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3D imaging of the Bayeux Tapestry using photogrammetry and integration into virtual reality: Results of a feasibility test

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ABSTRACT

The Bayeux Tapestry is one of the most famous pieces of medieval art. Our objective is to report on a 3D image processing experiment carried out to test and prepare further dedicated and more systematic observation campaigns. We have tested the capacity of the Structure-from-Motion photogrammetry range imaging technique to compute detailed 3D models of the Tapestry through its protecting window, using a Nikon Z7II full frame mirrorless camera. Tests have been carried out both at the global scale and at the local scale on four scenes, including the Halley comet. We show that 3D details up to the fabric weft level can be obtained locally using this photogrammetry technique, in addition to a global digital model. We have also computed a 3D model of the interior of the nearby Bayeux Cathedral. A Virtual Reality simulation has been created to showcase a subset of the Tapestry inside the Bayeux Cathedral, in order to validate a proof of concept for potential future digital outreach and scientific enhancement projects.

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1. Introduction

The Bayeux Tapestry is a medieval wool embroidery from the second part of the eleventh century, measuring 68 m long and 70 cm high on 9 pieces of linen containing 58 scenes. It represents a unique historical artifact documenting the Norman conquest of England in 1066 by William, Duke of the Normans against Harold II, King of English. It has been added on the UNESCO Memory of the World Register in 2007. Significant efforts to document the Tapestry have been undertaken over the past 10 years. UV fluorescence pictures, infrared reflectography, high-resolution color pictures, hyperspectral images give new insights on the artwork. Hyperspectral imagery helped for example to identify and map natural and synthetic dyes [1]. These documents are integrated into a digital Spatialized Documentary Information System (SDIS)

developed using GIS techniques, and dedicated to conservation experts, historians and researchers. It was created through a scientific collaboration between the DRAC Normandy, the City of Bayeux, the University of Caen and the CNRS [2,3]. It constitutes the major digital program carried out as part of the restructuring of the Bayeux Tapestry Museum, initiated in 2016 with a view to reopening of a new modernized establishment in 2027.

Besides substantial contributions of scientific documentation related to the work, collected, ordered and indexed, SDIS offers various layers of the whole embroidery recalibrated together, with one of them serving as a common reference representation. High-resolution panoramas [4], tiled and displayed online like a geographic map, give an unprecedented access to the 58 scenes of the whole Tapestry. This spatialized documentation system offers an exceptional set of information for historical studies and for the conservation of the artwork. In order to go one-step further into the imaging possibilities, one should note that the embroidery has also 3D topographic details contrarily to a simple 2D object. Hav-

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ing a complete 3D representation would therefore possibly provide additional information about the properties of the Tapestry such as its main fabric characteristics, the organization of strands of wool, or the previously restored areas. Moreover, it could play a role in the preservation of this famous artifact, and enable various outreach possibilities such as Augmented or Virtual Reality rendering. The value of 3D imaging in archaeology and museum objects for public engagement, preservation and research capabilities has been widely discussed in the literature [5–7].

The results of a 3D digitization campaign of the Tapestry performed in January 2021 are described in [8]. One objective was to produce high-detail 3D-printed mockups. Photogrammetry was investigated, but the alternative photometric stereo technique was finally used instead to investigate high-frequency details. In further works, a deep learning-based solution was investigated to convert the RGB panorama into a 2.5D normal map, allowing the creation of 3D objects that can be explored tactilely by visually impaired people [9].

2. Research aim

In our approach, we carried out a feasibility study to further test the possibility to use the Structure-from-Motion photogrammetric technique [10,11] to produce a 3D model of the Bayeux Tapestry through its protection window. The reconstruction is tested at both the global and local scales, allowing the comparison with other data sources. The second objective is to apply the photogrammetry technique to the nearby Bayeux Cathedral interior in order to create a Virtual Reality simulation, where subsections of the Tapestry can potentially be relocated at various locations and scales around the nave for demonstration purposes.

