

3D

Computer Vision
CSE455, Winter 2009
Steve Seitz

Structure from Motion

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Reading

- Snavely, Seitz, Szeliski, **Photo Tourism: Exploring Photo Collections in 3D**. *SIGGRAPH 2006*.

http://phototour.cs.washington.edu/Photo_Tourism.pdf

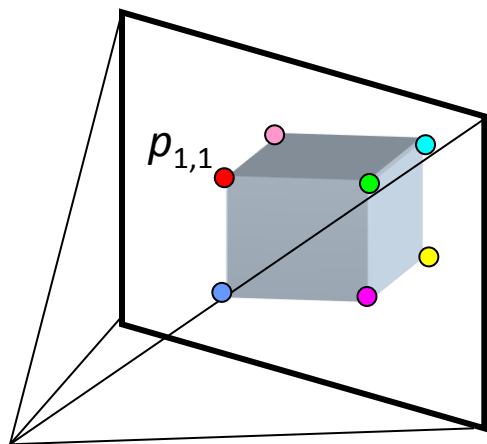
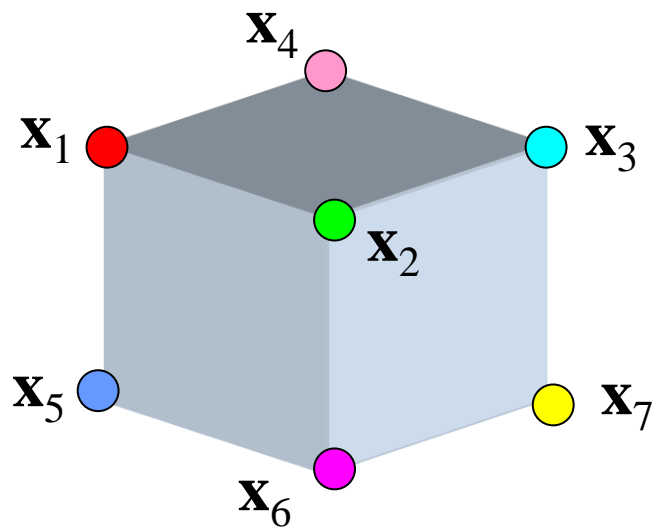


Image 1
 $\mathbf{R}_1, \mathbf{t}_1$

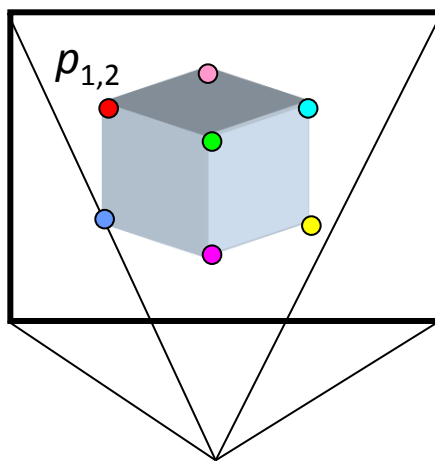


Image 2
 $\mathbf{R}_2, \mathbf{t}_2$

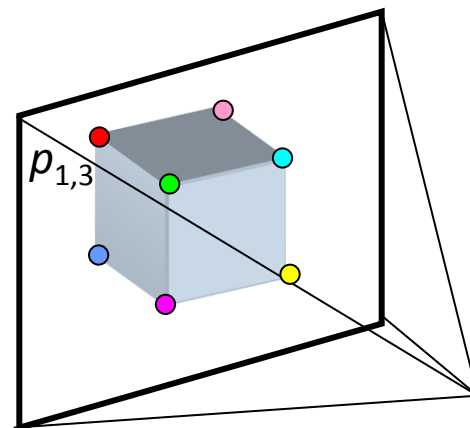
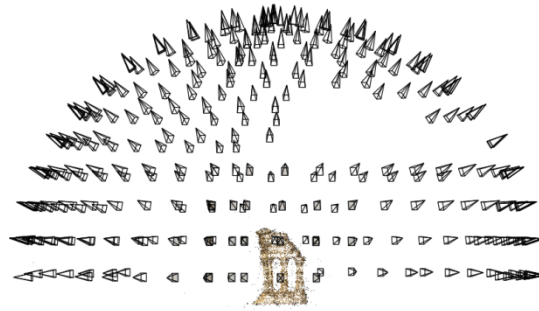
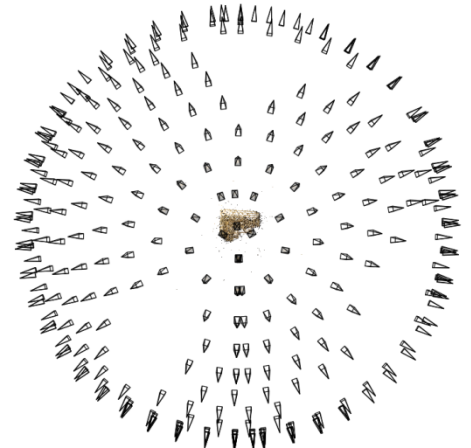


Image 3
 $\mathbf{R}_3, \mathbf{t}_3$

Structure from motion



Reconstruction (side)



(top)

