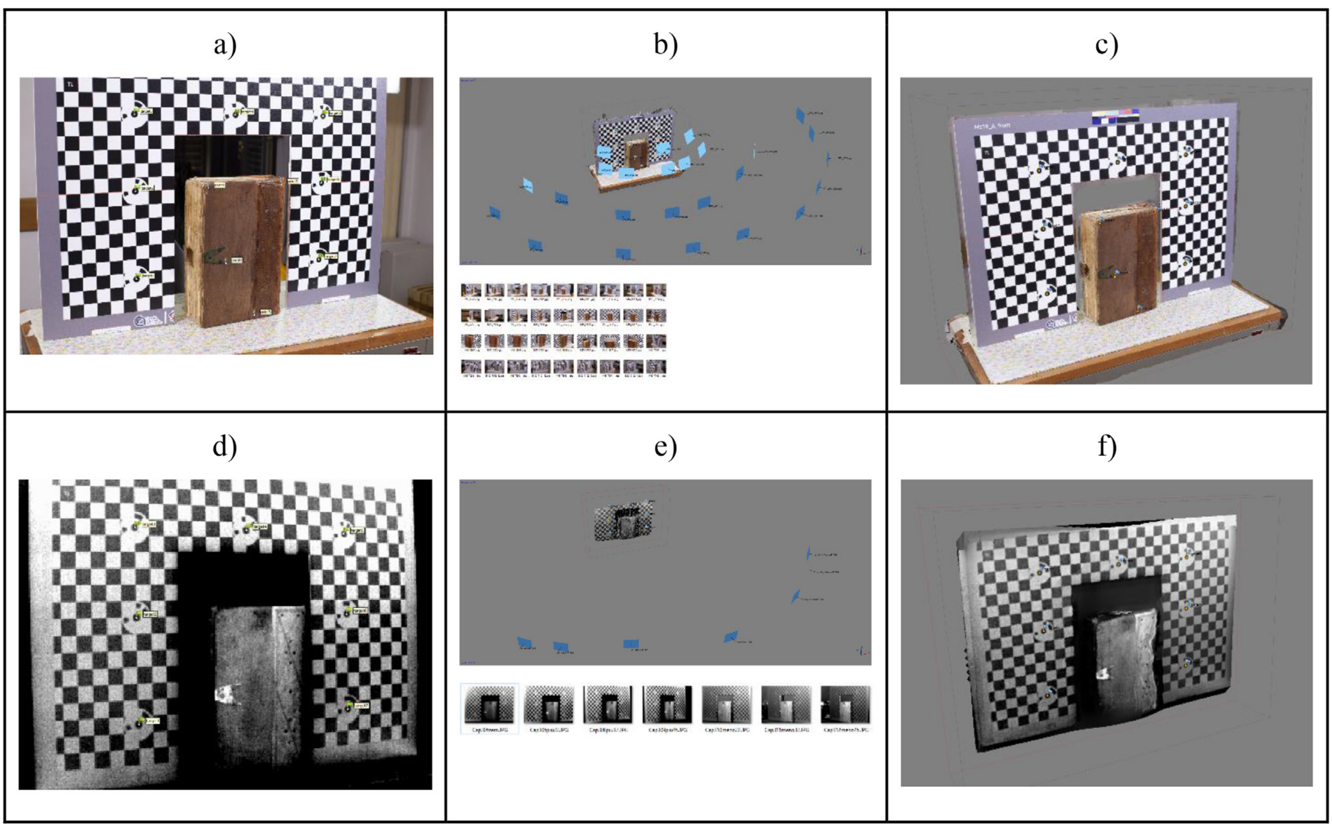

Fig. 2. Schematic view of the steps involved in the generation of the IR 3D model using the reference panel: a) automatic target recognition; b) SfM - RGB images; c) Hi res 3D Model RGB images; d) Semi-automatic target recognition; e) SfM - MWIR images; f) Low res 3D model IR calibrated images.

the same experimental conditions by means of the same IR camera, thus ensuring the exact correspondence of both the PT and the reflectographic images obtained over each investigated sample area.

3.2. Digitization: preparatory activities and challenges

As previously mentioned, one of the main goals of the project was to digitize the manuscripts with photogrammetric techniques integrating different kinds of data both from visible and infrared spectrum. The digitization of the ancient books was carried out using SfM Photogrammetry, a widely employed technique for reconstructing the volumetric 3D shape from a sequence of images. This method is well-established across various fields and widely adopted in the cultural heritage domain [1,36]. The SfM workflow typically consists of the following three primary stages [35]:

1. Acquisition: in situ acquisition is performed using photographic instrumentation;
2. Processing: the reconstruction of the photogrammetric model is performed through SfM algorithms and involves creating a point cloud with both *xyz* spatial information and RGB ones;
3. Post-processing: this stage includes the extraction of a polygonal solid model and the creation of a photographic texture for photorealistic rendering.

