EUROGRAPHICS Workshop on Graphics and Cultural Heritage (2023)
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4D Thermo-reflectography of Cultural Heritage

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Abstract

This paper proposes a new method for the study of cultural heritage. A 3Dmodel in the mid-wavelength spectral range of infrared radiation is realized for the depth-resolved study of artworks. In particular, pulsed thermography is used to obtain a virtual 4D representation of some artifacts. The goal is to facilitate the end-user experience making it possible to explore subsurface elements in a digital 3D model. In the proposed approach, the three-dimensional geometry of the artifact is reconstructed by directly processing the infrared images using Structure from Motion techniques. Finally, the results of the humanities and natural sciences studies are mapped onto the 4D model in the form of interactive semantic annotations and visualized in a 3D web platform

Keywords: SfM and thermal imaging; IR imaging; cultural heritage; digital 3D IR representation; virtual exploration

1. Introduction

In the context of the increasingly heated debate and the numerous initiatives launched in recent years at the European and Italian levels on the subject of 2D and 3D digitization and the sharing of digital data of cultural heritage, increasing attention is being drawn to the need to document not only the visible aspects of a cultural artifact (shape and appearance, volume and surface texture), but also the non-visible elements hidden in the underlying layers, which can provide important information about the materials, construction techniques and conservation history of the artifact itself.

This development is certainly due to the need to increase knowledge about cultural objects and to study them thanks to the proliferation of increasingly sophisticated and portable technologies, capable of moving from the laboratory to the place where the artifacts are kept without the risks and costs associated with transportation. A great impetus also comes from the awareness of the importance of sharing and validating cultural heritage data and processes through new quality standards to make them accessible and reusable.

The goal is to promote new models of knowledge, business, and cultural tourism that support open science models for research and study on the one hand, and new strategies of economic profit related to the digital arts market on the other. Government institutions, research organizations, academia, and creative industries are thus involved in different ways in this complex process of formalization, which is not easily reconciled with the legal framework and policies governing copyright management. The European Collaborative Cloud for Cultural Heritage (https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl2-2023-heritage-eccch-01-02) and the related tools that need to be developed are a major challenge at the European level, as well as the national plans for the digitization of cultural heritage that some countries such as Italy are promoting thanks to the funding from the National Recovery and Resilience Plan (https://www.governo.it/sites/governo.it/files/PNRR.pdf). The availability of such a rich heritage of digital data, taking into account both art historical and diagnostic aspects, will improve the accessibility of cultural heritage and it will create multiple scenarios for different types of users, from the conservator and restorer (thanks to digital twins) to the scholar, the museum curator, the school teacher, the video games developer.

Our contribution fits into this context and refers to the formalization of an innovative method for documenting and mapping the visible and invisible aspects of a cultural artifact through multidimensional virtual models by means of an integration of different techniques and their subsequent usability through diversified digital platforms and tools targeting different audiences. The innovative method described has been tested on different types of artifacts. However, in this paper, a special focus is given to ancient manuscripts, which are the subject of specific research and experimentation from 2021 to 2023 thanks to the project "Codex4D - 4 Dimensional Journey in Manuscript", funded by POR FESR LAZIO 2014/2020

2. Contribution to the research

The main goal of this research is to create a 3D mid- wavelength infrared radiation (MWIR) model of cultural heritage artifacts, allowing their three dimensional and stratigraphic exploration. This is made possible by a method, based on the use of an apparatus,

DOI: 10.2312/gch.20231168

for the three-dimensional digital representation of a cultural heritage item and its virtual exploration by means of infrared images acquired by reflectography and thermography techniques.

Infrared thermography is a method of investigation, widely used in the field of cultural heritage, which enables the identification and characterization of sub-surface and structural elements. In the configuration referred to as "pulsed thermography", the infrared radiation emitted by the sample surface as a result of heating generated through the use of flash lamps is analyzed. The radiation is recorded by an infrared camera, in the 3-5 μm spectral range, which provides a sequence of temperature maps called thermograms. The sequence of images allows a stratigraphic description of the surface and subsurface structure of the artifact. In fact that the pulsed heating is responsible for inducing a heat diffusion process through the sample volume. The possible presence of subsurface heterogeneities may affect the heat diffusion and, consequently, areas of different temperature are generated on the corresponding surface, thus giving rise to contrasted features in the recorded thermograms. For instance, in

the field of ancient codices, thermography allows the detection of structural elements and texts on fragments embedded within the bindings as reused material, generally hidden beneath the end papers or spines. In the analysis of illuminations, it also makes it possible to identify structural heterogeneities, such as gold leaf detachments, voids, etc., and subsurface graphic and pictorial elements, such as repentances and preparatory drawings [MBC*18].

