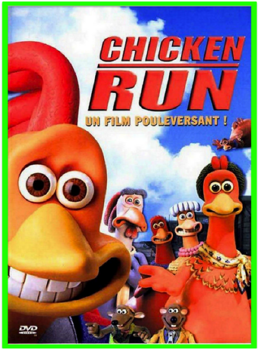
Homography (Part I)

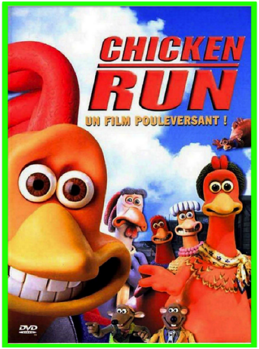
What Transformation Really Happened To My DVD?



$T?$

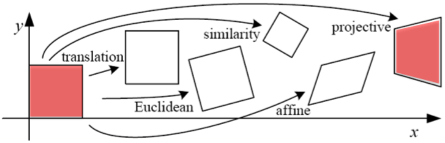
What Transformation Really Happened To My DVD?

- A rectangle goes to **quadrilateral**



$T?$

2D Image Transformations



Transformation	Matrix	# DoF	Preserves	Icon
translation	$\begin{bmatrix} \boldsymbol{I} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	2	orientation	
rigid (Euclidean)	$\begin{bmatrix} \boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	3	lengths	
similarity	$\begin{bmatrix} s\boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	4	angles	
affine	$\begin{bmatrix} \boldsymbol{A} \end{bmatrix}_{2\times 3}$	6	parallelism	
projective	$\begin{bmatrix} \tilde{\boldsymbol{H}} \end{bmatrix}_{3\times 3}$	8	straight lines	

- These transformations are a nested set of groups
- Closed under composition and inverse is a member

[source: R. Szeliski]

Projective Transformations

- Homography:

$$w \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

Properties:

- Origin does not necessarily map to origin
- Lines map to lines
- Parallel lines do not necessarily remain parallel
- Ratios are **not** preserved
- Closed under composition
- Rectangle goes to quadrilateral
- Affine transformation is a special case, where $g = h = 0$ and $i = 1$

[Source: N. Snavely, slide credit: R. Urtasun]

What Transformation Really Happened to My DVD?

For **planar** objects:

- Viewpoint change for planar objects is a **homography**
- Affine transformation **approximates** viewpoint change for planar objects that are far away from camera

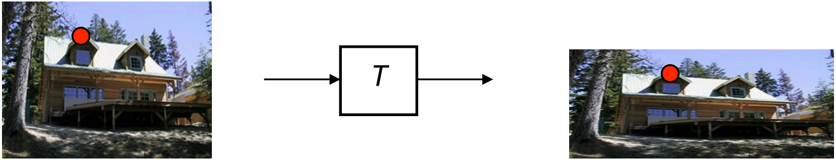
What Transformation Happened to My DVD?

- Why should I care about homography?
- Now that I care, how should I estimate it?
- I want to understand the geometry behind homography. That is, why aren't parallel lines mapped to parallel lines in oblique viewpoints? How did we get that equation for computing the homography?

Homography

- Why should I care about homography? **Let's answer this first**
- Now that I care, how should I estimate it?
- I want to understand the geometry behind homography. That is, why aren't parallel lines mapped to parallel lines in oblique viewpoints? How did we get that equation for computing the homography?

Warping an Image with a Global Transformation



p = (x,y) **p'** = (x',y')

- Transformation T is a coordinate-changing machine:

$$[x', y'] = T(x, y)$$

- What does it mean that T is global?
  - Is the same for any point p
  - Can be described by just a few numbers (parameters)

[Source: N. Snavely, slide credit: R. Urtasun]