Such a standard workflow, typically designed for RGB images, has been adapted to incorporate the IR images obtained from both Thermography and Reflectography. The goal was to include in the resulting 3D model the textures obtained in both the visible range and in the infrared one. The integration of the data into a single 3D model required that both datasets, RGB and IR, share the same reference system. However, the alignment of the RGB and IR datasets could not be processed together since they were captured with different optics systems. As shown later on, in the RGB acquisition a Canon EOS 6D with a 20-megapixel full-frame CMOS sensor with a resolution of 5472×3648 pixels was used while for the IR ones a CEDIP Jade III camera with a resolution of 320 × 240 pixels was employed. Consequently, it was necessary to process the two sets of images in distinct photogrammetric project and merge them in a later stage. This activity revealed the following challenges. Firstly, the IR images had a low resolution, making it difficult to align them through photogrammetric software tools without any supplementary data. To address this challenge, we employed the automatic lens calibration tool within Agisoft Metashape.[2] This tool calculated parameters for correcting lens distortions and generated a full calibration matrix of the optical imaging system of the IR camera (Fig. 1S). Subsequently, this calibration matrix was used in the alignment processing improving the accuracy of the photogrammetric reconstruction.

Secondly, artificial intelligence algorithms, Gigapixel AI were adopted to improve the resolution of the IR images by up to four times (Fig. 1). Such a software relies on advanced machine learning techniques through which an accurate pixel-by-pixel analysis of the images is carried out. In addition, it employs deep convolutional neural networks to effectively eliminate blurring while preserving image quality ([15], 2). This tool not only increased the efficiency of automatic target recognition on the grid but also improved the identification of control points on the IR image itself making it possible to apply SfM techniques. In this respect, a reference panel has been specifically designed to address the issues concerning the scaling and alignment of the two datasets. It includes a PVC board equipped with coded targets and geometric patterns, which were meant to be positioned around the volumes during both the IR and RGB photogrammetric surveys. This panel provided a common reference between the datasets, thus facilitating their alignment in the same local reference system (Fig. 2a).

Its graphic features worked as metric references for both the scale control and survey accuracy, along with automatic target recognition. These features were crucial for computing the camera position relative to the sample in the RGB model and for aligning IR images during the image processing stage. The alignment between the panel and the manuscript was crucial because of the IR camera's limited depth of field (approximately 10 cm). To achieve accurate results, it was essential to keep both the manuscript and the control points on the panel in focus (Fig. 2).

Once the above-mentioned issues were resolved, the image acquisition stage took place. Both IR and RGB images were recorded by moving the cameras around the object with an angular step of approximately 15°, thus ensuring the use of small acquisition angles and significant overlaps of about 90% between consecutive pairs of images. Given the nature of the books as not rigid objects, handling them as minimally as possible was crucial to prevent alterations in their configuration. While RGB photogrammetric acquisition is a well-established and conventional methodology, the IR one is still rather challenging. In the present research activity, the design of the acquisition process was not only aimed at integrating RGB and IR data but also at generating virtual models directly from IR images. This approach proves particularly advantageous in diagnostic scenarios, especially when a preliminary RGB photogrammetric survey is considered not feasible due to extended acquisition times and/or the complexity of the dataset.

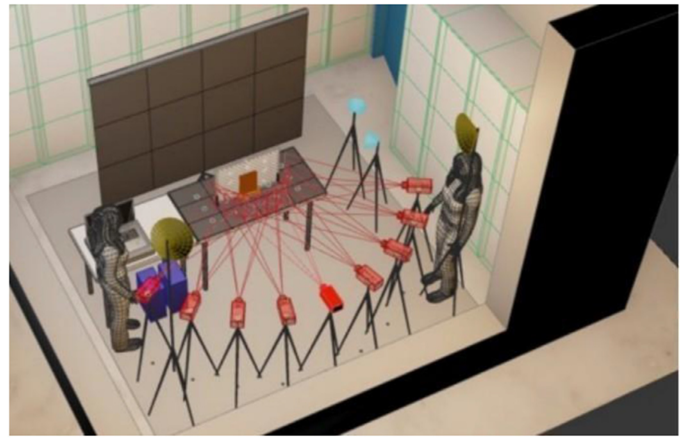

Fig. 3. Schematic representation of the MWIR Reflectography and PT images recording procedure.

