

N-D Reconstruction for Cultural Heritage Accessibility: Multimodal and 3D Digitization of the Bayeux Tapestry

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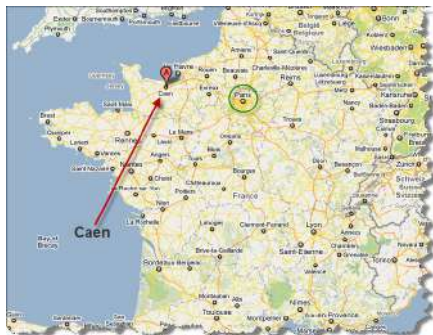
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About me

- 2015: PhD in computer vision in Toulouse
- Since 2018: CNRS researcher with the GREYC laboratory, in Caen (Normandy)



Aim of the talk



The Bayeux Tapestry

Multimodal Panorama



3D-reconstruction

Multi-spectral and 3-dimensional digitization of a unique cultural artefact, in order to permit an inclusive access

Outline

- 1 The Bayeux Tapestry and the IMG project
- 2 Tactile representation through 3D-reconstruction
- 3 Multispectral panorama digitization

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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



William's armada crossed the Channel

The Bayeux Tapestry



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

The Inclusive Museum Guide (IMG) Project

- Goal: Make visual artworks accessible in an “inclusive” approach (to all, from everywhere, at any time)
- Funding: Normandy region and ANR projects “Inclusive Museum Guide” (2019-2024)
- Partners: Caen univ., Rouen univ., CNRS, Bayeux museum, Royal Holloway univ., Westminster univ.



Accessibility-related issues



- How can we make visually-impaired people “feel” such artifacts which they cannot see or touch ?
→ **tactile representations through 3D-reconstruction**
- How can we make scientists and researchers access this exceptionally large artwork at anytime, from everywhere ?
→ **multispectral panorama digitization**

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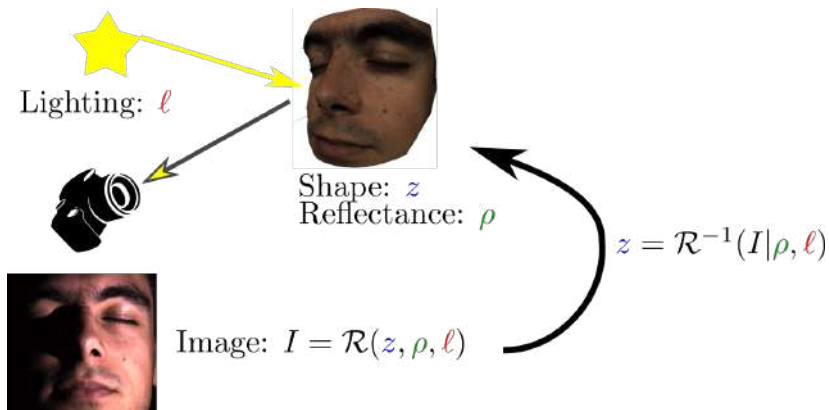
Towards a tactile representation of visual artworks



Goal: extract thin geometric structures of the scene (“texture”),
in view of 3D-printing

Challenges: no direct access (behind glass), fragility to light
exposure, color changes, thinness of the wool strings...

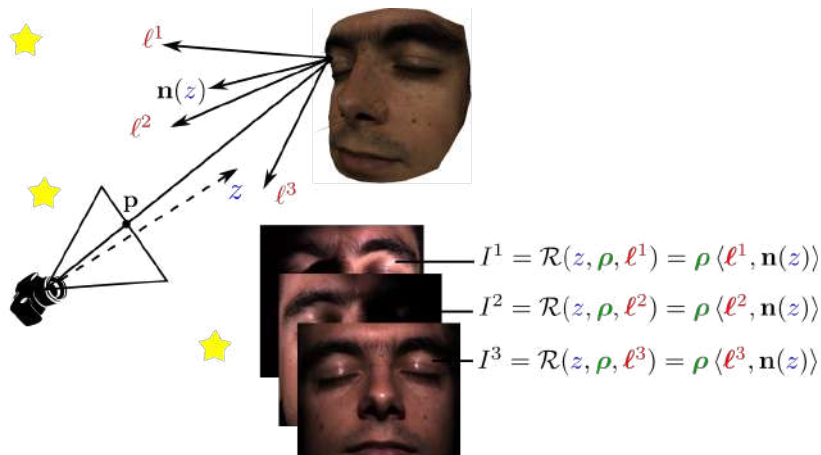
Photometric 3D-reconstruction as an inverse problem