Warping an Image with a Global Transformation

- Example of warping for different transformations:

translation

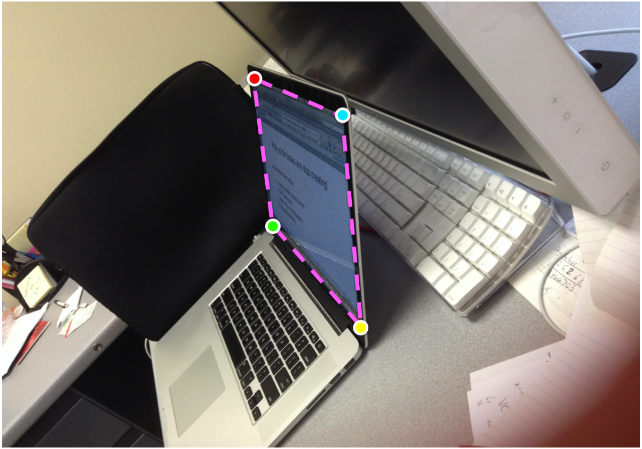
rotation

aspect

affine

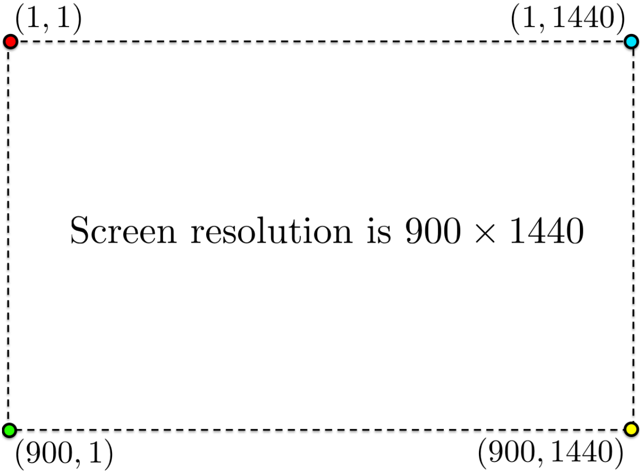
perspective

Application 1: a Little Bit of CSI



- We want to transform the picture (plane) inside these 4 points into a rectangle (laptop screen)

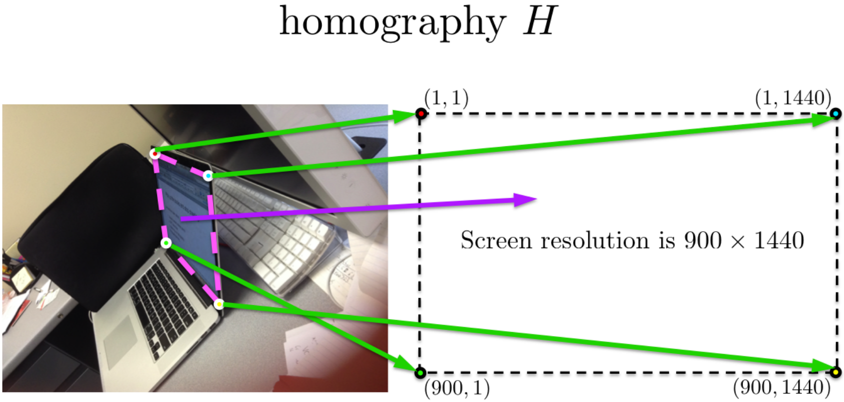
Application 1: a Little Bit of CSI



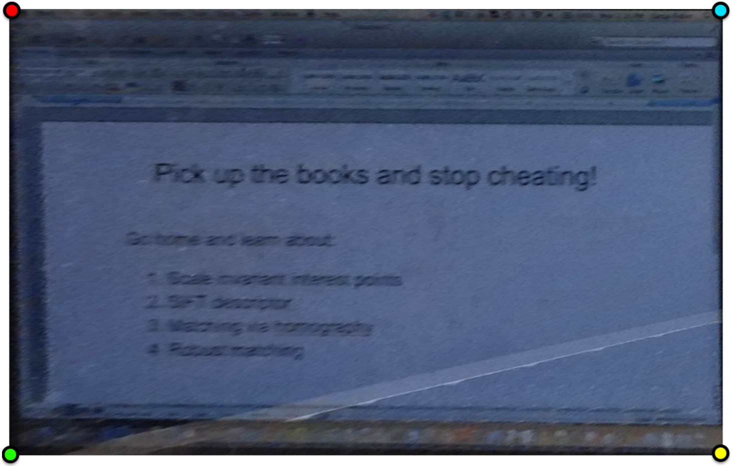
- We want it to look like this. How can we do this?