3.3. Experimental procedure

3.3.1. Set-up and IR photogrammetric acquisition

In the MWIR Reflectography image recording, both the manuscript and the calibrator are illuminated by means of carbon filament IR sources whose output radiation is characterized by a significant component over the detected 3–5 μm spectral range. Special care was taken to reduce the sample heating and, hence, the IR emitted component from the sample by minimizing the power of the incident IR radiation. The IR image detection was carried out by means of an IR camera CEDIP Jade III operating with a 320 × 240 pixels InSb focal plane array, sensitive in the 3–5 μm MWIR range. As mentioned before, MWIR Reflectography and PT images were consecutively recorded on the same sample area by means of the same IR camera to ensure the exact correspondence to the recorded images and of the investigated sample area. In the case of PT, the sample heating was induced by two halogen flash lamps (Bowens Estime 3.000, maximum power of 650 W) delivering 2 ms long pulses. Optical filters were specifically placed in front of the flash lamps to cut off the emitted IR component to prevent possible spurious components that originated from the IR reflection at the sample surface and the ultraviolet component.

As shown in Fig. 3, both the MWIR Reflectography and PT images are recorded from different point of view corresponding to a fixed distance between the camera and the artefact and predefined orientation angle set of the camera axis with respect to the sample surface This has been achieved by moving the acquisition apparatus, according to a sequence of positions corresponding to the references fixed on the ground around the artefact. The main advantage of this procedure is that it does not require to move the artefact as often required for logistical or safety reasons. As an example, Fig. 4 shows the MWIR reflectographic images of the spine of the *MS. 59* preserved at the *Casanatense Library* in Rome, recorded from different points of view.

Once recorded, the IR images have been then processed through SfM techniques, in order to obtain the 3D model. In the SfM initial stage, the pixel areas in the MWIR reflectographic images characterised by a relatively high contrast are identified to evaluate the position of the IR camera with respect to that of the sample and, consequently, the relative orientation of the images. As mentioned earlier on, a commercial software tool (Gigapixel AI) has been employed to increase the spatial resolution and, hence, the contrast of

[2] https://www.agisoft.com/.

Fig. 4. MS. 59 (Casanatense Library in Rome). MWIR reflectographic images of the spine recorded from different point of view.

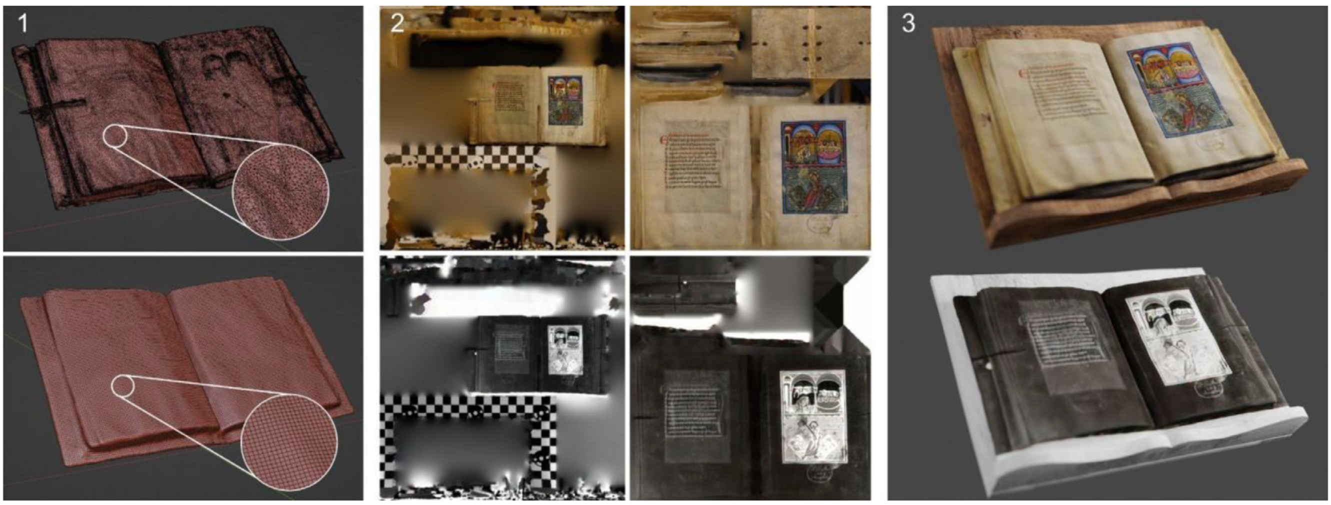

Fig. 5. 1) Triangulated mesh generated by photogrammetry processing that is then converted into a quadrangular mesh; 2) Comparison between a texture generated by automatic unwrapping in photogrammetric software and a texture created through manual unwrapping; 3) Manuscript RGB and IR textured models obtained by means of custom UV.

Fig. 6. PBR textures used to simulate the physical properties of surfaces in the web app.

the reflectographic images in order to obtain a better visualization of the geometric patterns that have been specifically printed on the reference panel. Such patterns enabled to facilitate the alignment procedure and to improve the 3D reconstruction accuracy through the reflectographic image resizing so as to obtain a uniform sample magnification between the MWIR reflectographic images recorded from different points of view. Thanks to the reference panel, it has been also possible to evaluate the accuracy of the photogrammetric model generated using the IR dataset. Finally, from the SfM point cloud a mesh model has been computed.

