Image homographies
Course announcements

• Homework 2 was posted on **Friday**.
  - Due on **February 23**\(^{rd}\) at midnight.
  - Start early cause it is much larger and more difficult than homework 1.

• Homework schedule has been adjusted.
  - Homeworks are due on and are released on Fridays.

• Posting code on Piazza.
Overview of today’s lecture

- Motivation: panoramas.
- Back to warping: image homographies.
- Computing with homographies.
- The direct linear transform (DLT).
- Random Sample Consensus (RANSAC).
Slide credits

Most of these slides were adapted from:

- Kris Kitani (15-463, Fall 2016).
- Noah Snavely (Cornell).
Motivation for image alignment: panoramas.
How do you create a panorama?

Panorama: an image of (near) 360° field of view.
How do you create a panorama?

Panorama: an image of (near) 360° field of view.

1. Use a very wide-angle lens.
Wide-angle lenses

Fish-eye lens: can produce (near) hemispherical field of view.

What are the pros and cons of this?
How do you create a panorama?

Panorama: an image of (near) $360^\circ$ field of view.

1. Use a very wide-angle lens.
   - Pros: Everything is done optically, single capture.
   - Cons: Lens is super expensive and bulky, lots of distortion (can be dealt-with in post).

Any alternative to this?
How do you create a panorama?

Panorama: an image of (near) $360^\circ$ field of view.

1. Use a very wide-angle lens.
   • Pros: Everything is done optically, single capture.
   • Cons: Lens is super expensive and bulky, lots of distortion (can be dealt-with in post).

2. Capture multiple images and combine them.
Panoramas from image stitching

1. Capture multiple images from different viewpoints.

2. Stitch them together into a virtual wide-angle image.
How do we stitch images from different viewpoints?

Will standard stitching work?
1. Translate one image relative to another.
2. (Optionally) find an optimal seam.
How do we stitch images from different viewpoints?

Will standard stitching work?
1. Translate one image relative to another.
2. (Optionally) find an optimal seam.

Translation-only stitching is not enough to mosaic these images.
How do we stitch images from different viewpoints?

What else can we try?
How do we stitch images from different viewpoints?

Use image homographies.
Back to warping: image homographies
Classification of 2D transformations

<table>
<thead>
<tr>
<th>Name</th>
<th>Matrix</th>
<th># D.O.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>translation</td>
<td>$\begin{bmatrix} I &amp; t \end{bmatrix}_{2\times3}$</td>
<td>2</td>
</tr>
<tr>
<td>rigid (Euclidean)</td>
<td>$\begin{bmatrix} R &amp; t \end{bmatrix}_{2\times3}$</td>
<td>3</td>
</tr>
<tr>
<td>similarity</td>
<td>$\begin{bmatrix} sR &amp; t \end{bmatrix}_{2\times3}$</td>
<td>4</td>
</tr>
<tr>
<td>affine</td>
<td>$\begin{bmatrix} A \end{bmatrix}_{2\times3}$</td>
<td>6</td>
</tr>
<tr>
<td>projective</td>
<td>$\begin{bmatrix} \tilde{H} \end{bmatrix}_{3\times3}$</td>
<td>8</td>
</tr>
</tbody>
</table>
Classification of 2D transformations

Which kind transformation is needed to warp projective plane 1 into projective plane 2?
Classification of 2D transformations

Which kind transformation is needed to warp projective plane 1 into projective plane 2?

- A projective transformation (a.k.a. a homography).
Warping with different transformations

- Translation
- Affine
- Projective (homography)
View warping

original view  synthetic top view  synthetic side view

What are these black areas near the boundaries?
Virtual camera rotations

original view

synthetic rotations
Image rectification

two original images

rectified and stitched
Street art
Understanding geometric patterns

What is the pattern on the floor?

magnified view of floor
Understanding geometric patterns

What is the pattern on the floor?

magnified view of floor

rectified view

reconstruction from rectified view
Understanding geometric patterns

Very popular in renaissance drawings (when perspective was discovered)

rectified view of floor

reconstruction
A weird drawing

Holbein, “The Ambassadors”
A weird drawing

Holbein, “The Ambassadors”

What’s this???
A weird drawing

Holbein, “The Ambassadors”

rectified view

skull under anamorphic perspective
A weird drawing

Holbein, “The Ambassadors”

DIY: use a polished spoon to see the skull
Panoramas from image stitching

1. Capture multiple images from different viewpoints.

2. Stitch them together into a virtual wide-angle image.
When can we use homographies?
We can use homographies when...

1. ... the scene is planar; or

2. ... the scene is very far or has small (relative) depth variation → scene is approximately planar
We can use homographies when...

