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AI-BASED GENERATION OF A MULTI-MODAL PANORAMA FOR THE BAYEUX TAPESTRY

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Reconstruction of a multimodal panorama of the Bayeux Tapestry, enhancing the accessibility of the artwork. Target modalities, and corresponding imaging tools:

- ▶ daylight → well-tuned heuristics ;
- ▶ multispectral → variational methods ;
- ▶ geometry → deep learning.

The multimodal reconstruction can be explored through a web interface:

<https://redon213.users.greyc.fr/>.

1. The Bayeux Tapestry
2. Keypoint-based daylight panorama generation
3. Low-rank multispectral registration
4. Deep image-to-geometry translation

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The Bayeux Tapestry



70m-long medieval wool and linen *embroidery* telling the conquest of England by William, Duke of Normandy, in 1066.

The Bayeux Tapestry



Story starts with the death of old king Edward.

The Bayeux Tapestry



Edward had chosen his cousin William for his succession on the British throne.

The Bayeux Tapestry



Yet Edward's brother-in-law, Harold, took the throne.

The Bayeux Tapestry



Hence William's armada crossed the Channel.

The Bayeux Tapestry



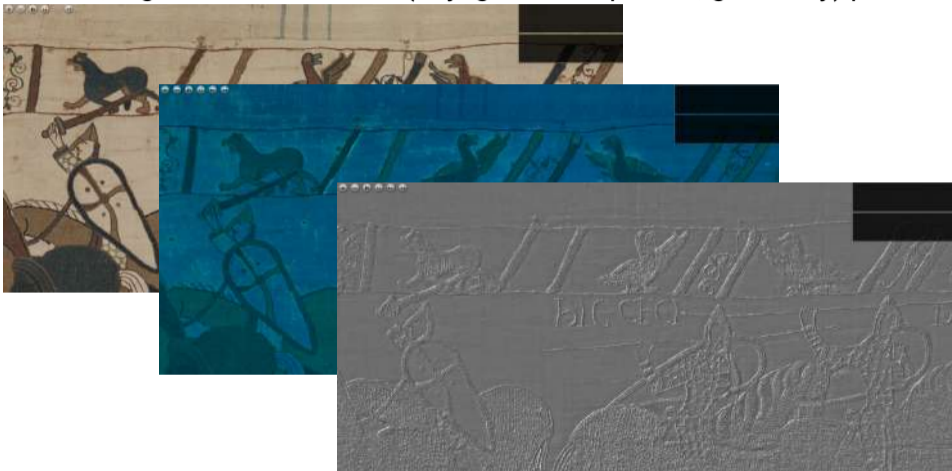
And William eventually defeated Harold during the battle of Hastings, hence becoming the King of England.



- ▶ Research complicated by: the number of visitors (400,000 per year), the exceptional size (70m long and 50cm high), the profusion of scenes (55), and the protective glass.
- Zoomable online interface for remote exploration.
- ▶ Unknown stages of the artistic process of its assembly and realization, inspection of the current state of the artwork.
- Multispectral and geometric modalities.

The multimodal digital twin

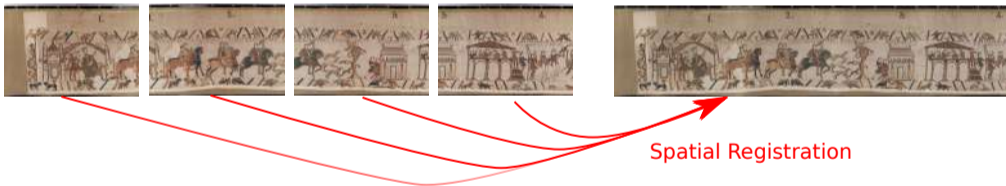
Zoomable, registered multimodal (daylight, multispectral, geometry) panorama:



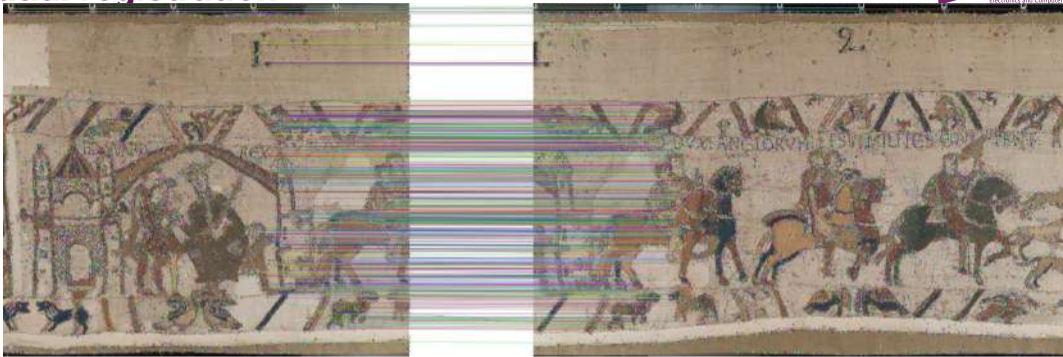
Online viewing: <https://redon213.users.greyc.fr/>.

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- ▶ Input: 86 high resolution images, acquired in 2017 by La Fabrique de patrimoines en Normandie under daylight ;
- ▶ Output: $480,000 \times 6,000$ px RGB panorama.



Berthelot et al. (2017), *La reconstruction du panorama de la Tapisserie de Bayeux comme fond de référence d'un système d'information documentaire spatialisée*, In *Situ Revue des patrimoines*.



Registration procedure

1. SIFT keypoint detection and matching;
2. Moving least-squares deformation estimation;
3. Warp next image and stitch it.

The reconstructed $480,000 \times 6,000$ px panorama can obviously not be viewed natively.

→ Custom tiling procedure¹, and visualization using OpenSeaDragon.

consecutive input images



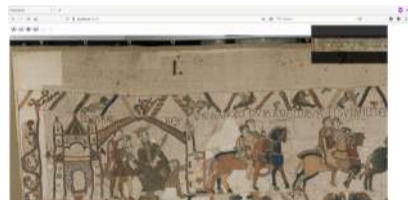
zoomtiler



deepzoom format



zoomable tiled images generation



OpenSeadragon Web image viewer

¹ Pizenberg (2021). *Zoomtiler, a simple CLI program to generate zoomable tiled images.*
<https://github.com/mpizenberg/zoomtiler>.

Online exploration of the artwork in daylight

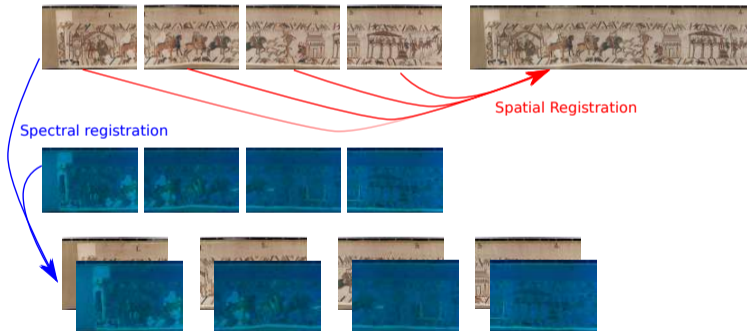
The history told by the artwork can eventually be explored in a zoomable web interface:



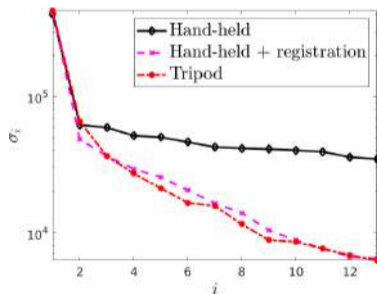
1. The Bayeux Tapestry
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Spectral registration

- ▶ Input: **86 images**, captured under **6 imaging modalities** (natural lighting, UV, IR, etc.), with $\approx 100px$ sensor displacements between modalities.
- ▶ Output: 86 pixel-accurate registered multispectral images, which can then be stitched exactly as the daylight ones.