In the proposed approach the three-dimensional geometry of an artifact is reconstructed by directly processing, through Structure from Motion Techniques (SFM) [REH06], the infrared images collected, even under thermal equilibrium conditions. The results of humanistic and scientific studies are then mapped onto the 4D model in the form of interactive semantic annotations and visualized in a 3D web platform, based on the ATON framework and developed by CNR ISPC (http://osiris.itabc.cnr.it/aton/) [FFD*21]. The platform enabling the multilevel visualization and exploration of the asset, can be approached at two levels: 1) through an editor profile, requiring authentication, 2) as common user. The first one allows modifying and creating new contents as semantic annotations in the virtual model, the second one makes it possible to explore and query the model. The aim is to create an interdisciplinary experience with the cultural object, both from art- historical and diagnostic perspectives.

2.1. State of the art

In previous studies and patents some solutions regarding the integration between 3D and thermographic images visualization have been introduced. For instance the patent "Method and apparatus for three-dimensional thermographic analysis" No. 0001406058, proposed by some of the authors of the present paper, is aimed, as the present methodology, at producing a 3D thermographic model. Unlike the previous approach, in the present study the 3D rendering was produced from reflectograhic images recorded by means of the same IR camera adopted in the thermographic investigations. The subject of a second patent, still proposed by some of the present authors, "System and process for the acquisition of images of an artwork or an environment" No. TO2010A000780/102010901874715, can be considered close to the presented methodology as regards the integration of diagnostic imaging techniques with the three-dimensional shape

reconstruction ones obtained in the visible, the UV and the near- infrared portions of the spectrum. Differently, the presented methodology enables the creation of three-dimensional reconstructions starting directly from images in the mid-infrared, which can also be explored at different depths, thanks to the use of pulsed thermography operating in the same spectral range.

Besides, in other studies and applications the 3D model is not obtained directly from thermal images but the latter have been adapted and applied on a 3D model obtained through laser scanner acquisition or photogrammetry, in the spectrum of visible light. Also in the studies where the 3D model was obtained directly from thermal images [**?**, SLDM18, MK19] there is no possibility to have a stratigraphic 3D model, nor processes to increase resolution are needed; moreover most of these applications are not related to cultural heritage. Topics such as the realization of 3D temperature map from a pair of calibrated thermal cameras and the calibration of a stereo pair of low resolution have already been discussed in the literature [PYLC06, ZFCD18]. Moreover, the use of designed calibration pattern for stereo vision systems [YLD*13] and the possibility to perform real-time investigations by a 3D thermography system [VPS14] have been proposed.

Finally no combination with reflectography MWIR has been proposed. This paper focuses in particular on the methodology to obtain such virtual models, starting from the integration of photogrammetric, reflectographic and thermographic techniques

3. Innovation

Digitizing the shape and appearance of an artifact can be accomplished using a variety of range or image-based technologies. In this case we chose digital photogrammetry, a widely used technique that can provide 3D data from a series of images, to enhance the contribution of IR imaging to 3D reconstruction.

Digital photogrammetry, after acquiring images in the visible spectral range from different points of view, includes the following reconstruction steps: i) feature detection, ii) feature matching, iii) image orientation, iiii) dense stereo reconstruction, iiiii) mesh computation, iiiiii) texture building. The use of IR imaging poses a serious problem in both the feature detection and matching, leading to poor or impossible computation of the camera position. For this reason, the method of acquisition and processing presented in this paper has been modified with additional steps of pre- and postprocessing, to work with datasets consisting exclusively of infrared images acquired in the MWIR spectral range, the range where thermography is most commonly used.

Thus, the goal is to create a 3D model from MWIR images acquired with the IR camera. This goal is hindered by three main factors:

For approximately homeothermic samples (e.g., a statue in thermal equilibrium with its surroundings), images taken in the MWIR region without thermal stimulation typically result in images with low contrast and/or high noise, leading to difficulty in feature detection, and therefore unsuitable for 3D reconstruction.