Application 1: a Little Bit of CSI

- A transformation that maps a projective plane (a quadrilateral) to another projective plane (another quadrilateral, in this case a rectangle) is a homography



Application 1: a Little Bit of CSI



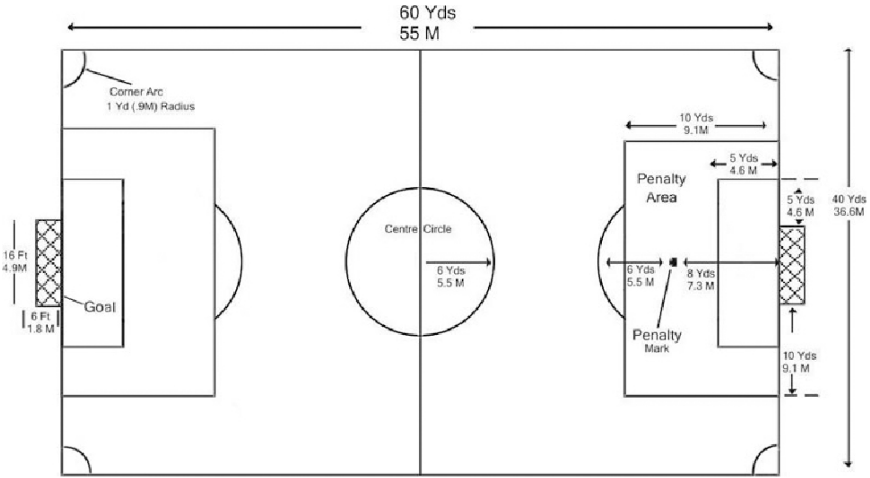
- If we compute the homography and warp the image according to it, we get this

Application 2: How Much do Soccer Players Run?

Application 2: How Much do Soccer Players Run?

- How many meters did this player run?

Application 2: How Much do Soccer Players Run?

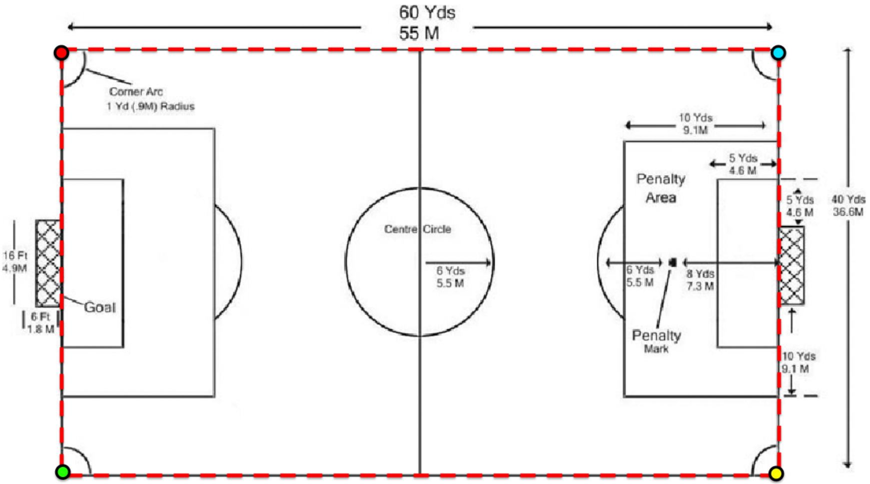


- Field is planar. We know its dimensions (look on Wikipedia).

Application 2: How Much do Soccer Players Run?

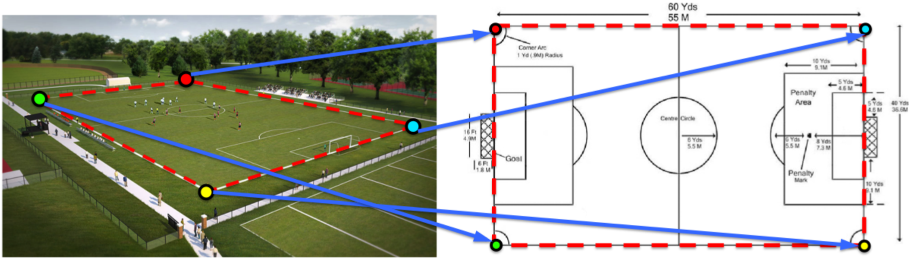
- Let's take the 4 corner points of the field

Application 2: How Much do Soccer Players Run?