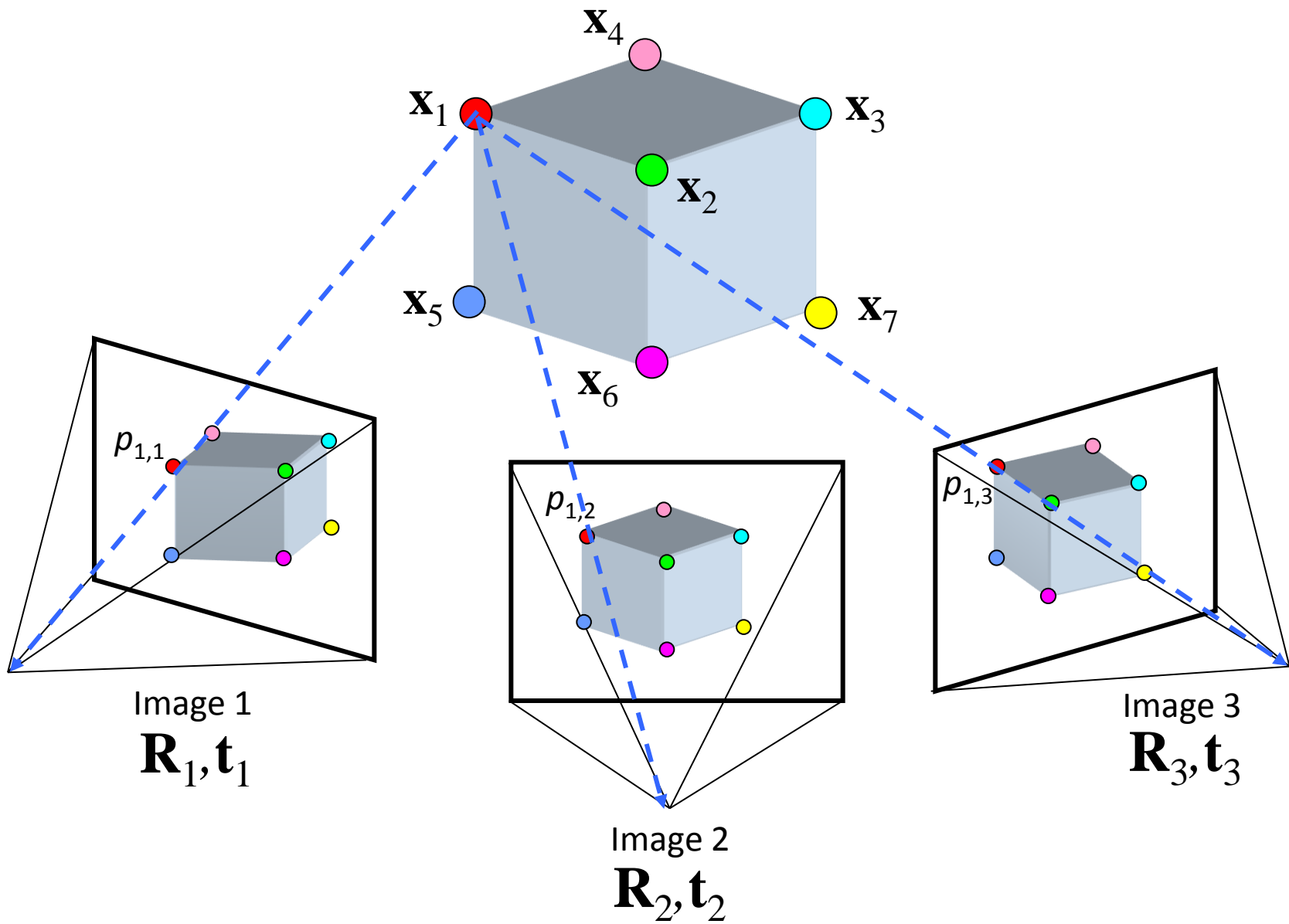
- Input: images with points in correspondence

$$p_{i,j} = (u_{i,j}, v_{i,j})$$

- Output

- structure: 3D location \mathbf{x}_i for each point p_i
- motion: camera parameters $\mathbf{R}_j, \mathbf{t}_j$

- Objective function: minimize *reprojection error*



SfM objective function

- Given point \mathbf{x} and rotation and translation \mathbf{R}, \mathbf{t}

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \mathbf{R}\mathbf{x} + \mathbf{t} \quad \begin{matrix} u' = \frac{fx'}{z'} \\ v' = \frac{fy'}{z'} \end{matrix} \quad \begin{bmatrix} u' \\ v' \end{bmatrix} = \mathbf{P}(\mathbf{x}, \mathbf{R}, \mathbf{t})$$

- Minimize sum of squared reprojection errors:

$$g(\mathbf{X}, \mathbf{R}, \mathbf{T}) = \sum_{i=1}^m \sum_{j=1}^n w_{ij} \cdot \left\| \underbrace{\mathbf{P}(\mathbf{x}_i, \mathbf{R}_j, \mathbf{t}_j)}_{\substack{\text{predicted} \\ \text{image location}}} - \underbrace{\begin{bmatrix} u_{i,j} \\ v_{i,j} \end{bmatrix}}_{\substack{\text{observed} \\ \text{image location}}} \right\|^2$$

Solving structure from motion

- Minimizing g is difficult:
 - g is non-linear due to rotations, perspective division
 - lots of parameters: 3 for each 3D point, 6 for each camera
 - difficult to initialize
 - gauge ambiguity: error is invariant to a similarity transform (translation, rotation, uniform scale)
- Many techniques use non-linear least-squares (NLLS) optimization (*bundle adjustment*)
 - Levenberg-Marquardt is one common algorithm for NLLS
 - Lourakis, **The Design and Implementation of a Generic Sparse Bundle Adjustment Software Package Based on the Levenberg-Marquardt Algorithm**, <http://www.ics.forth.gr/~lourakis/sba/>
 - http://en.wikipedia.org/wiki/Levenberg-Marquardt_algorithm

Photo Tourism

- Structure from motion on Internet photo collections

The screenshot shows the Flickr website interface. At the top, there's a navigation bar with 'Home', 'The Tour', 'Sign Up', and 'Explore'. A search bar contains the text 'trevi fountain'. Below the search bar, there are tabs for 'Photos', 'Groups', and 'People'. The search results section shows '27,761 results for photos matching trevi and fountain.' A grid of 16 photo thumbnails is displayed, each with a caption indicating the user who uploaded it. On the right side, there are several sponsored advertisements for travel and hotel services related to the Trevi Fountain.

flickr LOVES YOU™ You aren't signed in [Sign In](#) [Help](#)
[Home](#) [The Tour](#) [Sign Up](#) [Explore](#) [Search](#)

Search [Photos](#) [Groups](#) [People](#)

[SEARCH](#) [Advanced Search](#)
[Search by Camera](#)