Thermograms of thermally stimulated samples (e.g., pulsed thermography surveys) have good contrast but are highly dependent on timing and acquisition configuration (relative position of the source, artifact, and IR camera). This leads to difficulties in feature matching, and is therefore not suitable for processing for 3D reconstructions.

IR cameras provide images with a resolution (320 x 240 pixels) that is often insufficient, limiting the feature detection, for a robust processing of 3D digital models.

Our method solves this problem by reconstructing from reflectographic images obtained by illuminating the artifact with a MWIR source. Moreover, the thermograms are acquired with the same device and from the same reflectogram position, and the two datasets overlap perfectly by pixel-to-pixel texturing. In this way, a 3D thermal model can be created using the MWIR images from the reflectography, even if the thermograms homogeneity is not suitable for 3D modeling.

Moreover, we have increased the resolution to four times the original resolution using the commercial software Gigapixel AI. Thus, the innovation of this method is to overcome the limitations of other methods of 3D thermography, where camera-based images (thermograms) with mid-wave infrared radiation (MWIR) must be manually collimated onto 3D digital models obtained from images acquired in other spectral regions, e.g., in the visible and with other equipment, or where the infrared images used for 3D reconstruction must be acquired on non-homothermal artifacts. It also overcomes the procedure involving the implementation of GAN (Generative Adversarial Network) to achieve camera alignment.

4. Methods and Results

4.1. Description of the apparatus

The apparatus described below enables the solution of the problems limiting the possibility of 3D digital reconstruction of the artifact by directly processing the images acquired with the IR camera in the MWIR. The apparatus enabling the application of the proposed method is outlined in Figure 1 and consists of:

A MWIR irradiation apparatus for generating reflectographic images (1);

A calibration apparatus consisting of targets and geometric patterns (calibrator) (2)

A thermal stimulation apparatus for the generation of thermographic images (3)

An apparatus for capturing thermographic and reflectographic images (thermal camera) (4);

An apparatus for processing/displaying the acquired data (5). The MWIR source (1) allows the irradiation of the sample during the acquisition of the reflectographic images with a beam intensity that does not produce thermal effects, but ensures a contrast suitable for the acquisition of reflectograms that can be used directly for the creation of the 3D IR model. The use of a calibrator with strongly contrasting geometric patterns in the MWIR (2) allows the identification of common reference points between the reflectograms taken at different angles with the device (4), which is also used for taking thermal images.

The calibrator is a useful tool to scale a model in 'real world units' and especially to increase the number of recognizable homologous points between two photos in the image matching phase. The calibrator consists of a PVC plate on which both a checkerboard pattern (grid) and some coded targets for automatic target detection are printed. The grid serves as a metric reference to check the scale and accuracy of the survey. The targets are essential for the image matching algorithm and the calculation of the camera position of the IR images. Infrared images are acquired according to a scheme involving fixed distances from the artefact and fixed camera angles (Figure 2). This can be achieved either 1) by moving the artefact and its calibrator (for example by placing them on a rotating platform) and keeping the acquisition apparatus fixed, or 2) by moving the acquisition apparatus, according to a sequence of positions corresponding to predefined angles and indicated by references fixed on the ground, arranged around the artifact. The second option is generally chosen when the artifact cannot be moved for logistical or safety reasons.

The use of the stimulation apparatus (3), consisting of visible light flashes, makes it possible to obtain, with the acquisition apparatus (4), thermographic sequences which allow the 3D IR thermographic model to be explored at different depths. The use of the same device (4) for the recording of the reflectographic images of the artifact, which can be obtained by illuminating it

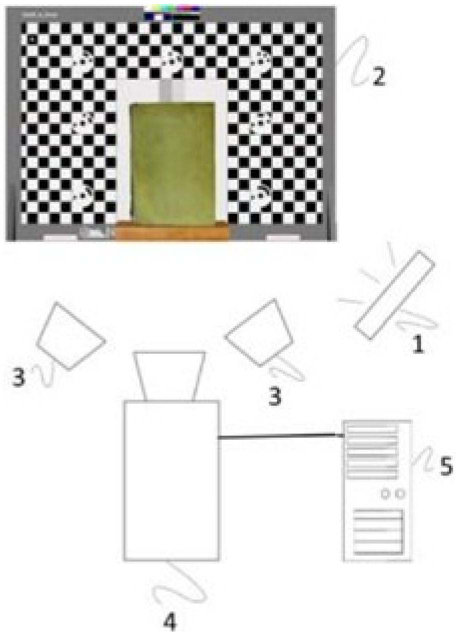

Figure 1: *The apparatus components*

with the MWIR irradiation apparatus (1), guarantees the pixel-to- pixel correspondence between the reflectograms used for the generation of the 3D model and the corresponding thermograms,