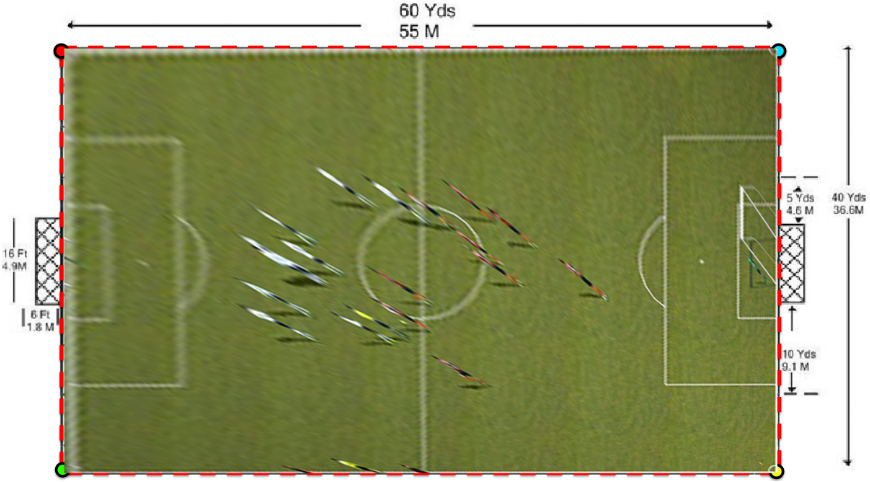
- We need to compute a homography that maps them to these 4 corners

Application 2: How Much do Soccer Players Run?

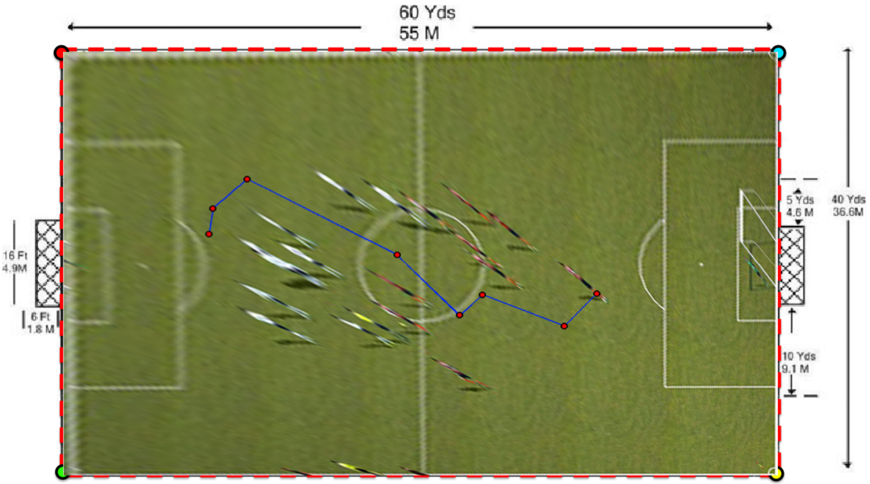


- We need to compute a homography that maps the 4 corners. Any other point from this plane (the field) also maps to the right with the same homography

Application 2: How Much do Soccer Players Run?

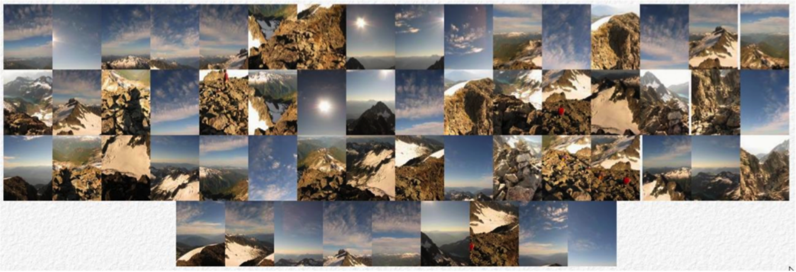


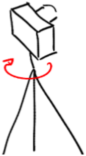
Application 2: How Much do Soccer Players Run?