3.3.2. Post-processing

Once obtained by means of SfM techniques, the digital renderings of the manuscript underwent additional processing though computer graphics software tools for their seamless integration into the Web3D platform based on the ATON framework, an open source designed and developed by CNR ISPC [13]. To this aim, new mesh topologies were generated through Instant Mesh,[3]a quad-based auto-retopology software [43]. Thanks to such a process, more regular topologies were obtained which have proven to facilitate the next UV mapping which has been carried out through Blender. UV mapping is the process that defines the spatial relationship between the 3D geometry of the object and the 2D texture images. While photogrammetry software tools can automatically perform this process, we chose to manually control the unwrapping phase using computer graphics software. Such a manual control enabled us to prioritize pixel detail in specific areas of interest, such as text and images (Fig. 5.2). Finally, after the optimization, the model was then imported into the photogrammetry software Metashape to perform the texture building process. Using the custom UV mapping that was previously created, this process

[3] https://github.com/wjakob/instant-meshes.

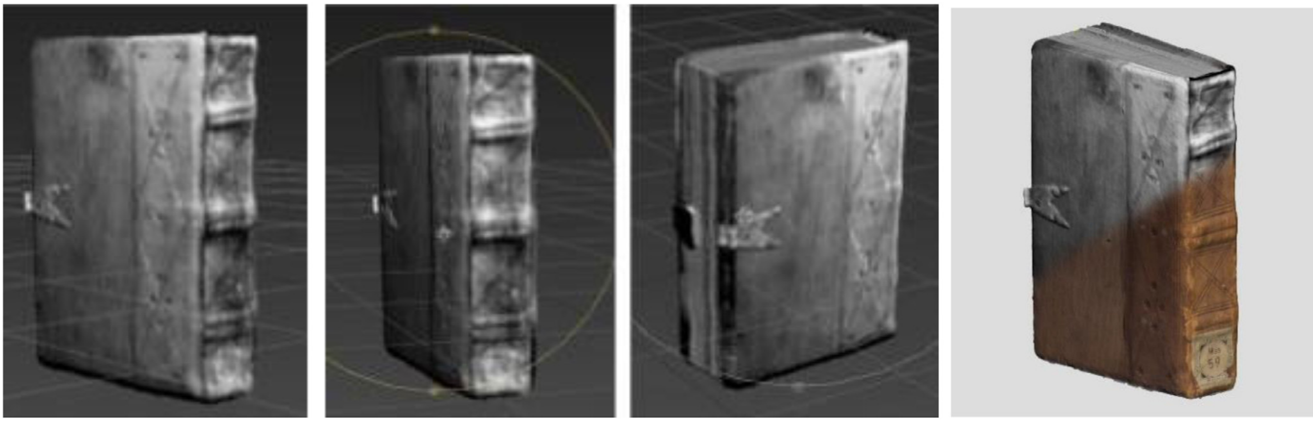

Fig. 7. MS. 59 (Casanatense Library in Rome). Three different views of the model obtained from the MWIR reflectographic images. The right side image shows the overlapping between RGB and IR models.