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allowing the direct conversion of the reflectographic 3D models into thermographic 3D ones (Figure 3). A processing apparatus (5) enables the processing of the reflectographic and thermographic images; beside it introduces an image processing method to increase the resolution of the IR images.

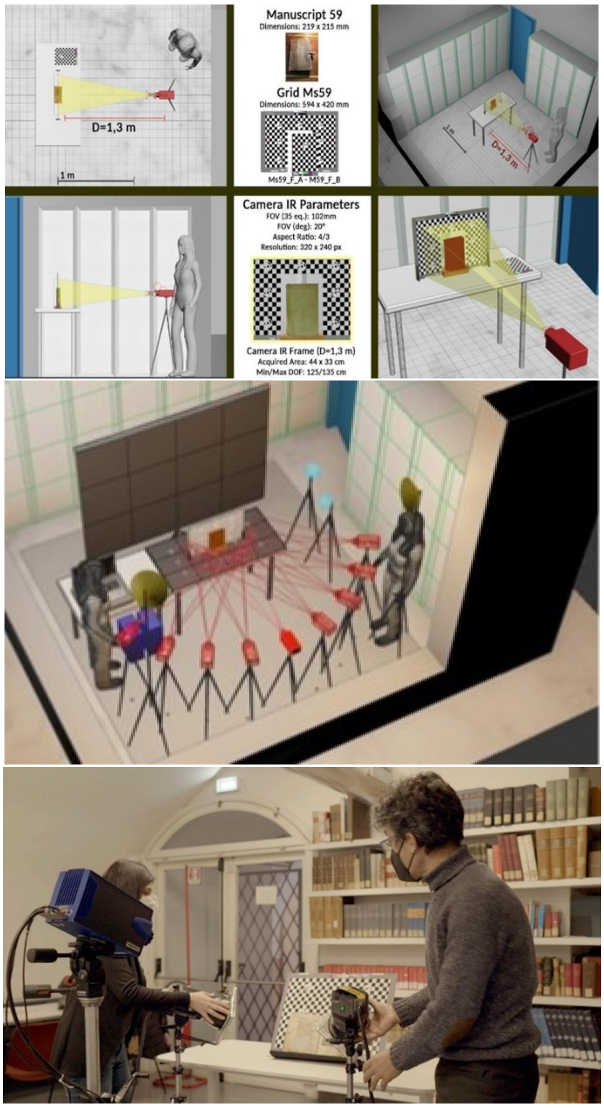

Figure 2: *Upper and middle images: virtual simulation of the acquisition setup with thermal camera. Below: acquisition of a manuscript in the library.*

4.2. Data processing

The SfM process begins with feature detection or identification of pixel areas (key points) with high contrast or distinct texture. The

key points are identified in all images by different algorithms. Regardless of which algorithm is used for feature detection, all of these methods are affected by the low contrast and low image resolution, making feature matching, correct camera positioning and satisfactory 3D reconstruction almost impossible.

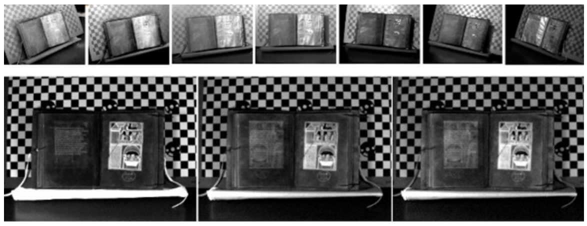

Figure 3: *Upper line: sequence of reflectography images. Low line: processing and alignment of thermal images, captured at different temporal intervals, through SFM techniques(Ms 1474, De Balneis Puteolanis, Angelica Library, Rome).*

To solve this problem, a commercial software, Gigapixel AI, was used to increase the resolution of the images (Figure 4) [KM18]. In addition, the targets and geometric patterns help to facilitate the alignment and verify the accuracy of the work, as well as assign a correct scale value to the whole system.