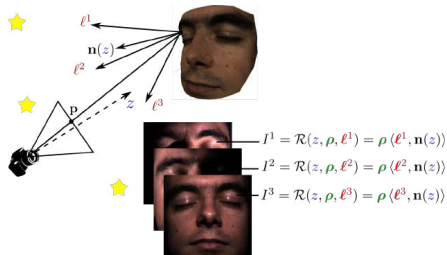
- Goal: invert the radiance function \mathcal{R} to recover the shape z and reflectance ρ , given lighting ℓ
- Use varying light source to separate reflectance from shading: **photometric stereo** technique (Woodham, 1978)

Lambertian photometric stereo model

Assuming: pure diffuse reflectance without shadowing,
collimated lighting characterized by known directions $\{\ell^i\}_i$;
and denoting ρ the unknown albedo
and $\mathbf{n}(z)$ the unknown surface normal:



Basic solving strategy



Linear system in $\mathbf{m}(\boldsymbol{\rho}, \mathbf{z}) := \boldsymbol{\rho} \mathbf{n}(\mathbf{z}) \in \mathbb{R}^3$:

$$\begin{bmatrix} I^1 \\ I^2 \\ \vdots \\ I^m \end{bmatrix} = \begin{bmatrix} \ell^{1T} \\ \ell^{2T} \\ \vdots \\ \ell^{mT} \end{bmatrix} \mathbf{m}(\boldsymbol{\rho}, \mathbf{z})$$

- If: a) $m \geq 3$, b) lighting vectors ℓ^i are known, and c) they are non-coplanar ;
- Then vector $\mathbf{m}(\boldsymbol{\rho}, \mathbf{z})$ can be estimated in each pixel ;
- We deduce the normal and albedo by

$$\boldsymbol{\rho} = |\mathbf{m}(\boldsymbol{\rho}, \mathbf{z})|$$
$$\mathbf{n}(\mathbf{z}) = \frac{\mathbf{m}(\boldsymbol{\rho}, \mathbf{z})}{|\mathbf{m}(\boldsymbol{\rho}, \mathbf{z})|}$$

- Eventually, normals $\mathbf{n}(\mathbf{z})$ are *integrated* into depth z

Data acquisition

Acquisition of the death of Harold sequence:

Robust estimation techniques required for: reflections on glass,
shadows cast by the calibration balls, non-uniform flash
lighting, etc.

The death of Harold sequence

Acquired data, with reflective spheres for light calibration:



The death of Harold sequence

Acquired data, with unpredicted shadows cast by the spheres:

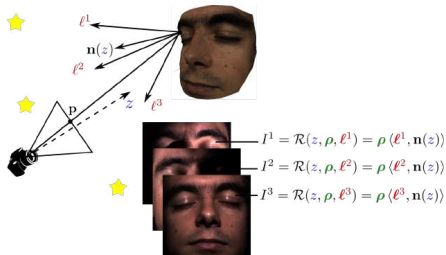


The death of Harold sequence

Acquired data, with unpredicted non-uniform lighting:



Robust photometric stereo formulation



Linear system in $\mathbf{m}(\rho, \mathbf{z}) := \rho \mathbf{n}(z) \in \mathbb{R}^3$:

$$\begin{bmatrix} I^1 \\ I^2 \\ \vdots \\ I^m \end{bmatrix} = \begin{bmatrix} \ell^{1T} \\ \ell^{2T} \\ \vdots \\ \ell^{mT} \end{bmatrix} \mathbf{m}(\rho, \mathbf{z})$$

Possible strategies to cope with outliers:

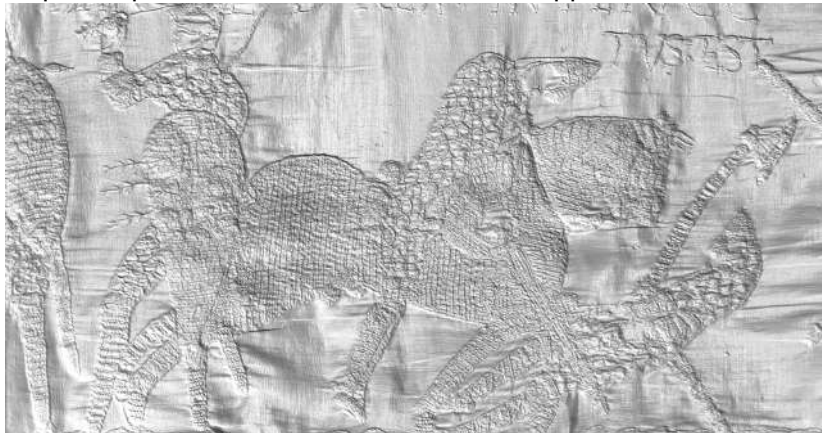
- 1) Considering a more evolved reflectance model
- 2) Deep learning on a large dataset
- 3) Adopting a robust solving strategy [Queau et al., CVPR 2017]

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

with ϕ a robust estimator (1-norm, Cauchy, etc.)