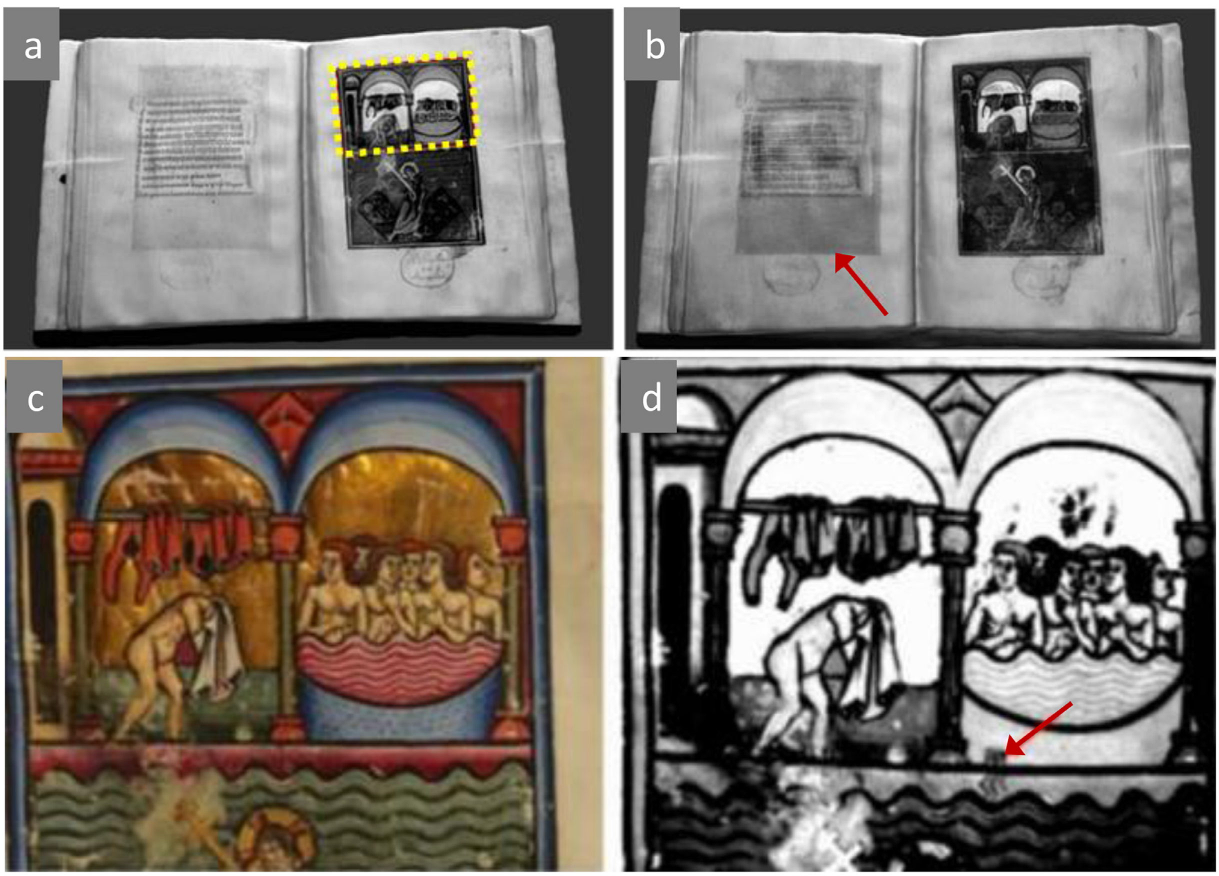

Fig. 8. Carta 9 verso and carta 10 recto, De Balneis Puteolaneis. Model obtained from the thermograms recorded a) soon after the pulse and b) at larger delays. c) Magnification and d) corresponding thermogram of the area marked by the dashed rectangle in Fig. 6a. The arrow in Fig. 6d) indicates a pentimento consisting in a jellyfish.

was used to create texture information for both RGB and IR textures.

The textured 3D model was then exported in .gltf format so as to enable its implementation in the webapp (see Section 4.2). Given the capabilities of the ATON framework in handling Physically Based Rendering (PBR) texturing, we created a set of PBR textures to emulate the physical properties of surfaces, enhancing the realism and visual appeal of interactive virtual manuscripts (Fig. 6). To achieve photorealistic rendering of the manuscript, different kinds of PBR textures such as the roughness, the metalness and the normal one were generated along with the RGB and IR texture. In particular, the roughness one was intended to stimulate the surface micro-relief, and to influence the light behaviour depending on the specific material such as paper, gold foil, or ink. The metalness texture was used to set a material as metallic or non-metallic. When combined with the roughness one, it appropriately regulates the reflection intensity. Finally, the normal map was employed to enhance visual details by simulating the surface irregularities of the pages.

3.4. The investigated manuscripts

The proposed method has been tested on some ancient books preserved in both the Angelica and the Casanatense Libraries in