Pizenberg et al. (2021), *Low-rank registration of images captured under varying, unknown lighting, SSVM*.



Singular values of the observations matrix

Reorganize observations into a matrix $M \in \mathbb{R}^{N_{\text{observations}} \times N_{\text{modalities}}}$, then find the transformation \mathcal{T} such that

$$\text{rank}(\mathcal{T}(M)) \rightarrow \min .$$

This nonconvex problem can be relaxed into:

$$\min_{A, \mathcal{T}} \|A\|_{\star} + \lambda \|A - \mathcal{T}(M)\|_1 .$$

and solved efficiently using augmented Lagrangian methods:

$$\begin{aligned} \min_{A, e, \mathcal{T}} \|A\|_{\star} + \lambda \|e\|_1 \\ \text{s.t. } e = A - \mathcal{T}(M). \end{aligned}$$

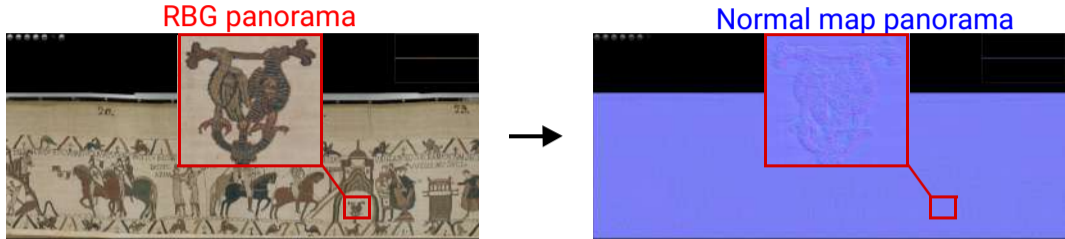
Online exploration of the artwork in UV

Exploring the UV modality may reveal damaged part, e.g. moisture:



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3D-digitization of the Bayeux tapestry



Goal: construct a 2.5D panorama of this 70 m-long medieval wool and linen *embroidery*, in view of geometry inspection and tactile experiments for visually-impaired people.

- ▶ RGB panorama readily available;
- ▶ Can we convert it to geometry?

Redon et al. (2023), *3D surface Approximation of the Entire Bayeux Tapestry for Improved Pedagogical Access*, ICCV workshops.

Proposed strategy



Spatial Registration

Daylight panorama, to be converted to normals

Proposed strategy for 3D-digitization

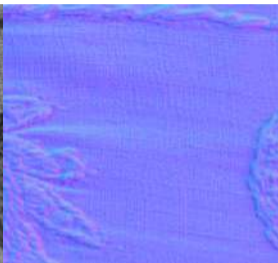
1. Store the estimated daylight spatial registration parameters (cf. Sect. 2);
2. Turn each RGB image to 2.5D using deep learning;
3. Apply the same spatial registration to the 2.5D images → geometric panorama.

Deep image-to-geometry learning

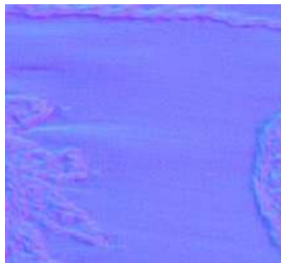
Input
image



Ground truth
normal map



Estimated
normal map



Proposed strategy for 3D-digitization

1. Store the RGB spatial registration parameters;
2. Turn each RGB image to 2.5D using deep learning:
→ a) ground truth acquisition; b) deep network architecture;
3. Apply the same spatial registration to the 2.5D images.