After aligning the cameras and images and creating the three-dimensional model, it is possible to replace the dataset of magnified images with the original images.

Also, in the IR mapping of a 3D model created with RGB photos, the use of targets is essential, as they allow to align both data sets, RGB and IR models, with an insignificant deviation in the same reference system.

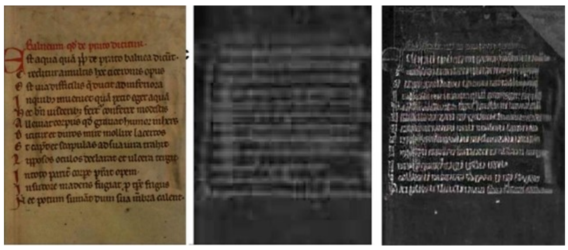

Figure 4: *The resolution of thermal images has been increased through an AI algorithm, as an alternative solution to generative adversarial network (GAN), to make it possible to apply SFM techniques.*

4.3. Experimental description

The experiment can be summarized in the following steps:

1. Test of automatic determination of camera positions without calibration.

An attempt was made to automatically detect homologous pixels in the reflectograms to apply SfM without first performing camera calibration. The lack of calibration did not allow a correct determination of the camera positions with respect to the object and consequently the relative orientation of the images.

2. Test of automatic determination of camera positions with calibration.

In advance, a calibration of the distortions caused by the camera's optics was performed using the calibration panel. Thanks to the calibration, the determination of the position of the cameras and, consequently, the orientation of the thermographic images improved considerably, but it was not always exhaustive due to the low resolution of the images from the IR camera.

The software used in this phase were Metashape and Reality Capture (Figure 5).

Figure 5: *successful alignment test of RGB and IR images after lens calibration.*

3. Increasing the resolution of the reflectograms. Gigapixel AI software has been used to increase the resolution of the reflectograms by a factor of 4, in order to better detect homologous pixels. The procedure to detect the relative positions of the camera with respect to the object was then performed again using the same software as described in point 2. The procedure was always successful in this case. The critical problem of the low resolution of the images of the IR camera was thus overcome (Figure 4).

4. Final optimization of the design of the acquisition set. Once the acquisition methodology was well established, the acquisition set was carefully designed and finalised by carrying out virtual simulations, taking into account the focal length, depth of field and technical requirements of the thermal camera. In this way, it was possible to assess the necessary space and to set up the camera positions in cultural venues (libraries, museums) and so correctly replicate the procedure (Figure 2 upper and middle images). During the on-field digitization activities, color images have been captured using a Canon Eos 6D camera, to compute a "standard RGB 3D model and use it both for the geometric assessment of the IR 3D model and for producing RGB textures to be used in the VR Web App Platform.

5. Acquisition in the relevant environment (the library), SFM and creation of the mesh model. At this point, the mesh model was created from the SfM point cloud, on which all thermograms taken at different depth levels could be coherently overlaid (Figure 6). For this reason, the model can be considered as 4-dimensional, since it contains formal volumetric and stratigraphic information. This process was performed in several steps and with the following software: Reality Capture, Agisoft Metashape, Instant Mesh and Blender.

6. Firstly, two data sets were processed in Reality Capturing or Agisoft Metashape, the RGB photos and the reflectograms. Both

Figure 6: *3D mesh model of a manuscript obtained through SFM point cloud, using RGB images and IR thermal images as textures (Ms.459 Libro d'Ore, Angelica Library, Rome).*

were aligned to a local reference system integrated with the calibrated grid behind the manuscript (Figure 7). The two point clouds were then imported into Cloud Compare. Both were optimized (subsample 2 mm) to obtain comparable point density, and finally the distance between the point clouds was calculated. As expected, the cloud obtained from the reflectograms has some noticeable irregularities, but the errors are quite uniform on the surface, with an average spacing of 5 mm. (Figure 8).