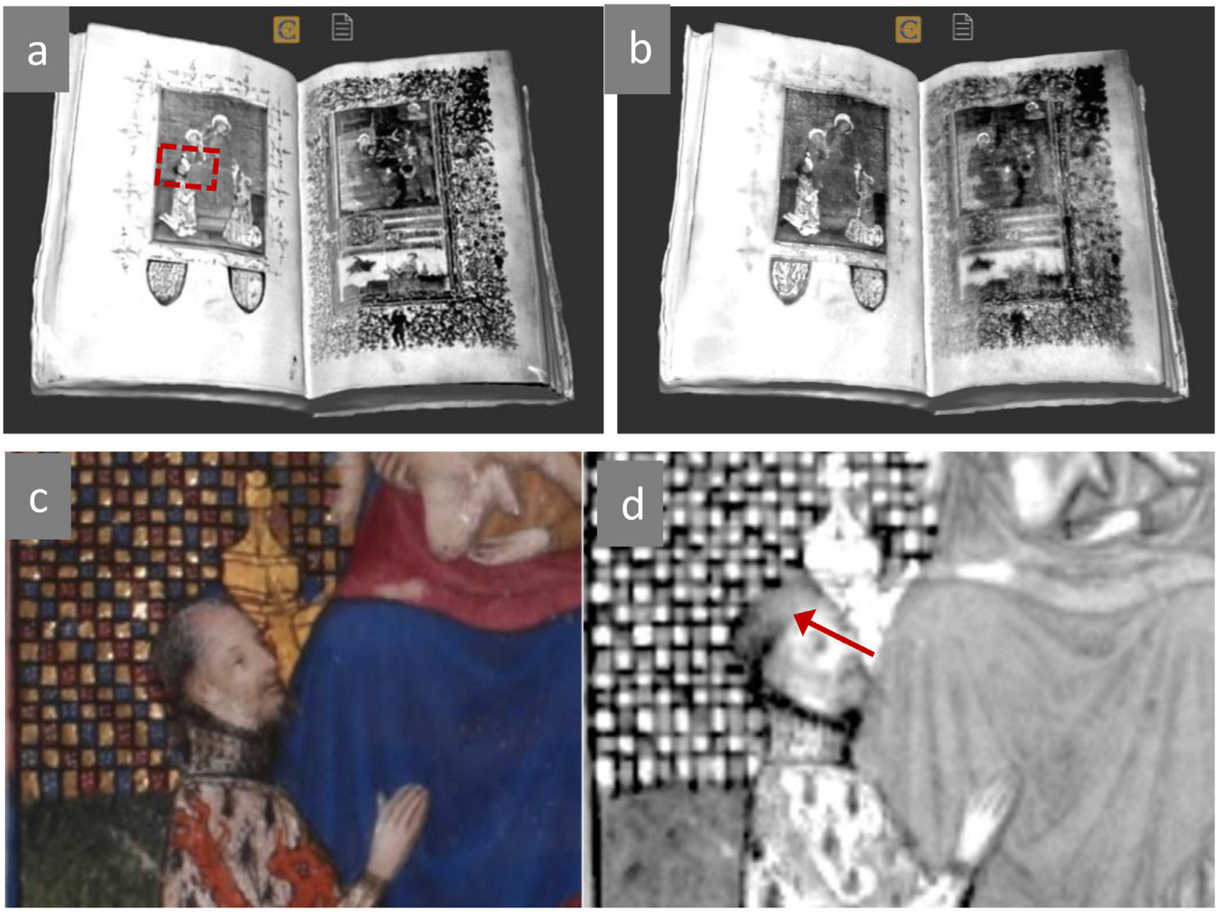

Fig. 9. Carta 21 verso and carta 22 recto, MS. 459 Libro d'Ore. Model obtained from the thermograms recorded a) soon after the pulse and b) at larger delays; c) magnification and d) corresponding thermogram of the area marked by the dashed rectangle in Fig. 9a. The arrow in d) indicates a pentimento.

Rome. The first selected book is MS. 59 (Casanatense Library), a 15th-century miscellany whose size is 219×145 mm (Fig. 3.1S). Besides its historical and artistic importance, such a choice has been motivated by the presence of different features made of leather, wood and metal in both the binding and book-cover which were supposed to be successfully imaged by means of PT. The other manuscripts were selected from the collection of the Angelica Library. The first is the *Libro d'Ore* (MS. 459), a compendium of devotional texts in Latin, which dates back to the first half of the 15th century [8-1996), (Fig. 3.2S) The codex is made on parchment with a size of 235×160 mm and, amongst other, it is richly illustrated with 15 full-page illuminations. The second codex is De Balneis Puteolanis, MS. 1474, a poem in Latin composed by Pietro da Eboli ([10], (Fig. 3.3S). The dating of the book, of which the size is 184×130 mm, is uncertain although according to some scholars it is in the 1258–1266 range. Finally, the third codex is Dante Alighieri's *Divina Commedia*, MS.1102, dated back between 1351 and 1400 (Fig. 3.4S). The manuscript, of which the size is 345×240 mm, is on parchment and presents several decorations. In particular, the Inferno is enriched with several illuminations that show abrasions and censorship, such as the one on the nudity of the demons [28].

4. Results and discussion

4.1. Virtual exploration of the manuscript in the invisible layers

As reported earlier on, the proposed method is aimed at producing 4D virtual exploration of manuscripts and, as an example, Fig. 7 shows three different views of the 4D model obtained on MS. 59 through the processing of the recorded MWIR reflectographic images.

The information gathered from PT have been also included in the model, thus allowing its depth resolved exploration and, hence, the visualisation of the elements that belong to different subsurface layers of the book. For instance, in Fig. 8 the 4D model images corresponding to *carta* 9 *verso* and *carta* 10 *recto* of *De Balneis Puteolaneis* are depicted. In particular, Fig. 8a has been obtained from the thermogram recorded right after the onset of the heating pulse and, consequently, it enables the visualisation of shallow features. Fig. 9b, on the other hand, shows the reconstruction obtained from the thermogram recorded at later time delay where, in comparison with Fig. 8a, deeper elements are also detected, such as the darker rectangle indicated by the red arrow that corresponds to the illumination on *carta* 9 *recto (the leaf behind the visible one).* As regards the area highlighted by the dashed rectangle in Fig. 8a, its magnification is depicted in figure Fig. 9c where the corresponding thermogram of Fig. 8d reveals a jellyfish which is not visible in the photograph of Fig. 8c. As it appears evident from Fig. 8, it is of crucial importance to display the position of the detected subsurface features in a 4D representation since it enables a virtual browsing inside the book structure showing in a 4D fashion all those otherwise non-visible parts.