- We can now also transform the player's trajectory → and we have it in meters!

Application 3: Panorama Stitching

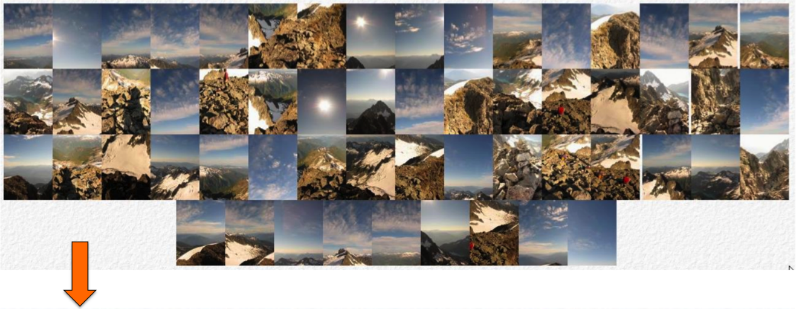




Take a tripod, rotate camera and take pictures

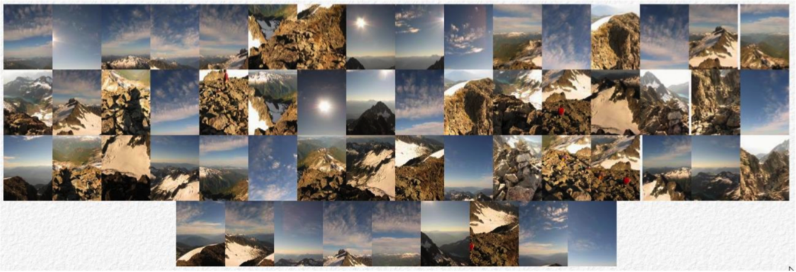
[Source: Fernando Flores-Mangas]

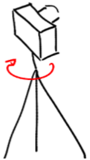
Application 3: Panorama Stitching

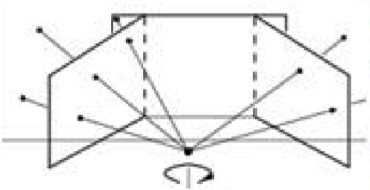


[Source: Fernando Flores-Mangas]

Application 3: Panorama Stitching







- Each pair of images is related by homography! **If we also moved the camera, this wouldn't be true** (next class) [Source: Fernando Flores-Mangas]

Application 3: Panorama Stitching

- To do panorama stitching, we need to:
  - Match points between pairs of images I and J
  - Compute a transformation between the between matches in I and J : a homography
  - Do it robustly (RANSAC)
  - Warp the first image to the second using the estimated homography
- Apart from the last point, this is exactly the same procedure as for the problem of matching planar objects across viewpoints
- So this should motivate the **why do I care part** of the homographies

Homography

- Why should I care about homography?
- Now that I care, how should I estimate it? **Let's do this now**
- I want to understand the geometry behind homography. That is, why aren't parallel lines mapped to parallel lines in oblique viewpoints? How did we get that equation for computing the homography?

Solving for Homographies

- Projective mapping between any two projection planes with the same centre of projection
- Let (x_i, y_i) be a point on the reference (model) image, and (x'_i, y'_i) its match in the test image
- A homography H maps (x_i, y_i) to (x'_i, y'_i):

$$\begin{bmatrix} ax'_i \\ ay'_i \\ a \end{bmatrix} = \begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ h_{20} & h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix}$$

Solving for Homographies

- Projective mapping between any two projection planes with the same centre of projection
- Let (x_i, y_i) be a point on the reference (model) image, and (x_i', y_i') its match in the test image
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- We can get rid of that a on the left (we need a 2D image):

$$\begin{aligned} x_i' &= \frac{h_{00}x_i + h_{01}y_i + h_{02}}{h_{20}x_i + h_{21}y_i + h_{22}} \\ y_i' &= \frac{h_{10}x_i + h_{11}y_i + h_{12}}{h_{20}x_i + h_{21}y_i + h_{22}} \end{aligned}$$

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- Hmmmm... Can I still rewrite this into a linear system in h?