3. Materials and methods

3.1. Experimental setup

We acquired the input dataset at the Bayeux Tapestry Museum in January 2023, using a Nikon Z7II camera equipped with a Nikon Z 24–70 mm lens. 5504 × 8256 pixels photographs were taken through the protective glass window (situated at 25 cm from the object, Fig. 1a), at 800 ISO without additional lighting. For the global imaging campaign, we adapted the distance so that the 70-cm height Tapestry could fit within a single frame in portrait mode (Fig. 1b), using a focal of 70 mm. 441 photographs were taken systematically perpendicular to the window, with an overlap of about two thirds between images for the entire 68 m-long Tapestry. The significant overlap between images is required for the successful Structure-from-Motion processing [10]. In four areas of specific interest, additional images have been taken as close as possible to the protective window, in order to maximize the level of details (see examples in Fig. 1c and 1d).

3.2. Data processing

Images were pre-processed using the DXO PhotoLab software to correct for lens distortion. We then used the Agisoft Metashape photogrammetric software, which proved to be useful in a variety of situations [12–15]. In Metashape, the first step consists in the images' alignment. This alignment is made possible by the significant overlap from one image to the next, allowing the automatic identification of tie points. Images are automatically replaced at their location by the correlation process (see blue squares in Fig. 2). The next step is the generation of depth maps. Then, a polygonal mesh based on the depth map data is computed (seen in purple in Fig. 2 for scenes 1–14). The final step is the generation of a texture, which corresponds to an interpolated mosaic of

the original images draped over the 3D mesh. The number of tiles constituting the texture is adapted to preserve the level of details in the original images, and computer handling limits.

4. Results and discussion

4.1. Tests on the whole Tapestry

We have processed 441 overlapping images covering the 68m-long Tapestry (Fig. 2). Two areas were covered with only 50% of overlap between adjacent images, which broke the automated alignment in two occasions. Due to this problem, we split the photogrammetric project in three main chunks, covering scenes 1–14, 14–47, and 47–58. We see in Fig. 2 that the overall shape of the whole Tapestry is well reconstructed, even the U-turn of the protection display at the middle of the Tapestry. Once integrated, the whole set of data represents 3D models of 292 million polygons.

In order to produce a model that can be easily manipulated with traditional computers, the model should preferably be split in tiles, or downsampled. An example of a low-resolution version of scenes 1 to 7 can be viewed on the Sketchfab web platform at <https://skfb.ly/oWT6E>. The global comprehensive rendering at full resolution falls out of the scope of this study, where the highest resolution (achieved when the camera is placed up to the protective window) is restricted to subsections only. In addition to the global mapping test, we took additional close-up images on four specific areas of interest in Scenes 30, 32, 46 and 47, in order to evaluate how far we can go into the level of details. In the following, we only describe scene 32.

4.2. Close-up details on scene 32 containing the representation of the halley comet

Fig. 3 shows the result of a close-up investigation performed on Scene 32. In this experiment, we used 285 individual images taken from a short distance up to the protective glass window (~25 cm). A subset of the images is shown in Fig. 3a. Images were aligned in Metashape in order to produce a dense point cloud of 380 million points (Fig. 3b) and a mesh of 40 million polygons (Fig. 3c), textured with the set of images (Fig. 3d). Figs. 3e and 3f show a zoom on the Halley comet.

This capability to observe details on the 3D digitalization of the embroidery can help for condition reports. The realization of such a report in 2020 required the work of several restorers directly in front of the object, which had to be moved inside its showcase to carry out precise visual observations [16]. Forthcoming condition report studies could benefit from the use of fine scale digital 3D models such as the ones produced during our work to prevent excessive manipulation.

