

Announcements

Midterm: out by the end of the week
Project 1 artifact winners

Global Alignment and Structure from Motion

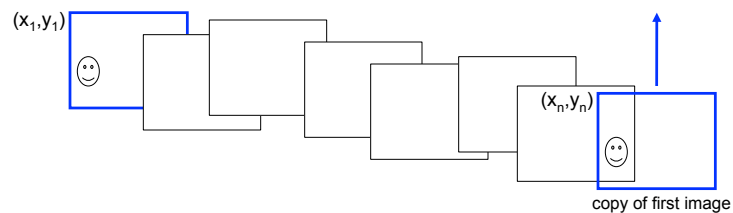


(Adapted from slides by Noah Snavely)

Today's Readings

- Photo Tourism (Snavely et al., SIGGRAPH 2006)
– http://phototour.cs.washington.edu/Photo_Tourism.pdf

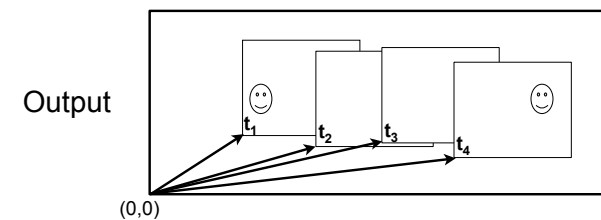
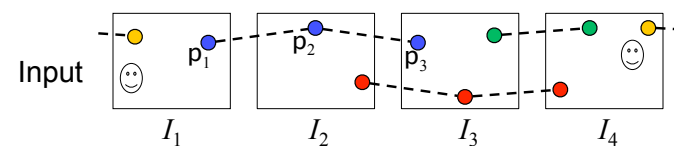
Problem: Drift



Solution

- add another copy of first image at the end
- this gives a constraint: $y_n = y_1$
- there are a bunch of ways to solve this problem
 - add displacement of $(y_1 - y_n)/(n - 1)$ to each image after the first
 - compute a global warp: $y' = y + ax$
 - run a big optimization problem, incorporating this constraint
 - » best solution, but more complicated
 - » known as “bundle adjustment”

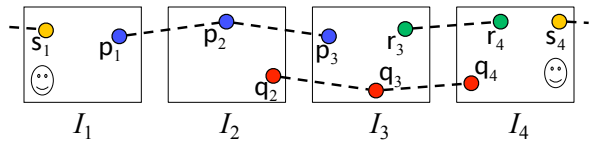
Global optimization



We want to estimate t_i . We know p_i

- how do t_i relate to p_i ?

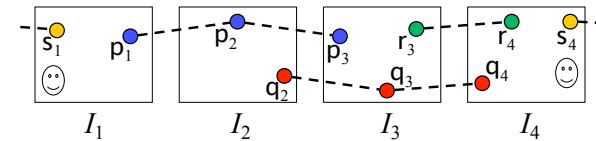
Global optimization



Recipe

1. Identify the **variables** you want to estimate
 - in our case: t_i
2. Identify a set of **objectives** you want to satisfy
 - in our case: $p_i - p_j = t_i - t_j$ and similar for q, r, s
3. Define an **objective function** F over these variables, whose minimum occurs at the “answer” for these variables
4. Find the **minimum** of F

Objective function

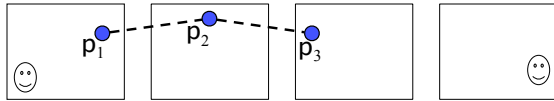


Objective function

$$\sum_{i=2}^3 \|(p_i - p_{i-1}) - (t_i - t_{i-1})\|^2$$

+ similar terms for q, r, s

Objective function



Objective function $\sum_{i=2}^3 \|(p_i - p_{i-1}) - (t_i - t_{i-1})\|^2$

Matrix form

$$\begin{bmatrix} -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \\ x_3 \\ y_3 \\ x_4 \\ y_4 \end{bmatrix} = \begin{bmatrix} u_2 - u_1 \\ v_2 - v_1 \\ u_3 - u_2 \\ v_3 - v_2 \end{bmatrix}$$