Ground truth geometry acquisition campaign

Photometric stereo-based 3D-reconstruction of a few scenes:



Left: three input images, taken from the same viewing angle but varying lighting.

Right: output high-resolution mesh (5M triangles).

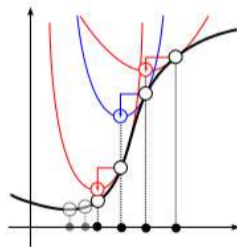
Data acquisition for photometric stereo

Image capture from fixed viewpoint, but varying illumination:

Given images $I^i : \Omega \subset \mathbb{R}^2 \rightarrow \mathbb{R}$, estimate shape $z : \Omega \rightarrow \mathbb{R}$ and reflectance $\rho : \Omega \rightarrow \mathbb{R}$ as solution of a variational problem:

$$\min_{z, \rho} \sum_{i=1}^m \int_{x \in \Omega} \Phi \left(\left| \rho(x) \ell^i \cdot \left[\nabla z(x)^\top, -1 \right]^\top - I^i(x) \right| \right) dx.$$

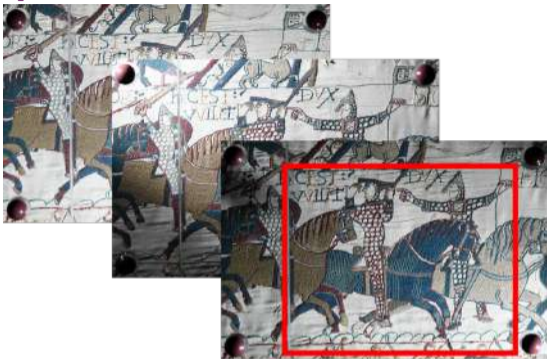
- ▶ ϕ : robust (non-convex) redescending M-estimator;
- ▶ Optimization by alternating MM.



QUÉAU, MECCA and DUROU (2016), *Unbiased photometric stereo for colored surfaces*, CVPR.

QUÉAU et al. (2017), *A non-convex variational approach to photometric stereo under inaccurate lighting*, CVPR.

Shape and reflectance reconstruction



Left: input images. Right: image, reconstructed albedo and reconstructed normals.

The reconstructed albedo encodes the intrinsic properties of the object's material ; the reconstructed normals encode the geometric variations of its surface.

Ground truth (image, geometry) pairs



We have ≈ 30 couples (RGB, normals) of size 3000 px^2 .

→ Thousands of 128 px^2 patches for learning the mapping $\text{RGB} \mapsto \text{geometry}$.