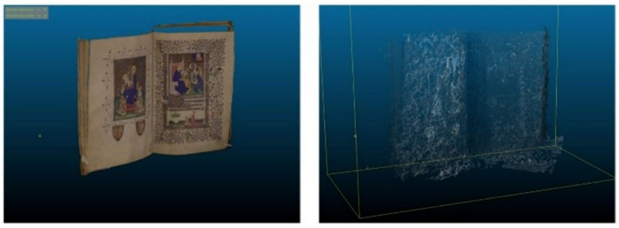

Figure 7: *The point clouds generated by RGB (left) and IR datase (right).*

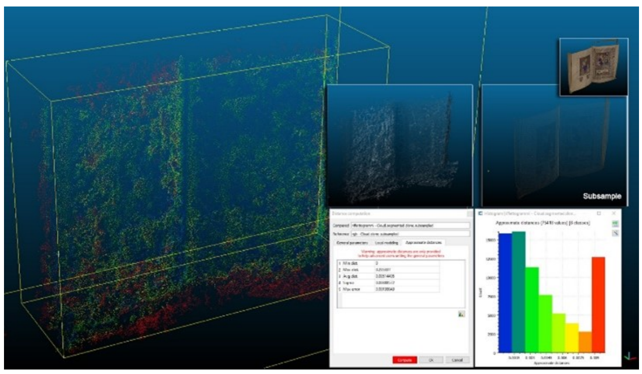

Figure 8: *Comparison in Cloud Compare of the two point clouds generated by RGB and IR dataset after subsampling at 2 mm.*

7. Then, the triangulated mesh was generated in SfM software

using the IR dataset but before computing the texture, further optimization was performed in other 3D modeling software such as Instant Mesh and Blender.

8. Instant Mesh was used for improving the mesh obtained from SfM. This software uses unified local smoothing operator to “remesh” the original surface and thus optimizing both the edge orientations and vertex positions in the final mesh while maintaining the original shape and border [JTPSH15] (Figure 9, upper image).

9. The optimized mesh was then post-processed in Blender in order to fill small gaps and, above all, to manually control the UV Mapping, the process of projecting a 3D model's surface to a 2D space for the subsequent texture mapping. In this way it was possible to weigh the detail in pixels giving higher priority to the areas of greatest interest over others (Figure 9, medium and low image).

10. Finally the texture mapping was computed in Reality Capturing or Agisoft Metashape by using the respective texture building algorithms, which project the oriented images on the 3D model’s surface to generate both IR and RGB atlas textures. The textures were computed keeping the previously created UV coordinates (Figure 10).

11. Finally, models (obj, fbx etc) were obtained with various textures and editable orthophotos in interoperable formats (jpg, tiff, png), and they were exported in glTF format and visualized in the 3D Web App platform [CAB23] (Figure 11).

5. Conclusion

The proposed methodology overcomes the limitations of other methods of 3D thermography in which camera- generated images (thermograms) with mid-wavelength infrared radiation (MWIR) must be collimated on digital 3D models obtained from images acquired in other spectral ranges, for example in the visible (VIS) and with other devices, or in which infrared images used for 3D reconstruction must be acquired on non-homothermic artifacts. Compared to the current state of the art, the methodology offers the following advantages: 1) possibility of digitally reconstructing the three-dimensional geometry of an artifact by processing even only infrared images acquired in thermal equilibrium conditions; 2) direct processing of infrared images acquired in the same configuration and with the same thermographic device (thermal camera) used to record sequences with active thermography techniques that allow virtual stratigraphic exploration of the internal structure.

In the previous literature there is also an absence of methods that require the integration of shape surveys with thermal- reflectographic ones, both for static and dynamic 3D reconstructions of depth, associated with thermal stimulation. In particular, there are no applications that can be linked to the proposed methodology in the fields of particular interest, such as cultural heritage.

There are no particular disadvantages in the proposed method. The system has not specific commercial, legislative or technical limitations, particularly with regard to the safety of operators and the environment in which it operates. The methodology has been applied to ancient manuscripts, as part of the project 'Codex4D: 4-dimensional journey through the manuscript'.