3. ... the scene is captured under camera rotation only (no translation or pose change)

More on why this is the case in a later lecture.
Computing with homographies
Which kind transformation is needed to warp projective plane 1 into projective plane 2?

- A projective transformation (a.k.a. a homography).
Applying a homography

1. Convert to homogeneous coordinates: \( p = \begin{bmatrix} x \\ y \end{bmatrix} \Rightarrow P = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \)

What is the size of the homography matrix?

2. Multiply by the homography matrix: \( P' = H \cdot P \)

3. Convert back to heterogeneous coordinates: \( P' = \begin{bmatrix} x' \\ y' \\ w' \end{bmatrix} \Rightarrow p' = \begin{bmatrix} x'/w' \\ y'/w' \end{bmatrix} \)
Applying a homography

1. Convert to homogeneous coordinates:
   \[ p = \begin{bmatrix} x \\ y \end{bmatrix} \Rightarrow P = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \]

   What is the size of the homography matrix?  
   Answer: 3 x 3

2. Multiply by the homography matrix:
   \[ P' = H \cdot P \]

   How many degrees of freedom does the homography matrix have?

3. Convert back to heterogeneous coordinates:
   \[ P' = \begin{bmatrix} x' \\ y' \\ w' \end{bmatrix} \Rightarrow p' = \begin{bmatrix} x' / w' \\ y' / w' \end{bmatrix} \]
Applying a homography

1. Convert to homogeneous coordinates:
   \[ p = \begin{bmatrix} x \\ y \end{bmatrix} \Rightarrow P = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \]

   What is the size of the homography matrix?  
   Answer: 3 x 3

2. Multiply by the homography matrix:
   \[ P' = H \cdot P \]

   How many degrees of freedom does the homography matrix have?  
   Answer: 8

3. Convert back to heterogeneous coordinates:
   \[ P' = \begin{bmatrix} x' \\ y' \\ w' \end{bmatrix} \Rightarrow p' = \begin{bmatrix} x'/w' \\ y'/w' \end{bmatrix} \]
Applying a homography

What is the size of the homography matrix?  Answer: 3 x 3

\[ P' = H \cdot P \]

How many degrees of freedom does the homography matrix have?  Answer: 8

How do we compute the homography matrix?
The direct linear transform (DLT)
Create point correspondences

Given a set of matched feature points \( \{p_i, p'_i\} \) find the best estimate of \( H \) such that

\[
P' = H \cdot P
\]
Determining the homography matrix

Write out linear equation for each correspondence:

\[ P' = H \cdot P \quad \text{or} \quad \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \alpha \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \]
Determining the homography matrix

Write out linear equation for each correspondence:

\[ P' = H \cdot P \text{ or } \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \alpha \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \]

Expand matrix multiplication:

\[
x' = \alpha(h_1x + h_2y + h_3)
\]

\[
y' = \alpha(h_4x + h_5y + h_6)
\]

\[1 = \alpha(h_7x + h_8y + h_9)\]
Determining the homography matrix

Write out linear equation for each correspondence:

\[ P' = H \cdot P \quad \text{or} \quad \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \alpha \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \]

Expand matrix multiplication:

\[
\begin{align*}
    x' &= \alpha(h_1x + h_2y + h_3) \\
y' &= \alpha(h_4x + h_5y + h_6) \\
    1 &= \alpha(h_7x + h_8y + h_9)
\end{align*}
\]

Divide out unknown scale factor:

\[
\begin{align*}
    x'(h_7x + h_8y + h_9) &= (h_1x + h_2y + h_3) \\
y'(h_7x + h_8y + h_9) &= (h_4x + h_5y + h_6)
\end{align*}
\]