$t_i = (x_i, y_i)$ $p_i = (u_i, v_i)$

Objective Function

Adding in q, r, s give a larger matrix equation

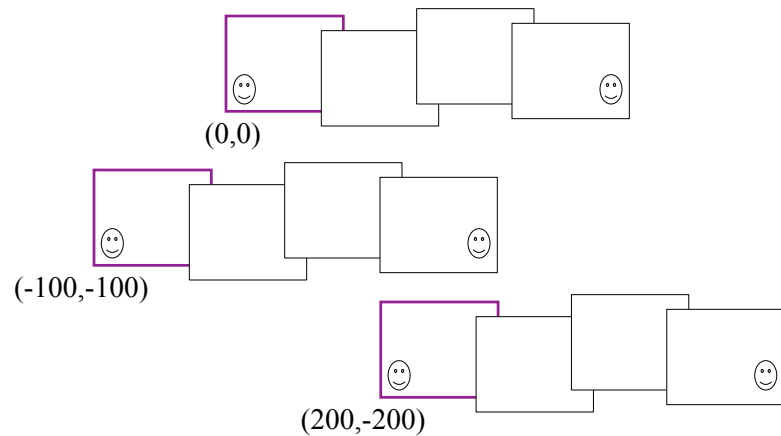
$$\begin{bmatrix} -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ & & & \vdots & & & & \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \\ x_3 \\ y_3 \\ x_4 \\ y_4 \end{bmatrix} = \begin{bmatrix} u_2 - u_1 \\ v_2 - v_1 \\ u_3 - u_2 \\ v_3 - v_2 \\ \vdots \end{bmatrix}$$

A **x** **b**

Defines a least squares problem: minimize $\|\mathbf{Ax} - \mathbf{b}\|$

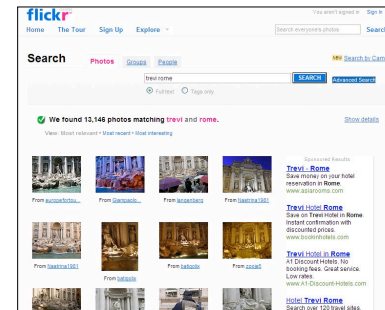
- Solution: $\hat{\mathbf{x}} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b}$
- Problem: there are multiple solutions for $\hat{\mathbf{x}}$! ($\det(\mathbf{A}^T \mathbf{A}) = 0$)
- We can add a global offset to a solution $\hat{\mathbf{x}}$ and get the same error

Ambiguity in the solution



- Each of these solutions has the same error
- Called the gauge ambiguity
- Solution: fix the translation of one image ($\mathbf{t}_1 = (0,0)$)

Structure from motion



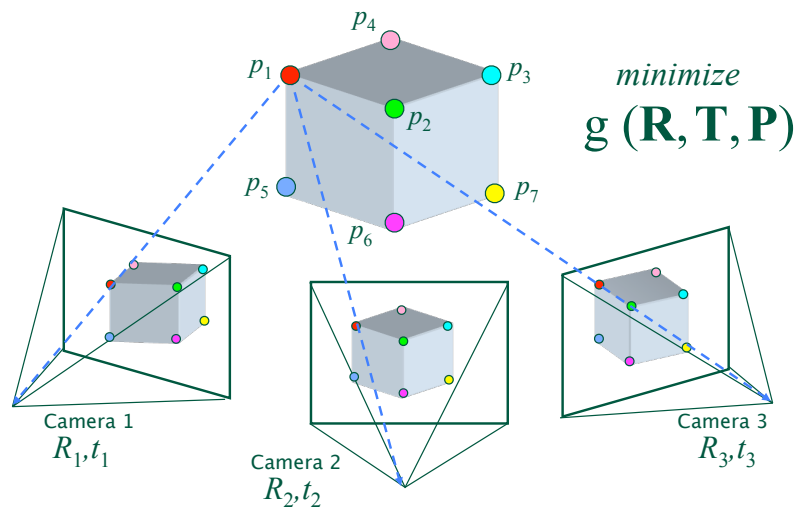
Images on the Internet



Computed 3D structure

Structure from motion

aka "bundle adjustment" (texts: [Zisserman](#); [Faugeras](#))



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:

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

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 optimization (*bundle adjustment*)

- Levenberg-Marquardt is a popular algorithm
- http://en.wikipedia.org/wiki/Levenberg-Marquardt_algorithm

Good code online

- Bundler: <http://phototour.cs.washington.edu/bundler/>
- Multicore: <http://grail.cs.washington.edu/projects/mcba/>