Full text Tags only

✓ We found **27,761 results** for photos matching **trevi** and **fountain**. [View as slideshow](#) (⌂)

View: [Most relevant](#) • [Most recent](#) • [Most interesting](#) Show: [Details](#) • [Thumbnails](#)

From [NupurB](#) From [BRUNO MÉNDEZ...](#) From [* Toshio *](#) From [*Maqik &...](#)

From [Christopher...](#) From [Nastrina1981](#) From [laki good](#) From [Fabrizio...](#)

From [...Skazi...](#) From [Alida's...](#) From [hbomb1947](#) From [David d'O](#)

From [aquilasteve](#) From [clayirving](#)

Sponsored Results
[Cruise The Mediteranian](#)
Enjoy 11 days in Spain, France and Italy on this Mediteranian tour.
[www.mayflower tours.com/medtour](#)

[Trevi Fountain Hotel](#)
Compare hotel prices from over 120 top websites and save up to 70%.
[Hotels.SideStep.com](#)

[Trevi Fountains](#)
Compare prices, brands, and more at Smarter.com.
[www.smarter.com](#)

[Hotels Trevi Fountain - Italy](#)
Book now and save up to 75%. No reservation fee and pay at your hotel.
[booking.com/hotels-trevi-Fountain](#)

[Fountain Trevi](#)
Enjoy Savings & Selection On **Fountain Trevi**.
[Shopzilla.com](#)

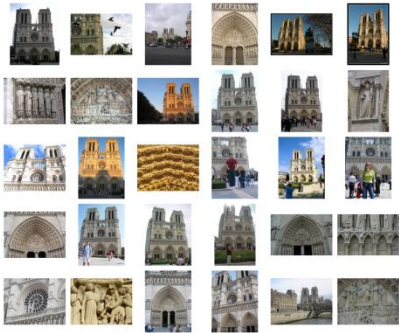
[Hotels Trevi Fountain](#)
Save up to 75% on Italy hotels. Pay at check-in. No booking fees.
[www.priceline-europe.com](#)

[Trevi Fountains – up to 75% Off](#)

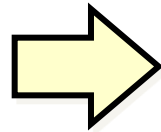
Photo Tourism



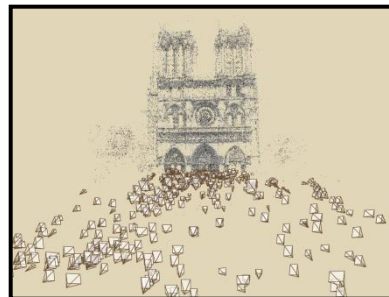
Photo Tourism overview



Input photographs



Scene
reconstruction



Relative camera positions
and orientations

Point cloud

Sparse correspondence

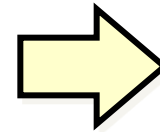
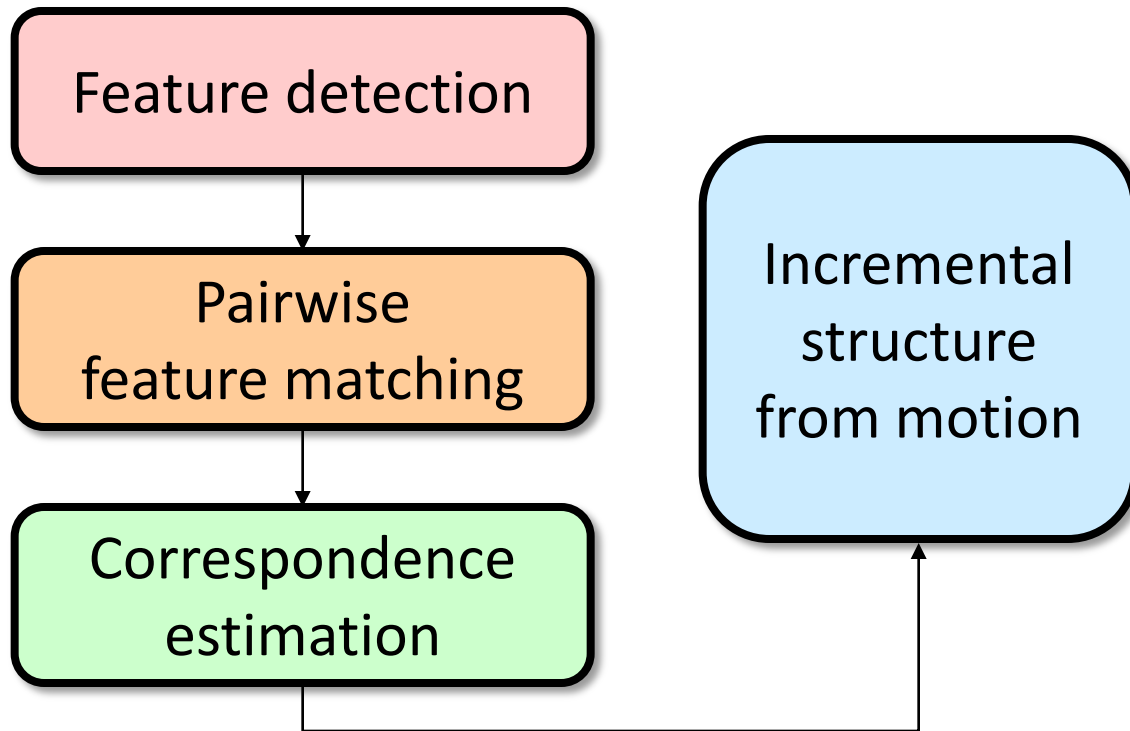