As another use-case example, we compared our 3D model of the main character in Scene 30 (available at <https://skfb.ly/oPUEH>) with wax casting from Stothard [17,18], published in *Vetusta Monumenta* between 1821 and 1823. Stothard's works recorded the state of the Bayeux Tapestry before the 19th century restorations. The comparison with our 3D model allows to identify a strand of wool in the neck of the middle character, which is missing in Stothard's record. It therefore corresponds to a late 19th century restoration. 3D models of characters of scenes 46 and 47 documented by Stothard in 1823 [18], are also available on Sketchfab for comparison. If such comparisons can also partly be made from simple photographs, it appears to be more efficient when using detailed 3D digital models for which the viewpoints and level of zoom can be easily adapted, independently of the protection window, and without the need to be standing in front of the actual Tapestry.



Fig. 1. The original Bayeux Tapestry, dating from the 11th century, exhibited at the Bayeux Tapestry Museum, Bayeux, Normandy (France). (a) The Bayeux Tapestry under its protective glass window. (b) Example of a single frame taken with a Nikon Z7II camera, from a distance allowing a complete coverage in height in a single pass. (c) Example of a close-up image on the Halley comet, taken close to the protection window (with a zoom in d showing the level of details).

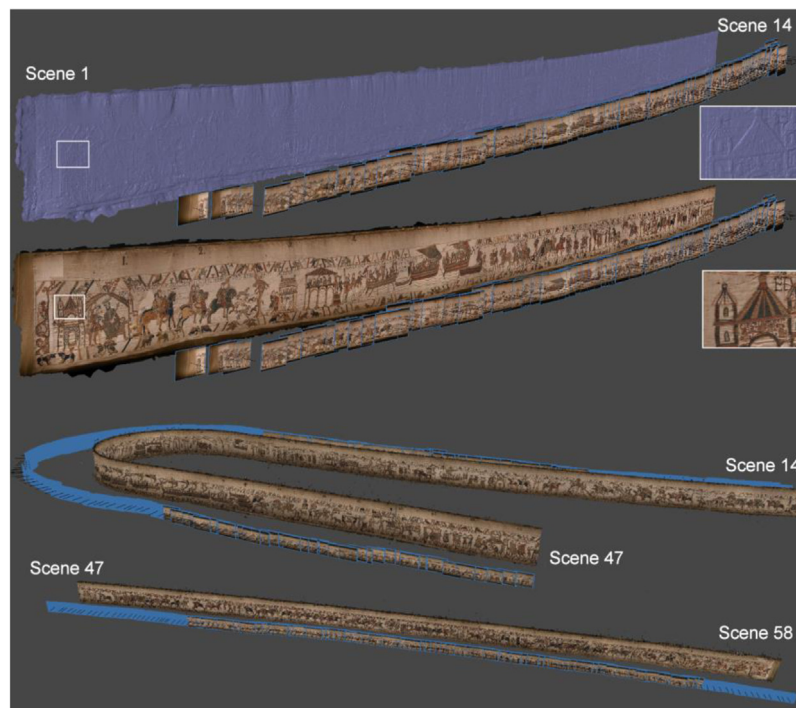


Fig. 2. Global view of the Metashape photogrammetric project of the whole Tapestry, separated in three chunks. Photographs are represented by blue squares. The alignment of 441 images allows the reconstruction of the whole Tapestry. The zoom in Scene 1 illustrates details in the white rectangle. The U-shaped turn of the actual setting display is even well reproduced. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