Solving for homographies

- From:

$$
\begin{aligned}
x_i' &= \frac{h_{00}x_i + h_{01}y_i + h_{02}}{h_{20}x_i + h_{21}y_i + h_{22}} \\
y_i' &= \frac{h_{10}x_i + h_{11}y_i + h_{12}}{h_{20}x_i + h_{21}y_i + h_{22}}
\end{aligned}
$$

- We can easily get this:

$$
\begin{aligned}
x_i'(h_{20}x_i + h_{21}y_i + h_{22}) &= h_{00}x_i + h_{01}y_i + h_{02} \\
y_i'(h_{20}x_i + h_{21}y_i + h_{22}) &= h_{10}x_i + h_{11}y_i + h_{12}
\end{aligned}
$$

- Rewriting it a little:

$$
\begin{aligned}
h_{00}x_i + h_{01}y_i + h_{02} - x_i'(h_{20}x_i + h_{21}y_i + h_{22}) &= 0 \\
h_{10}x_i + h_{11}y_i + h_{12} - y_i'(h_{20}x_i + h_{21}y_i + h_{22}) &= 0
\end{aligned}
$$

Solving for homographies

- We can re-write these equations:

$$\begin{aligned} h_{00}x_i + h_{01}y_i + h_{02} - x_i'(h_{20}x_i - h_{21}y_i - h_{22}) &= 0 \\ h_{10}x_i + h_{11}y_i + h_{12} - y_i'(h_{20}x_i - h_{21}y_i - h_{22}) &= 0 \end{aligned}$$

- as a linear system!

$$\begin{bmatrix} x_i & y_i & 1 & 0 & 0 & 0 & -x_i'x_i & -x_i'y_i & -x_i' \\ 0 & 0 & 0 & x_i & y_i & 1 & -y_i'x_i & -y_i'y_i & -y_i' \end{bmatrix} \begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Solving for homographies

- Taking all our matches into account:

$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1 x_1 & -x'_1 y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1 x_1 & -y'_1 y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_n x_n & -x'_n y_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_n x_n & -y'_n y_n & -y'_n \end{bmatrix}}_{\substack{\mathbf{A} \\ 2n \times 9}} \underbrace{\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix}}_{\substack{\mathbf{h} \\ 9}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}}_{\substack{\mathbf{0} \\ 2n}}$$

Solving for homographies

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$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1x_1 & -x'_1y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1x_1 & -y'_1y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_nx_n & -x'_ny_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_nx_n & -y'_ny_n & -y'_n \end{bmatrix}}_{\substack{\mathbf{A} \\ 2n \times 9}} \underbrace{\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix}}_{\substack{\mathbf{h} \\ 9}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}}_{\substack{\mathbf{0} \\ 2n}}$$

- This defines a least squares problem:

$$\min_{\mathsf{h}} ||\mathsf{Ah}||_2^2$$

Solving for homographies

- Taking all our matches into account:

$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1 x_1 & -x'_1 y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1 x_1 & -y'_1 y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_n x_n & -x'_n y_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_n x_n & -y'_n y_n & -y'_n \end{bmatrix}}_{\substack{\mathbf{A} \\ 2n \times 9}} \underbrace{\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix}}_{\substack{\mathbf{h} \\ 9}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}}_{\substack{\mathbf{0} \\ 2n}}$$

- This defines a least squares problem:

$$\min_{\mathrm{h}} ||\mathrm{Ah}||_2^2$$

- Can we use Moore-Penrose like last time?