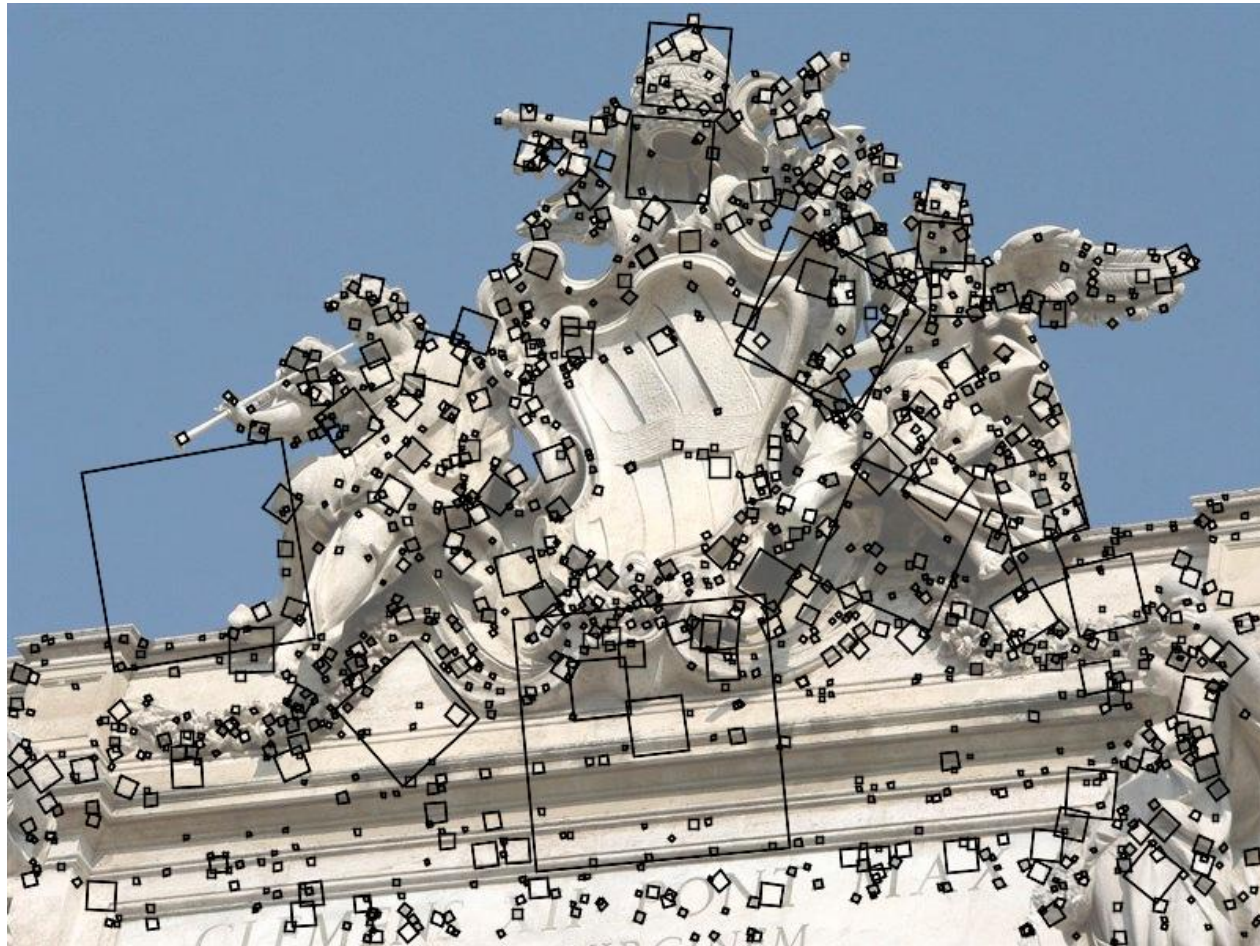
Photo Explorer

Scene reconstruction



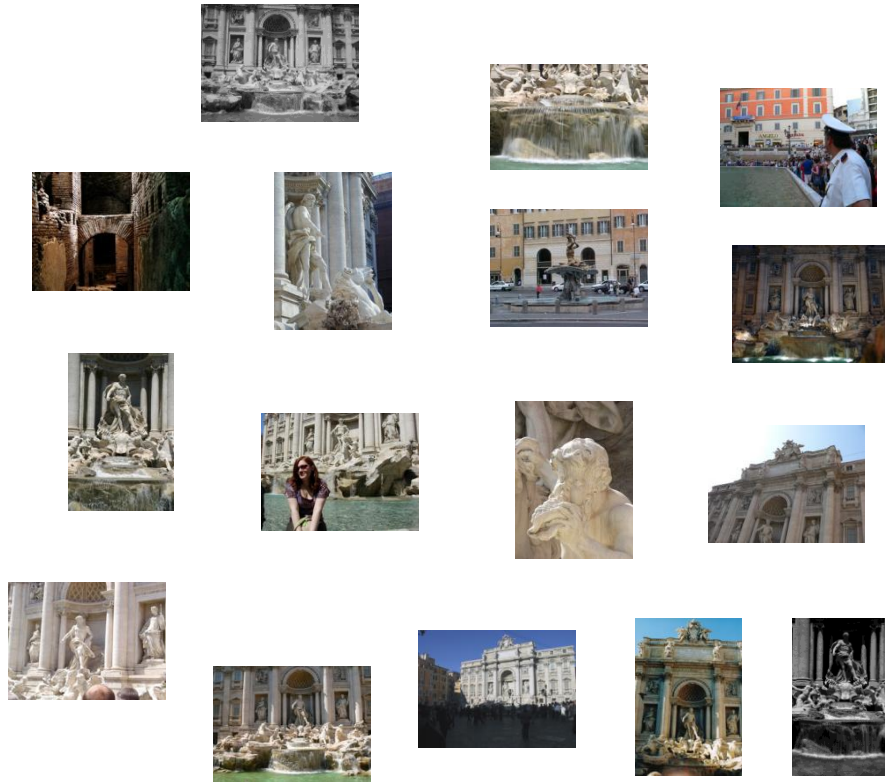
Feature detection

Detect features using SIFT [Lowe, IJCV 2004]