Another example is provided by the *pentimento* detected by PT on *carta* 21 *verso* of MS. 459 whose 4D model images, obtained from the thermograms recorded right after the flash and at a later delay time, are shown in Figs. 8a-b, respectively. In this respect, Fig. 9 displays the photographic magnification (Fig. 9c)

Fig. 10. The Codex 4D web app shown in an exhibition held in the Angelica Library in Rome. On the 3D model of MS. 1474 De Balneis Puteolanis annotations are displayed on both the RGB and IR layer. In the right panel the contents of the annotation, including text and multimedia are reported.

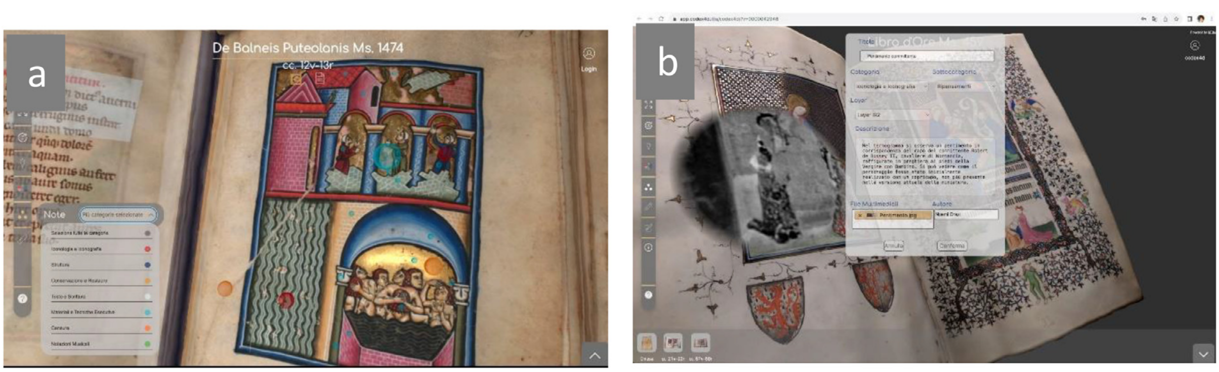

Fig. 11. a) Codex 4D web app interface where in the left panel it is possible to filter annotation selecting one or more categories. Annotations are contextualised on the 3D model of the MS. 1474 De Balneis Puteolanis, cc.12v-13r; b) Creation of an annotation in MS. 459 Libro d'Ore through the editor profile.

and the corresponding thermogram (Fig. 9d) of the Bishop Head highlighted by the dashed rectangle in Fig. 9a. In particular, the arrow in the thermogram indicates a Bishop's hair style different from the one observed in the photograph.

The 4D model can be virtually explored by means of different tools, such as the Web App and the holographic showcase, both designed in the frame of the "Codex 4D" project, as explained in the following paragraphs.

4.2. The framework for online exploration of the 4D models

Thanks to the recent improvements of the web technologies, there are now available new tools to interact with 3D content online, such as through a standard web browser without any installation necessary for final users. The open-source ATON framework [13] has been chosen for the development of the Codex 4D Web App. It is based on modern web standards and technologies and it can be used to create Web3D or WebXR applications interacting with CH objects and 3D scenes on the Web. It relies on a "*develop once, deploy everywhere*" approach, without requiring any installation since the 3D presentation automatically adapts to any device, whether mobile, desktop, museum kiosks, or immersive XR devices. These ingredients offer a fertile ground for creating and developing web-based interactive outputs dealing with the inspection and multi-dimensional exploration of manuscripts.

The Codex 4D Web App was specifically intended for the scholarly community. In fact, the Web App allows the display of the information obtained from diagnostic techniques as semantic

Fig. 12. The Codex 4D holographic showcase in the Angelica Library in Rome, November 2023.

annotations on the 4D model. The results gathered from different kinds of investigation such as the chemical and biological ones and literary studies are also included in the form of annotations to the model.