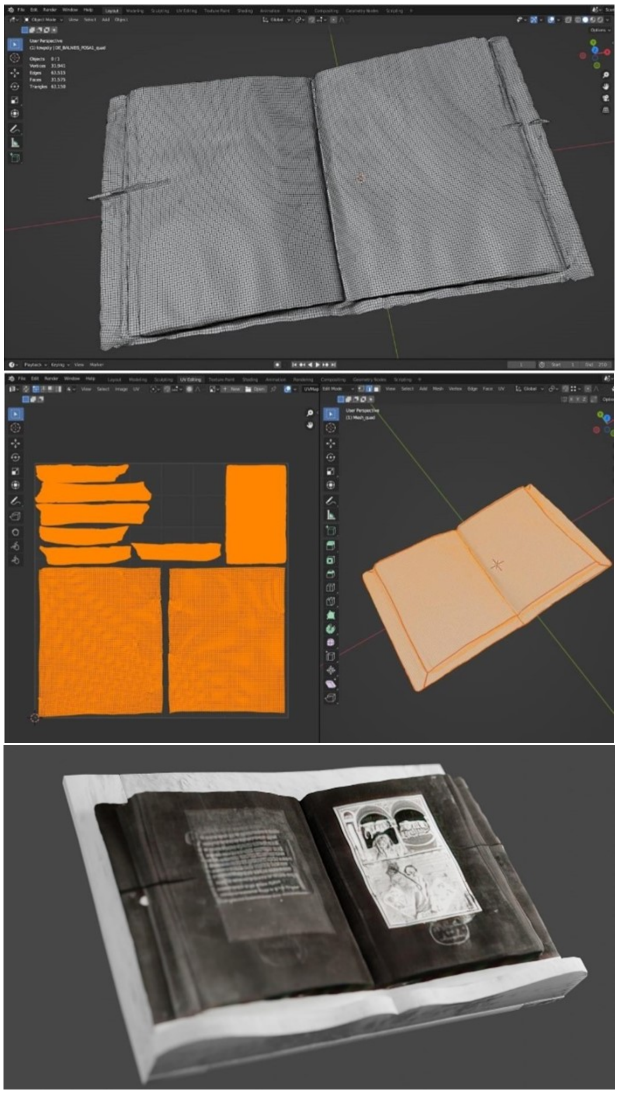

Figure 9: *Upper image: the Mesh model topology after remeshing process in Instant Mesh and geometry editing in Blender.. Medium Image: manual UV mapping of the 3D Model. Low image: the complete model.*

It has been developed in accordance with the process of generating value of cultural assets, and disseminating their knowledge, integrating diagnostic and historical artistic contents, facilitating protection and dissemination.

The proposed methodology can be applied in the following domains: Augmented Reality, Advanced 3D modeling for accessing and understanding European cultural assets, Advanced processing; Communication and dissemination platform, Virtual Museum.

Target markets may be connected to:

a) private companies that provide diagnostic tools and services for the study, research, conservation, enhancement of Cultural Heritage and the dissemination of their knowledge;

Figure 10: *RGB and IR Atlas texture created in SfM software using texture building algorithms.*

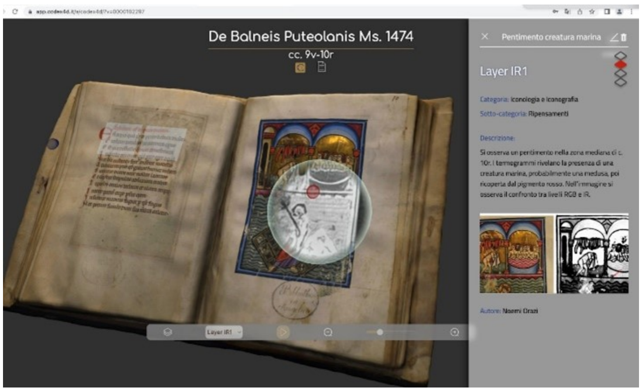

Figure 11: *Upper image: final model of the manuscript elaborated in Blender. Low image: 4D model of the manuscript implemented in the Codex4D web app, where it is possible to use a IR lens to explore stratigraphies and to open annotations referred to with specific points or areas on different layers of the model (Ms. 1474, De Balneis Puteolanis, Angelica Library, Rome).*

b) public and private institutions carrying out study, conservation and restoration activities, valorization of cultural heritage and dissemination of their knowledge through cultural and educational channels;
c) companies in industrial fields that provide for thermographic controls and inspections of products to which the proposed method would offer the possibility of visualizing the highlighted elements, placing them in the three-dimensional model of the artifact.
d) Manufacturers and developers of photogrammetric software interested in implementing IR photogrammetry services. The proposed methodology has been filed by the authors as patent no. 102023000004968 on 16 of March 2023.

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