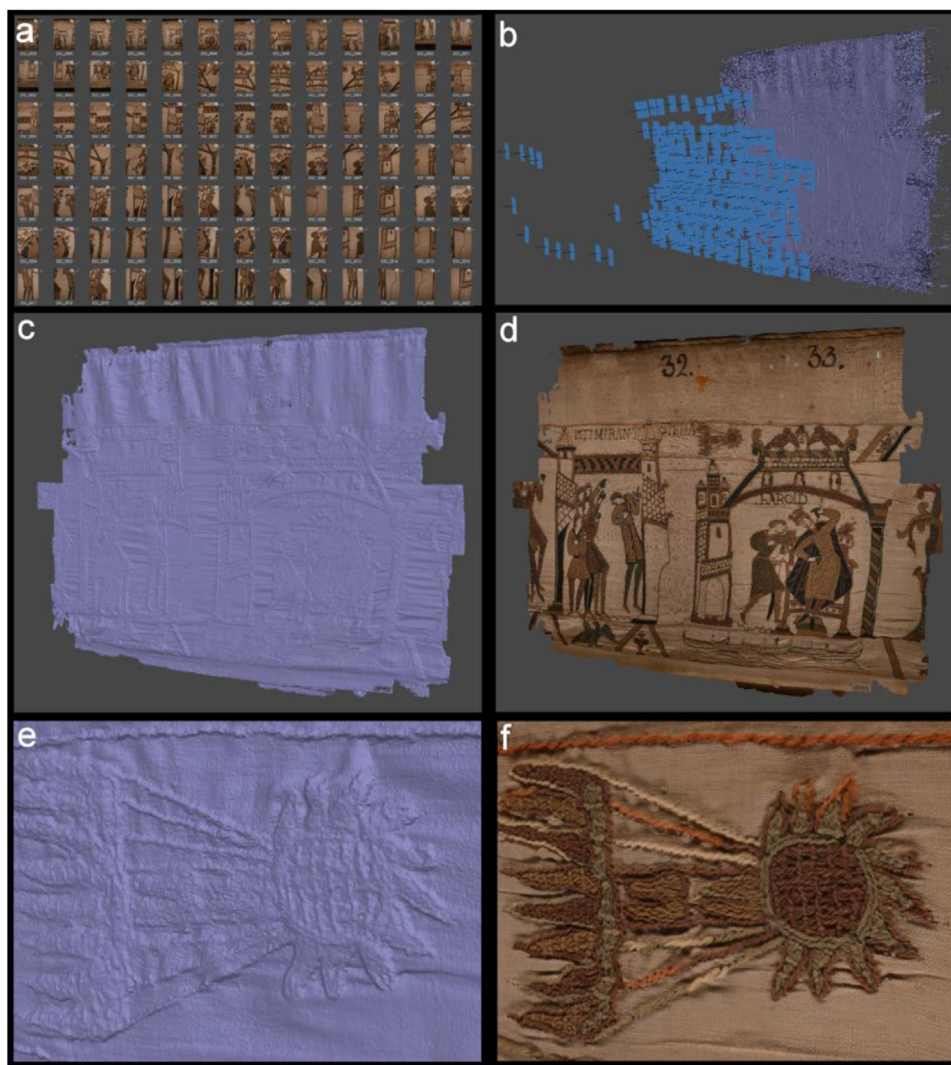


Fig. 3. Close up 3D model of Scene 32 containing the Halley comet. Images have been acquired as close as possible (~25 cm) considering the protection window. A low-resolution version of the 3D model can be freely manipulated at <https://skfb.ly/prGqE>. A full resolution extract of the 3D model centered on the Halley comet can be viewed at (<https://skfb.ly/prPup>). It can be used to evaluate the finest 3D details using the model inspector tool and the matcap rendering option in Sketchfab. The 40 million polygons photogrammetric model allows the reconstruction of fine sub mm-scale details down to the fabric weft. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Modeling the Bayeux cathedral and integration into virtual reality

The Bayeux Tapestry was displayed to the public for celebrations every July inside the Bayeux cathedral at least from 1476 (first known mention of the Tapestry within the Cathedral Treasury), and up to the end of the 18th century. It was a ceremony in honor of the relics of the cathedral. Before 1476, no source formally allows to replace the work in the cathedral of Bayeux, although it is proposed that it was originally created for the cathedral of Odon [19], and that it could have been exhibited in its old Romanesque nave.