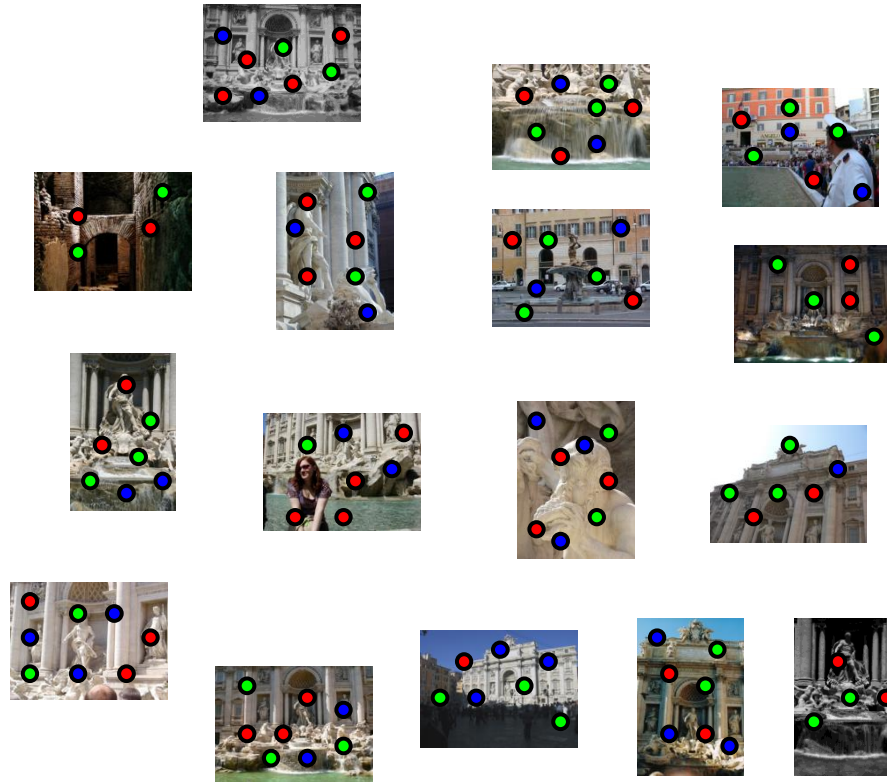
Feature detection

Detect features using SIFT [Lowe, IJCV 2004]



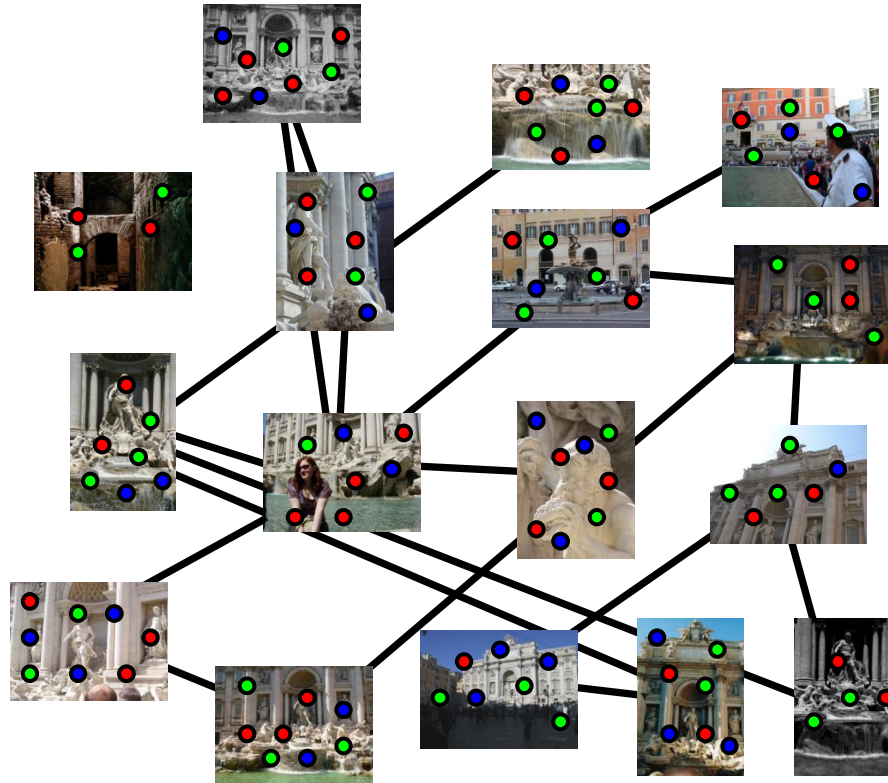
Feature detection

Detect features using SIFT [Lowe, IJCV 2004]