The Codex 4D Web3D app key-features are: a modular design of the application to handle/load multiple manuscripts and related poses; user-friendly inspection of the manuscript on mobile and desktop devices; responsive user interface; advanced tools for the interactive discovery of hidden layers, measurements and lighting; two profiles: public and editor, being the latter accessible through authentication layer offered by the framework; direct annotations by authenticated users (editor profile) on manuscripts' poses, on localised points/areas of interest with possibility to associate multimedia content; interactive queries and filtering of annotations by categories and layers (public profile). The Web3D application is currently hosted on a dedicated public virtual server, designed to load specific manuscripts and poses directly from url parameters, thus offering great flexibility and integration in websites or platforms. The public profile provides users with advanced tools to discover hidden layers exploiting the interactive lens metaphor (Fig. 10) [14,42], alongside direct measurements, interactive lighting and filtering of semantic annotations (Fig. 11a). The editor profile offers a restricted team (authenticated users) additional tools to perform 4D annotations on visible and invisible layers, through user-crafted punctual or volumetric shapes. A simple form allows to associate rich multimedia content to the annotation (Figs. 11b and 4S), that can be queried through the public profile.

4.3. The Codex 4D holographic showcase for museums

The holographic showcase was specifically designed in 2016 by the CNR ISPC team [33] for museum envinronments, since it enables to interact with its contents in an engaging way, through an emotional narration. It consists of a small theatre, provided with lights, scenography, buttons, sensors, and software to manage multimedia events and interaction. As it appears evident, the basic idea behind such a showcase relies on holography which is a well-known effective technique for generating high quality 3D images in terms of shape, colors and visual effects that enable users to perceive them as they were real objects. In the present situation, the illusion of reality effect is created by the Pepper's Ghost technique [32], derived from a theatrical technique. In our case, the theatrical mechanism is replicated with some differences, being the main one related to the reduced size (Fig. 5S). The purpose of the holographic showcase is to evoke the sensory and narrative dimension of the museum object preserved inside [29] (Fig. 6S).

The Codex 4D holographic showcase has implemented for the first time a 4D model. In fact, the Leap motion capture sensor[4] [38] allows the user to interact with the 4D model of the manuscript using his/her hand to explore both the surface layer and the sub-surface ones. The visitor can magnify details, exploring annotations associated with each layer about iconographic studies, text translations, investigations of pigments constituent materials, and the state of preservation. The holographic showcase is also innovative for the storytelling style, as a dramaturgy of the manuscript has been created inside. An imaginary character, played by an actress, lives in the parchment pages, in the miniatures and tells us about that world from the inside. She is as small as the illuminated figures, and she can activate tools so as to facilitate the reading and understanding of the codex. By so doing museum visitors can access the research contents, thus promoting the languages of scientific dissemination to new creative, engaging and playful frontiers. To manage the audiovisual streams and the interaction, a software tool was developed with Vvvv,[5] a visual programming platform known especially in the field of digital art [40].

The Codex 4D holographic showcase has been presented for the first time at the Science Festival in Genoa in October 2022 and a UX evaluation has been carried out, being the results very promising [41]. It was again exhibited at the University of Rome, Tor Vergata in June and July 2023 and finally, in an updated version, in the

[4] https://www.ultraleap.com/product/ (accessed on 29 of November 2023).

[5] Visual Programming.net (accessed on 29 of November 2023).

historical reading room of the Angelica Library in Rome (Fig. 12). In the latter exhibition, it was shown together with the web station described in 4.2 and next to the original real manuscripts which were included in a dedicated showcase aside.

5. Conclusions

In this paper a method for the thermographic 3D rendering of artefacts has been presented. Such a method is aimed at overcoming the limitations of the other procedures that are typically employed in 3D thermography where the IR images must be collimated on 3D models obtained from images recorded in other spectral ranges by means of different devices. Compared to the current state of the art, the methodology offers the possibility to reconstruct the shape of an artefact through the only processing of the MWIR Reflectography images. In addition, the same IR camera is also employed to record the Pulsed Thermography sequences under the same experimental conditions, thus enabling the depth- resolved exploration of the 3D model which can be regarded as a 4D one. To the best of our knowledge, 3D reconstruction techniques based on the combined use of MWIR Reflectography and Pulsed Thermography have never been reported before in the literature.

In the present study, the effectiveness of our method has been tested by carrying out 3D depth resolved investigations of ancient manuscripts where conventional 2D PT has been already proven an effective tool. Such investigations have been carried out in the framework of the Codex 4D project where, in the part devoted to virtual environments, tools have been developed that allow the 3D browsing of specific poses or maps, exploring their stratigraphic levels, opening or creating annotations related to the various information mapped on specific points of interest. Virtual reality is thus being used not only as the final output of a research work but, as a shared laboratory for the analysis, interpretation, and integration of data. The convergence of different skills, both on the humanities side and on the side of diagnostics and computer science, made possible this interdisciplinary research. All these skills played a crucial role in the design of virtual models that can contribute to disseminating knowledge about illuminated manuscripts in their extraordinary complexity, as such models may be possibly updated over time by the scientific community.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2024.05.007.

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