Solving for homographies Pt.2

$$\underset{\substack{2n \times 9}}{\mathbf{A}}\;\; \begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1x_1 & -x'_1y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1x_1 & -y'_1y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_nx_n & -x'_ny_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_nx_n & -y'_ny_n & -y'_n \end{bmatrix} \begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}$$

$$\underset{9}{\mathbf{h}} \qquad \underset{2n}{\mathbf{0}}$$

- This defines a constrained least squares problem:

$$\min_{\mathrm{h}} E = ||\mathrm{Ah}||_2^2$$

$$s.t. \qquad ||\mathrm{h}||_2 = 1 \tag{1}$$

$$\tag{2}$$

- Since h is only defined up to scale, solve for unit vector

Solving for homographies Pt.2

$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1x_1 & -x'_1y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1x_1 & -y'_1y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_nx_n & -x'_ny_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_nx_n & -y'_ny_n & -y'_n \end{bmatrix}}_{\substack{\mathbf{A} \\ 2n \times 9}} \underbrace{\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix}}_{\substack{\mathbf{h} \\ 9}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}}_{\substack{\mathbf{0} \\ 2n}}$$

- This defines a constrained least squares problem:

$$\begin{aligned} & \min_{\mathrm{h}} E = ||\mathrm{Ah}||_2^2 \\ s.t. \quad & ||\mathrm{h}||_2 = 1 \end{aligned} \qquad \begin{matrix} (1) \\ (2) \end{matrix}$$

- Since h is only defined up to scale, solve for unit vector
- This is an example of “Constrained” Optimization

Solving for homographies Pt.2

$$\underset{2n \times 9}{\mathbf{A}}\left[\begin{array}{ccccccccc} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1 x_1 & -x'_1 y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1 x_1 & -y'_1 y_1 & -y'_1 \\ & & & & & \vdots & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_n x_n & -x'_n y_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_n x_n & -y'_n y_n & -y'_n \end{array}\right] \underset{9}{\mathbf{h}}\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix} = \underset{2n}{\mathbf{0}}\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}$$

- This defines a constrained least squares problem:

$$\begin{aligned} & \min_{\mathrm{h}} E = ||\mathrm{Ah}||_2^2 \\ s.t. \quad & ||\mathrm{h}||_2 = 1 \qquad (1) \\ & \qquad (2) \end{aligned}$$

- Since h is only defined up to scale, solve for unit vector
- This is an example of “Constrained” Optimization
- Method of Lagrange Multipliers

Solving for homographies Pt.2

$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1 x_1 & -x'_1 y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1 x_1 & -y'_1 y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_n x_n & -x'_n y_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_n x_n & -y'_n y_n & -y'_n \end{bmatrix}}_{\substack{\mathbf{A} \\ 2n \times 9}} \underbrace{\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix}}_{\substack{\mathbf{h} \\ 9}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}}_{\substack{\mathbf{0} \\ 2n}}$$

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- Since h is only defined up to scale, solve for unit vector
- This is an example of “Constrained” Optimization
- Method of Lagrange Multipliers
- Solution: $\hat{\mathrm{h}}$ = eigenvector of $\mathrm{A}^T\mathrm{A}$ with smallest eigenvalue

Solving for homographies Pt.2

$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1'x_1 & -x_1'y_1 & -x_1' \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y_1'x_1 & -y_1'y_1 & -y_1' \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x_n'x_n & -x_n'y_n & -x_n' \\ 0 & 0 & 0 & x_n & y_n & 1 & -y_n'x_n & -y_n'y_n & -y_n' \end{bmatrix}}_{\substack{\mathbf{A} \\ 2n \times 9}} \underbrace{\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix}}_{\substack{\mathbf{h} \\ 9}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}}_{\substack{\mathbf{0} \\ 2n}}$$

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- This is an example of "Constrained" Optimization
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- Solution: $\hat{\mathrm{h}}$ = eigenvector of $\mathrm{A}^T\mathrm{A}$ with smallest eigenvalue
- How many matches do I need to estimate H?