As a supplementary test, we produced a first order 3D photogrammetric model of the Bayeux cathedral nave interior. 513 Images were taken from the ground level, using a focal of 24 mm. The set of images was successfully aligned in Metashape to produce a 3D mesh of 28 million polygons that we textured with ten 8K tiles and downsampled to 500,000 polygons for rendering purposes. A more complete 3D model would require a dedicated acquisition campaign with more images and/or the use

of a drone or a LIDAR [20]. Despite this, our first order 3D model was sufficiently detailed to setup a Virtual Reality scene, similar to the workflow proposed in [21] to reconstruct historical sites, such as the church of Orsanmichele, with their decorative interior using a combination of LIDAR 3D point clouds models of buildings and 3D photogrammetric models of artwork.

In our approach, we used photogrammetry both for the building and the artwork, and we opted for the SteamVR workshop environment to design a prototype VR collaborative scene for the rendering (Fig. 4). Users can freely investigate the first seven scenes of the Tapestry, together with an enlargement of Scene 32 containing the representation of the Halley comet. Both models are displayed inside the 3D model of the Bayeux cathedral. The immersive VR environment allows the users to investigate the embroidery as close as few centimeters only (bottom of Fig. 4), which is not possible in real life due to the protective window limiting the distance to 25 cm. This enables a precise investigation of the finest details of the Tapestry such as traces of exogenous matter, or restoration zones, which are particularly numerous at the beginning of the Tapestry. The three times magnification of scene 32



Fig. 4. Virtual Reality scene integrating parts of the Tapestry into the Bayeux Cathedral interior. The first seven scenes of the Tapestry are included for demonstration purposes, together with an enlargement of Scene 32 showing the Halley comet. The embroidery can be investigated from few cm only (closer than in real life because of the protecting window). The exaggerated size of scene 32 allows the users to discover details of the tapestry while being at the same height as the main characters, reinforcing the feeling of immersion into the scenery. The VR Scene is accessible at <https://steamcommunity.com/sharedfiles/filedetails/?id=2928526155>. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(seen on the left of the upper panel of Fig. 4) displays another way of investigating the scenery, emphasizing details and reinforcing the feeling of immersion into the storyboard.

Such an experience can be used for further researches. For example, no written source allows us to know how the embroidery was exhibited inside the nave. The old hanging marks found on the back of the Tapestry in 1982 [22] could not be compared to an architectural context. Norton [19] considered three different hanging height levels (middle of the pillars, level of the capitals, at the base of the gallery), questioning if iconographic proposal and Latin inscriptions remain readable by visitors traveling through the nave. This can be experimented in VR to shed light on the old hangings of the Bayeux Tapestry. The association of the 3D models of the Bayeux Tapestry and of the Cathedral interior could help in the future in determining where the Tapestry was actually hanged in by testing various proposed hanging heights and positions. All these aspects could potentially be further investigated in forthcoming studies using a more evolved version of our VR simulation.

5. Conclusion and perspectives

We have used the photogrammetry technique to compute a 3D model of the Bayeux Tapestry. We have performed our tests both at the global (on the 68-m long artwork) and local scales. The 3D method used can capture low-level features such as fabric weave. A first-order 3D model of the Bayeux Cathedral interior has also been produced. A Virtual Reality environment has been created to replace parts of the Tapestry inside the Cathedral, where it was historically displayed to the public during specific celebrations at least from 1476. This kind of 3D rendering can play a significant role in the preservation of a major cultural heritage artifact. It also provides unprecedented access to the Tapestry using Virtual and Augmented Reality techniques. In these cases, the investigation is not limited by the protective glass. It can be carried out without further manipulation of the original artifact, at different scales, and even from remote places.

Our objective was to report an image processing experiment and showcase proofs of concepts. Other digitizing campaigns could

be carried out in the future after the reopening of the new museum of the Tapestry, planned in 2027. The new museum will include a conservation room, which will facilitate the conditions of access to the Tapestry for study purposes. Multiple topics can be investigated, including Virtual and Augmented Reality rendition for the public, conservation assessment, 3D reconstruction for researchers and historians, or even physical reproduction of specific areas through 3D printing methods.

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