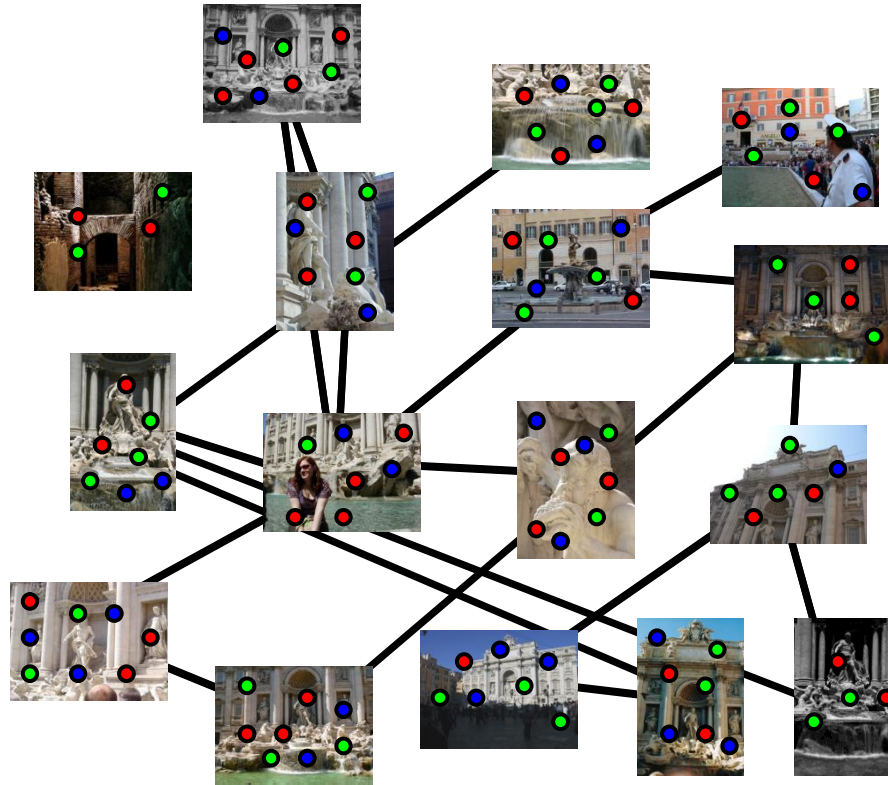
Feature matching

Match features between each pair of images

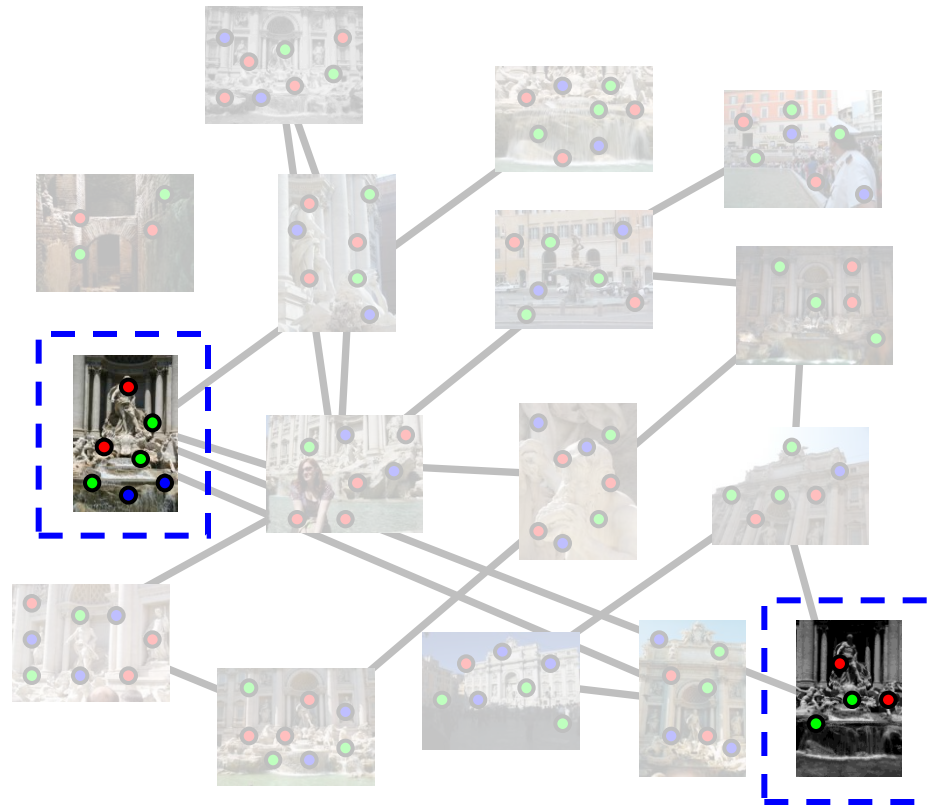


Feature matching

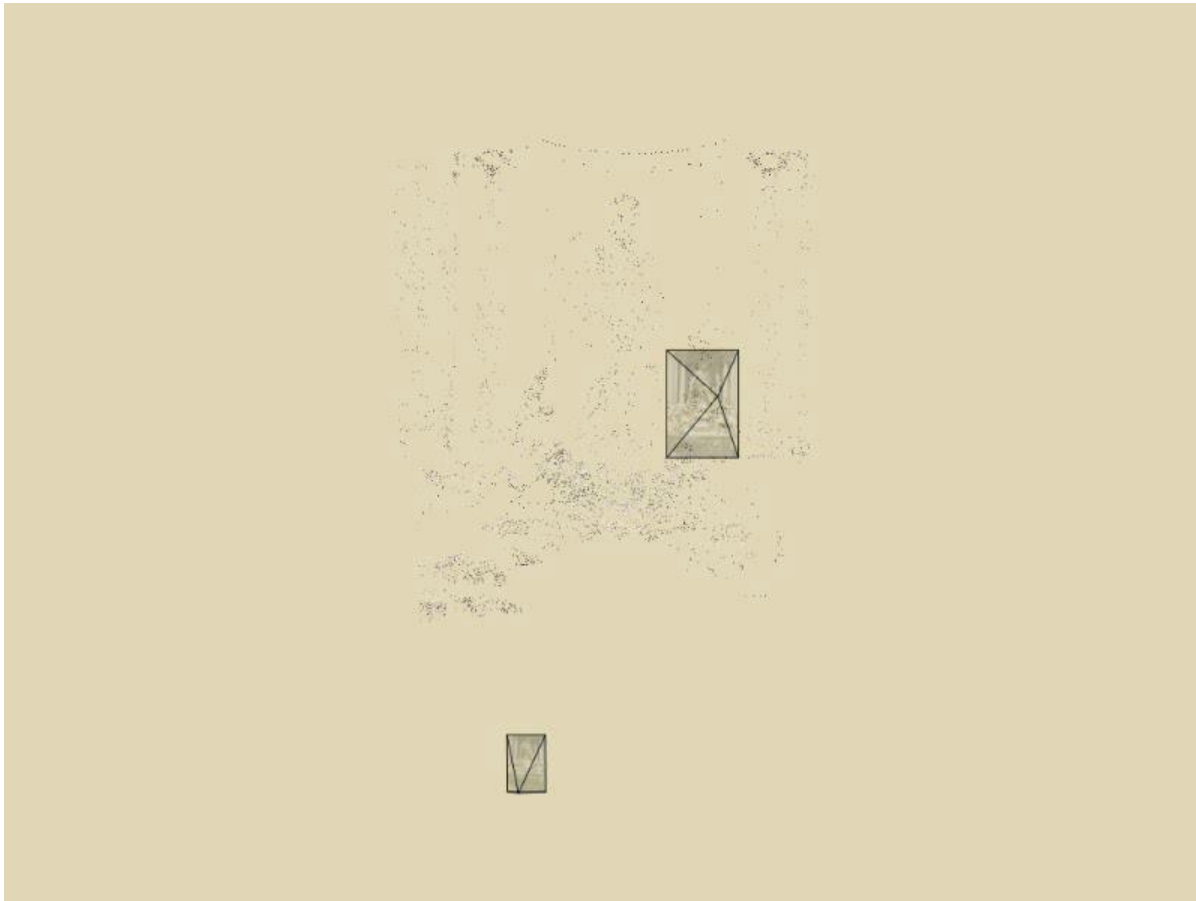
Refine matching using RANSAC [Fischler & Bolles 1987] to be consistent with a 3D rigid motion