How do you rearrange terms to make it a linear system?
\[ x'(h_7x + h_8y + h_9) = (h_1x + h_2y + h_3) \]
\[ y'(h_7x + h_8y + h_9) = (h_4x + h_5y + h_6) \]

Just rearrange the terms

\[ h_7xx' + h_8yx' + h_9x' - h_1x - h_2y - h_3 = 0 \]
\[ h_7xy' + h_8yy' + h_9y' - h_4x - h_5y - h_6 = 0 \]
Determining the homography matrix

Re-arrange terms:

\[
\begin{align*}
    h_7xx' + h_8yx' + h_9x' - h_1x - h_2y - h_3 &= 0 \\
    h_7xy' + h_8yy' + h_9y' - h_4x - h_5y - h_6 &= 0
\end{align*}
\]

Re-write in matrix form:

\[
A_i h = 0
\]

\[
A_i = \begin{bmatrix}
-x & -y & -1 & 0 & 0 & 0 & xx' & yy' & x' \\
0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y'
\end{bmatrix}
\]

\[
h = \begin{bmatrix}
h_1 & h_2 & h_3 & h_4 & h_5 & h_6 & h_7 & h_8 & h_9
\end{bmatrix}^T
\]

How many equations from one point correspondence?
Determining the homography matrix

Stack together constraints from multiple point correspondences:

$$Ah = 0$$

$$\begin{bmatrix}
-x & -y & -1 & 0 & 0 & 0 & xx' & yx' & x' \\
0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y' \\
-1 & 0 & 0 & -x & -y & -1 & xy' & yy' & y' \\
0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y' \\
0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y' \\
\vdots \\
0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y'
\end{bmatrix}
\begin{bmatrix}
h_1 \\
h_2 \\
h_3 \\
h_4 \\
h_5 \\
h_6 \\
h_7 \\
h_8 \\
h_9
\end{bmatrix}
= 
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}$$

*Homogeneous* linear least squares problem
Reminder: Determining unknown transformations

Affine transformation:
\[
\begin{bmatrix}
  x' \\
y'
\end{bmatrix} =
\begin{bmatrix}
p_1 & p_2 & p_3 \\
p_4 & p_5 & p_6
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
1
\end{bmatrix}
\]
Why can we drop the last line?

Vectorize transformation parameters:
\[
\begin{bmatrix}
x' \\
y'
\end{bmatrix} =
\begin{bmatrix}
x & y & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & x & y & 1 \\
x' & y' \\
x & y & 1 & 0 & 0 & 0 \\
y' \\
0 & 0 & 0 & x & y & 1
\end{bmatrix}
\begin{bmatrix}
p_1 \\
p_2 \\
p_3 \\
p_4 \\
p_5 \\
p_6
\end{bmatrix}
\]

Stack equations from point correspondences:

Notation in system form:
\[
Ax = b
\]
Reminder: Determining unknown transformations

Convert the system to a linear least-squares problem:

$$E_{LLS} = \|Ax - b\|^2$$

Expand the error:

$$E_{LLS} = x^T(A^TA)x - 2x^T(A^Tb) + \|b\|^2$$

Minimize the error:

Set derivative to 0

$$(A^TA)x = A^Tb$$

Solve for $x$

$$x = (A^TA)^{-1}A^Tb$$

In Matlab:

$$x = A \backslash b$$

Note: You almost never want to compute the inverse of a matrix.
Determining the homography matrix

Stack together constraints from multiple point correspondences:

\[ Ah = 0 \]

Homogeneous linear least squares problem

- How do we solve this?
Determining the homography matrix

Stack together constraints from multiple point correspondences:

\[ A h = 0 \]

\[
\begin{bmatrix}
-x & -y & -1 & 0 & 0 & 0 & xx' & yx' & x' \\
0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y' \\
-x & -y & -1 & 0 & 0 & 0 & xx' & yx' & x' \\
0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y' \\
. & . & . & . & . & . & . & . & . \\
-x & -y & -1 & 0 & 0 & 0 & xx' & yx' & x' \\
0 & 0 & 0 & -x & -y & -1 & xy' & yy' & y'
\end{bmatrix}
\begin{bmatrix}
h_1 \\
h_2 \\
h_3 \\
h_4 \\
h_5 \\
h_6 \\
h_7 \\
h_8 \\
h_9
\end{bmatrix} =
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}