3-D reconstruction of the death of Harold sequence

Depth map reconstructed with the robust approach:



From images to a printable 3D-model

The estimated surface being represented as a gridded 2.5D depth map, it is straightforward to triangulate, and add a filled support for 3D-printing:



Two of the input images, and output printable high-resolution mesh (with albedo mapped onto it or not)

Results on a “ship” sequence



Three of the input images, and output printable high-resolution mesh (5M triangles)

Results on a “ship” sequence

Relighting of the 3D-reconstructed mesh (5M triangles)

Ongoing work: semantic mesh simplification

Goal: segment the mesh into background, contours and interior wool strings ; and apply a different height to each

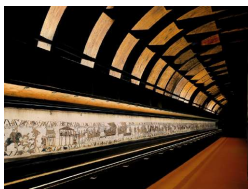


(work by Benjamin COUPRY, Marjorie REDON
and Florian VINCENT)

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Accessibility issues for scientists

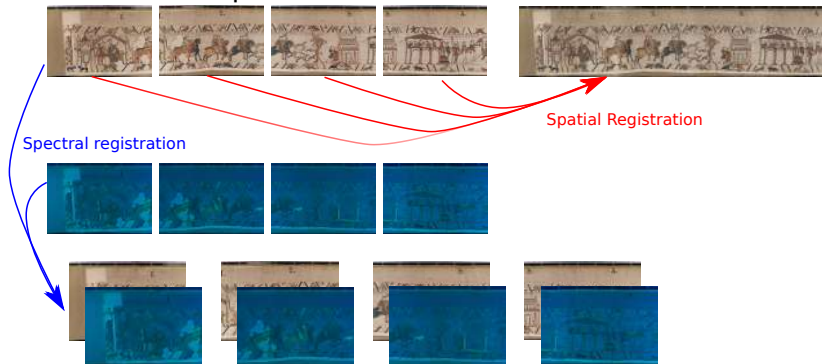


- Accessible to researchers only one month a year, when the museum is closed to visitors (more than 400 000 in 2019)
 - Exceptional size of the document: 70m long and 50cm high
 - Lack of a consensual reference system to find one's way around the work
 - Numerous restorations during the past millenium
- ⇒ Towards an open-access multispectral panorama



Joint spatial and spectral registration

Input: 86 images¹, captured under 6 imaging modalities
(natural lighting, UV, IR, etc.), with $\approx 100\text{px}$ sensor
displacements between modalities



- 1 Spectral registration of each modality wrt natural lighting
- 2 Spatial registration of natural lighting sequence
- 3 Visualization of the resulting multispectral panorama

¹ Image capture credits: La Fabrique de Patrimoines en Normandie

Spectral registration

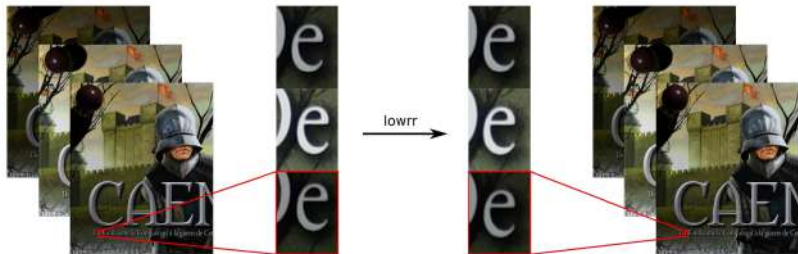
Reorganize observations into a matrix $M \in \mathbb{R}^{N_{\text{observations}} \times N_{\text{modalities}}}$, then find the transformation \mathcal{T} such that

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

This nonconvex problem can be relaxed into:

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

and solved efficiently using augmented Lagrangian methods [Pizenberg et al., SSVM 2021]²



Visualization of low-rank image alignment results

Left: input images ; Right: low-rank registration results

Spatial registration



Rough sketch of the stitching procedure in daylight:

- 1 SIFT keypoint detection and matching
- 2 Moving least-squares deformation estimation
- 3 Warp (**and store warping parameters**) and stitch

... and eventually, apply the same warping parameters to all modalities

Resulting high-resolution, multispectral panorama

Output panorama is of size 480 000 px \times 6 000 px \times 6 modalities



Online exploration of the panorama

Online exploration of the $480\,000 \times 6\,000$ px panorama,
with 6 registered modalities



References

- Quéau, Y., Wu, T., Durou, J.-D., Lauze, F., and Cremers, D. "A Non-Convex Variational Approach to Photometric Stereo under Inaccurate Lighting". In: *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. 2017.
- Durou, J.-D., Falcone, M., Quéau, Y., and Tozza, S. *Advances in Photometric 3D-Reconstruction*. Springer, 2020.
- Pizenberg, M., Quéau, Y., and Elmoataz, A. "Low-rank registration of images captured under unknown, varying lighting". In: *International Conference on Scale Space and Variational Methods in Computer Vision (SSVM)*. 2021.

Thank you for your attention !