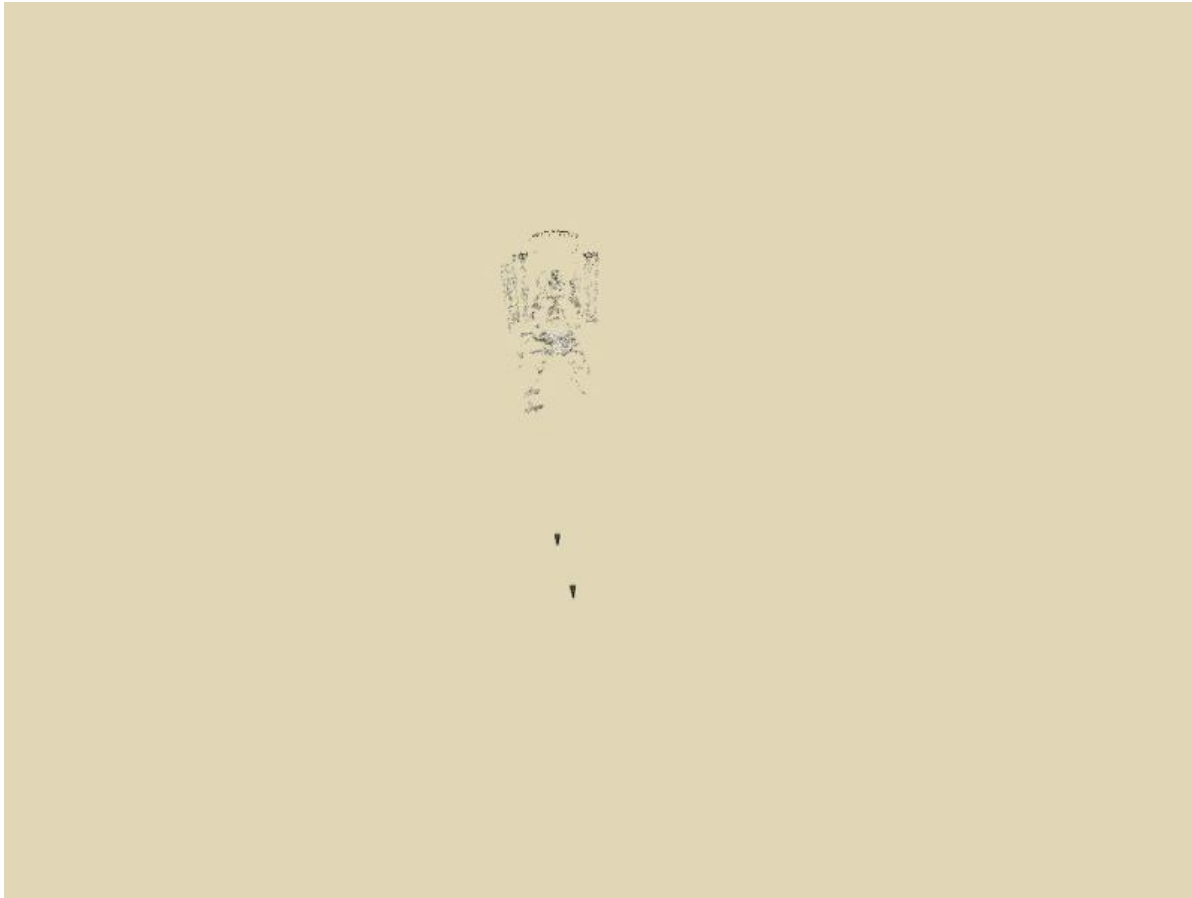
Incremental structure from motion



Incremental structure from motion



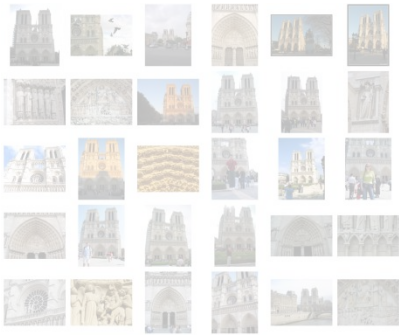
Incremental structure from motion



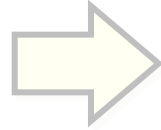
Problem size

- Trevi Fountain collection
 - 466 input photos
 - + > 100,000 3D points
 - = very large optimization problem