Photo Tourism



Photo Tourism

Microsoft

Exploring photo collections in 3D

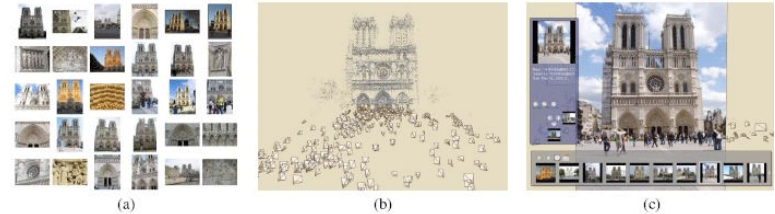


Photo tourism video: <http://www.youtube.com/watch?v=5Ji84zb2r8s>

Microsoft Photosynth: <http://photosynth.net/>

Google Photo Tours: <http://maps.google.com/phototours>

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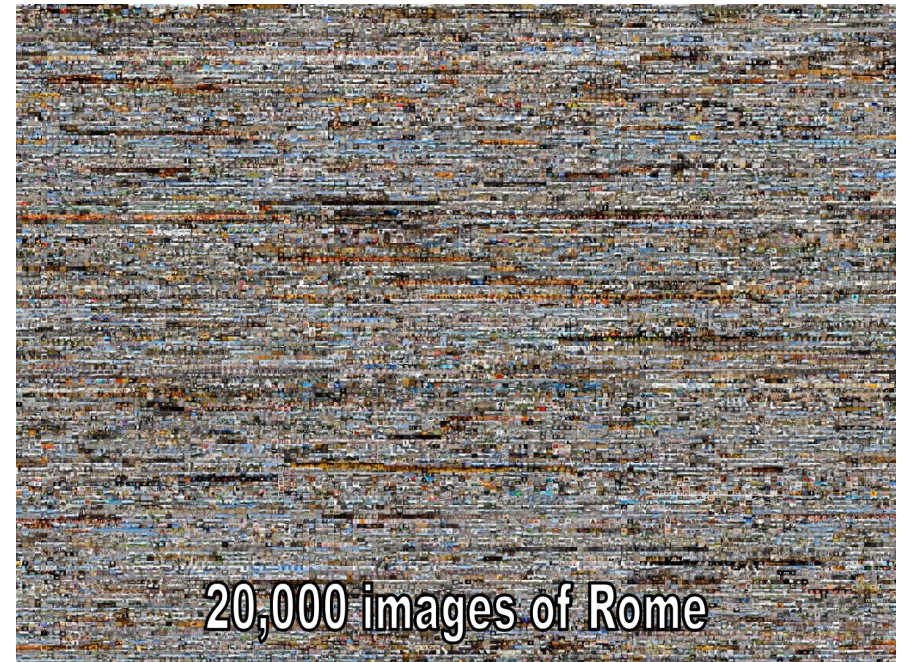
rome trevi fountain

ALL SIZES



The wife and I at the Trevi fountain in 2006

Would you like to comment?





Reconstructing Rome

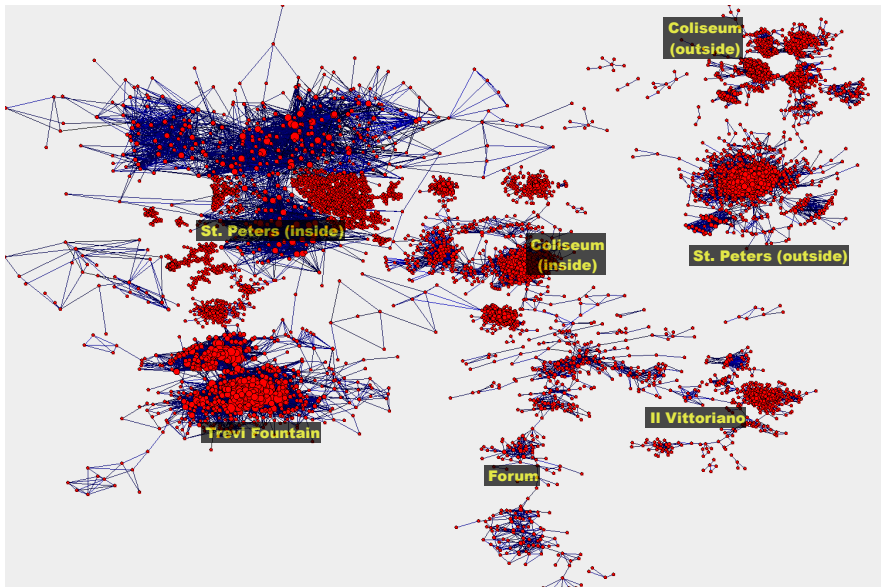
In a day...

From ~1M images

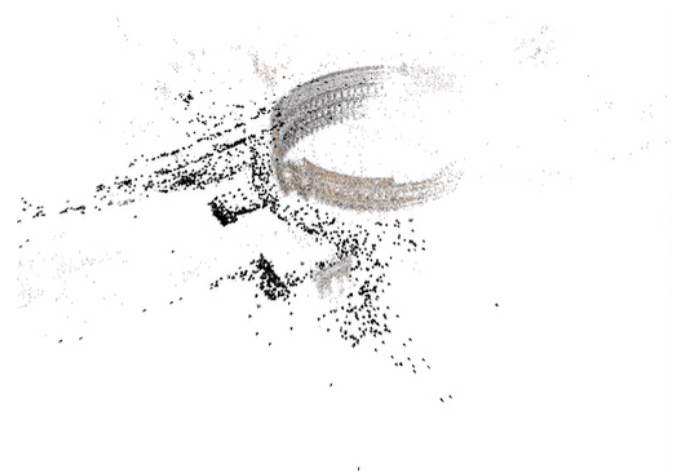
Using ~1000 cores

Sameer Agarwal, Noah Snavely, Rick Szeliski, Steve Seitz

<http://grail.cs.washington.edu/rome>



Rome 150K: Colosseum



Rome: St. Peters



Venice (250K images)



Venice: Canal



Dubrovnik



More info

- Rome-in-a-day page
 - <http://grail.cs.washington.edu/rome>