Solving for homographies Pt.2

$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1 x_1 & -x'_1 y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1 x_1 & -y'_1 y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_n x_n & -x'_n y_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_n x_n & -y'_n y_n & -y'_n \end{bmatrix}}_{\substack{\mathbf{A} \\ 2n \times 9}} \underbrace{\begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix}}_{\substack{\mathbf{h} \\ 9}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}}_{\substack{\mathbf{0} \\ 2n}}$$

- This defines a constrained least squares problem:

$$\min_{\mathrm{h}} E = ||\mathrm{Ah}||_2^2 \tag{1}$$

$$s.t. \qquad ||\mathrm{h}||_2 = 1 \tag{2}$$

- Since h is only defined up to scale, solve for unit vector
- This is an example of "Constrained" Optimization
- Method of Lagrange Multipliers
- Solution: $\hat{\mathrm{h}}$ = eigenvector of $\mathrm{A}^T\mathrm{A}$ with smallest eigenvalue
- How many matches do I need to estimate H?
- Works with 4 or more matches, only 8 unknowns!

[Source: R. Urtasun]

Image Alignment Algorithm: Homography

Given images I and J

1. Compute image features for I and J
2. Match features between I and J

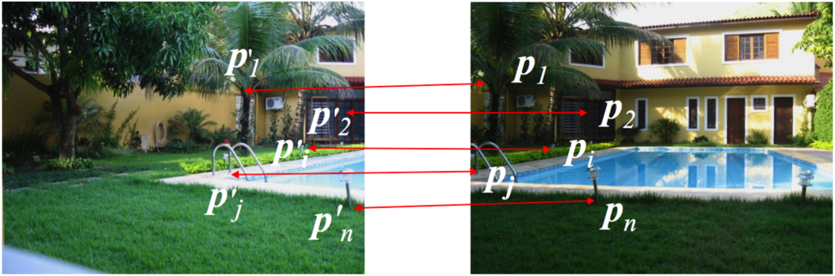
Image Alignment Algorithm: Homography

Given images I and J

1. Compute image features for I and J
2. Match features between I and J
3. Compute **homography** transformation A between I and J (with RANSAC)

[Source: N. Snavely]

Panorama Stitching: Example 1



- Compute the matches

[Source: R. Queiroz Feitosa]

Panorama Stitching: Example 1

- Estimate the homography and warp

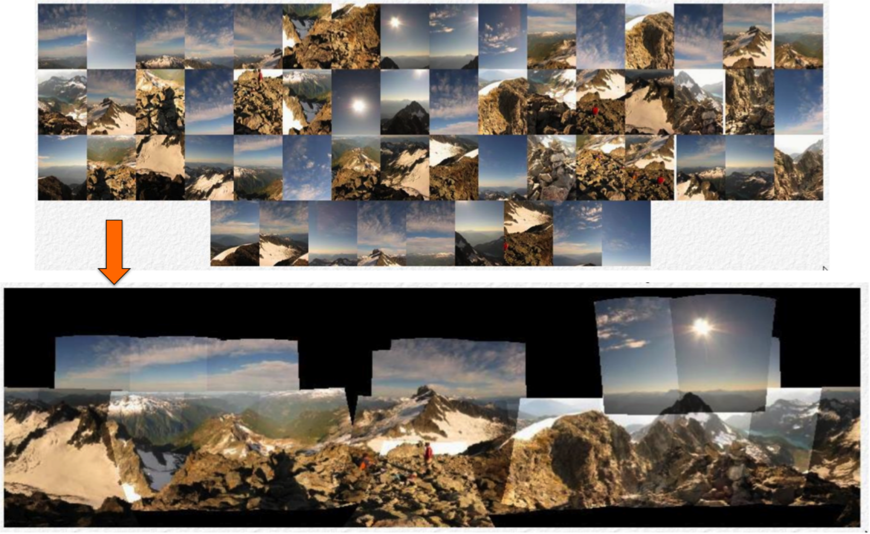
[Source: R. Queiroz Feitosa]

Panorama Stitching: Example 1

- Stitch

[Source: R. Queiroz Feitosa]

Panorama Stitching: Example 2



[Source: Fernando Flores-Mangas]

Panorama Stitching: Example 2

[Source: Fernando Flores-Mangas]

Panorama Stitching: Example 2

Laplacian Pyramid Blending ⇓ seams not visible anymore

(Brown & Lowe ; ICCV 2003) google " Lowe Brown Autostitch "

[Source: Fernando Flores-Mangas]