Photo Tourism overview



Input photographs



Scene
reconstruction

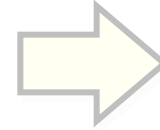
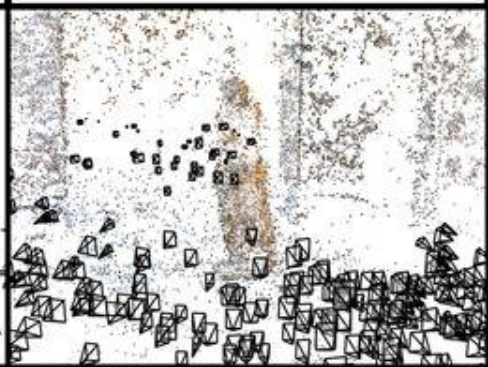
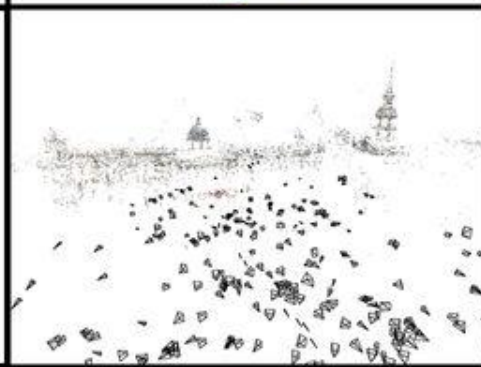
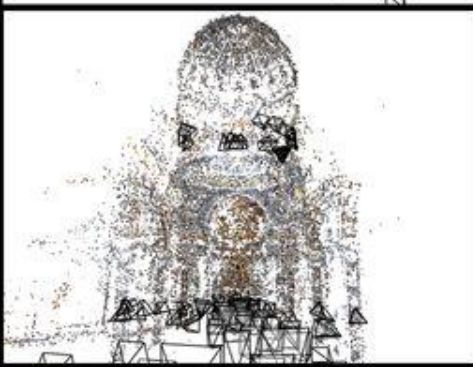
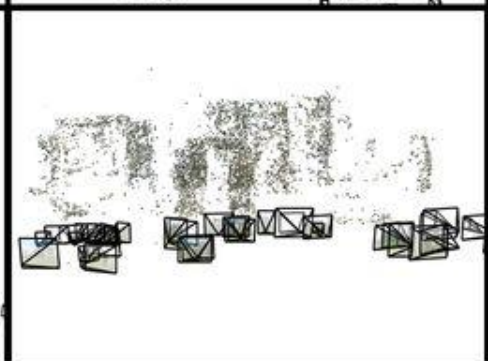
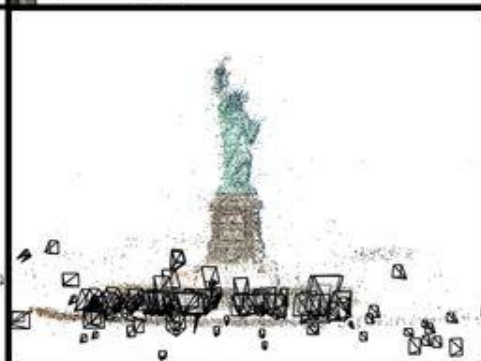
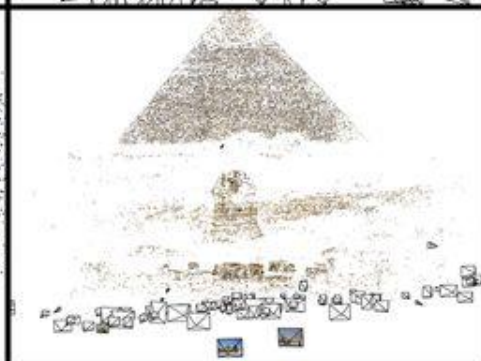
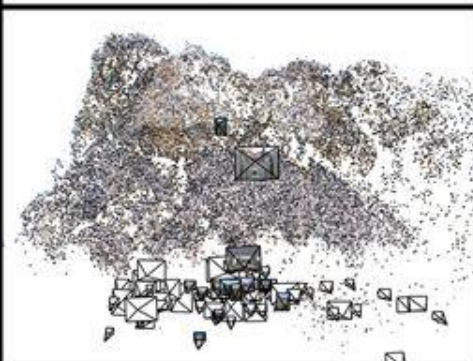
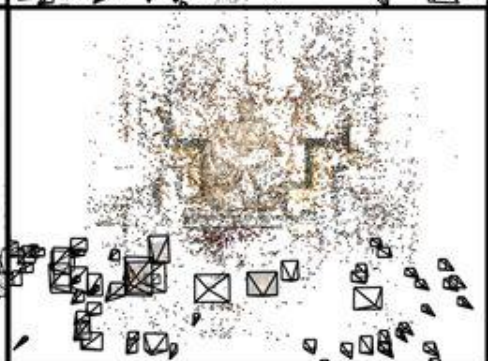
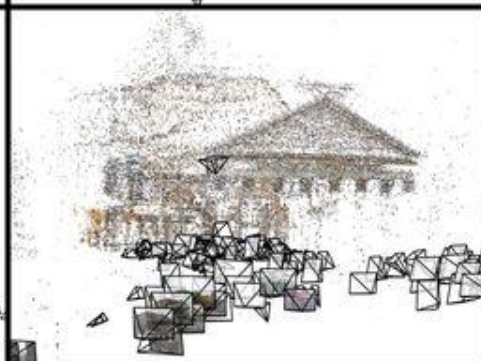
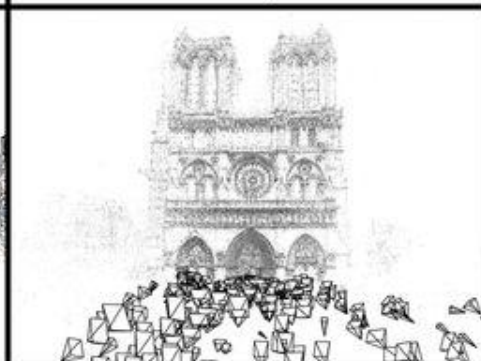
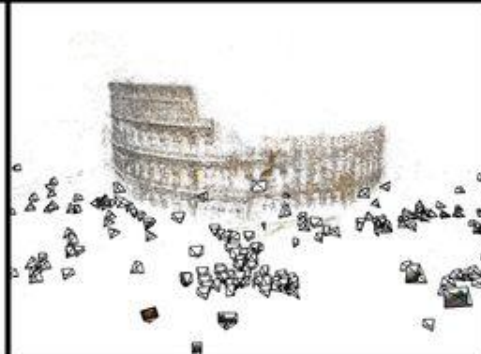


Photo Explorer

Photo Tourism Video



More information

- Paper: “Photo Tourism: Exploring photo collections in 3D,”
http://phototour.cs.washington.edu/Photo_Tourism.pdf
- <http://phototour.cs.washington.edu>
- <http://photosynth.net>
- <http://grail.cs.washington.edu/rome>