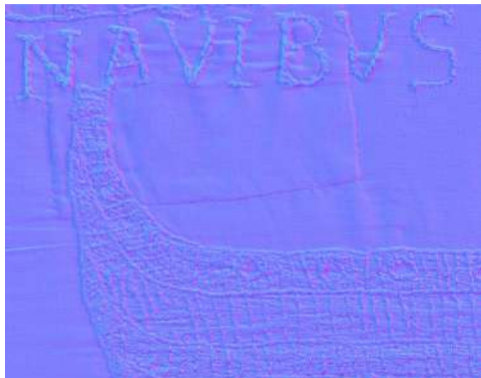
Ground truth (image, geometry) pairs



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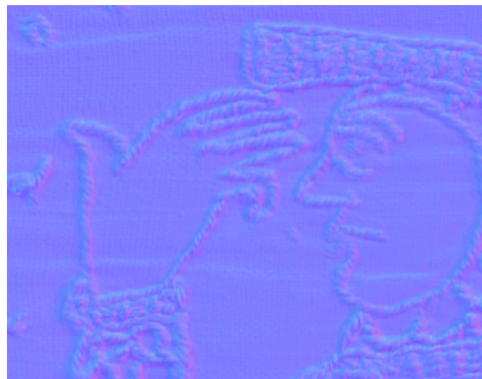
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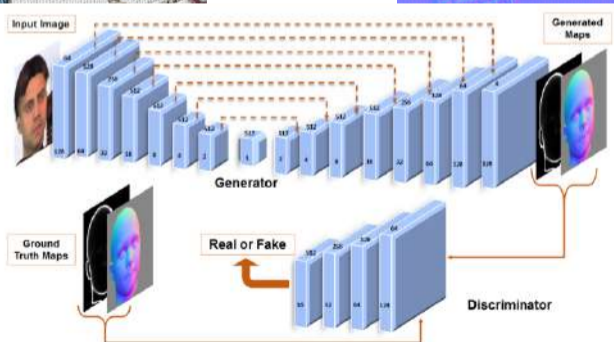
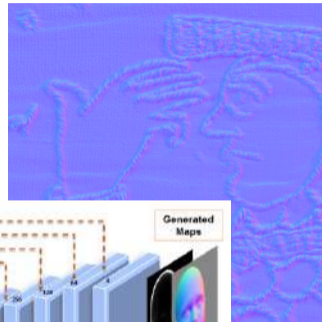
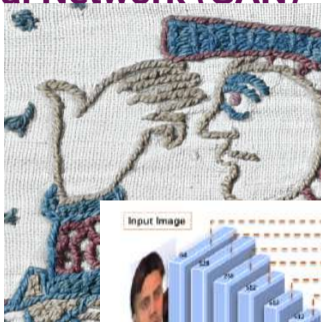
Ground truth (image, geometry) pairs



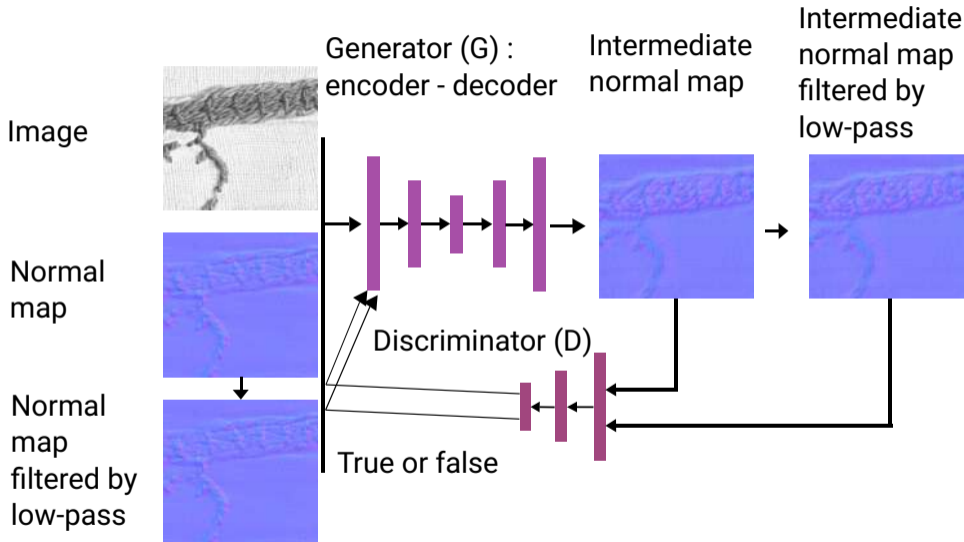
We have ≈ 30 couples (RGB, normals) of size 3000 px^2 .

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Learning the RGB \rightarrow geometry mapping via a Generative Adversarial Network (GAN)



Regularized GAN architecture



Proposed strategy for 3D-digitization

1. Store the RGB spatial registration parameters
2. Turn each RGB image to 2.5D using deep learning
→ a) ground truth acquisition ; b) deep network architecture
3. **Apply the same spatial registration to the 2.5D images**



Online exploration of the artwork's geometry

From the normal map images, we can eventually render shaded views of the artwork, highlighting the surface details:



Thank you

<https://redon213.users.greyc.fr>

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