*Homogeneous* linear least squares problem

- Solve with SVD (or \texttt{ldivide} in MATLAB)
Singular Value Decomposition

Each column of $V$ represents a solution for $Ah = 0$

where the singular value represents the reprojection error
Solving for H using DLT

Given \( \{x_i, x'_i\} \) solve for H such that \( x' = H x \)

1. For each correspondence, create 2x9 matrix \( A_i \)
2. Concatenate into single 2n x 9 matrix \( A \)
3. Compute SVD of \( A = U \Sigma V^T \)
4. Store singular vector of the smallest singular value \( h = v_i \)
5. Reshape to get \( H \)
General form of total least squares

(WARNING: change of notation. $x$ is a vector of parameters!)

$$E_{TLS} = \sum_i (a_i x)^2$$

$$= \|Ax\|^2 \quad \text{(matrix form)}$$

$$\|x\|^2 = 1 \quad \text{constraint}$$

minimize $$\|Ax\|^2$$ subject to $$\|x\|^2 = 1$$

Solution is the eigenvector corresponding to smallest eigenvalue of

$$(\text{Rayleigh quotient})$$

Solution is the column of $V$ corresponding to smallest singular value

$$(\text{equivalent})$$

$$A = U \Sigma V^T$$
Linear least squares estimation only works when the transform function is linear! (duh)

Also doesn’t deal well with outliers.
Create point correspondences

How do we automate this step?
The image correspondence pipeline

1. Feature point detection
   • Detect corners using the Harris corner detector.

2. Feature point description
   • Describe features using the Multi-scale oriented patch descriptor.

3. Feature matching
The image correspondence pipeline

1. Feature point detection
   • Detect corners using the Harris corner detector.

2. Feature point description
   • Describe features using the Multi-scale oriented patch descriptor.

3. Feature matching
good correspondence

bad correspondence

good correspondence
Random Sample Consensus (RANSAC)
**Algorithm:**

1. Sample (randomly) the number of points required to fit the model
2. Solve for model parameters using samples
3. Score by the fraction of inliers within a preset threshold of the model

Repeat 1-3 until the best model is found with high confidence
Algorithm:

1. **Sample (randomly) the number of points required to fit the model**
2. Solve for model parameters using samples
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**Algorithm:**

1. Sample (randomly) the number of points required to fit the model
2. Solve for model parameters using samples
3. Score by the fraction of inliers within a preset threshold of the model

**Repeat 1-3 until the best model is found with high confidence**
How to choose parameters?

• Number of samples $N$
  – Choose $N$ so that, with probability $p$, at least one random sample is free from outliers (e.g. $p=0.99$) (outlier ratio: $e$)

• Number of sampled points $s$
  – Minimum number needed to fit the model

• Distance threshold $\delta$
  – Choose $\delta$ so that a good point with noise is likely (e.g., prob=$0.95$) within threshold
  – Zero-mean Gaussian noise with std. dev. $\sigma$: $t^2=3.84\sigma^2$

$$N = \frac{\log(1 - p)}{\log \left( 1 - (1 - e)^s \right)}$$
Given two images...

find matching features (e.g., SIFT) and a translation transform
Matched points will usually contain bad correspondences.

**how should we estimate the transform?**
LLS will find the ‘average’ transform

solution is corrupted by bad correspondences
Use RANSAC

How many correspondences to compute translation transform?
Need only **one correspondence**, to find translation model
Pick one correspondence, count inliers.

(one correspondence)
Pick one correspondence, count inliers

2 inliers
Pick one correspondence, count inliers

one correspondence
Pick one correspondence, count inliers
Pick one correspondence, count inliers

Pick the model with the highest number of inliers!
Estimating homography using RANSAC

• RANSAC loop

  1. Get point correspondences (randomly)
Estimating homography using RANSAC

• RANSAC loop

  1. Get four point correspondences (randomly)

  2. Compute H using DLT

  3. Count inliers

  4. Keep if largest number of inliers

  5. Recompute H using all inliers
Estimating homography using RANSAC

- RANSAC loop
  1. Get four point correspondences (randomly)
  2. Compute $H$ using DLT
  3. Count
Estimating homography using RANSAC

- RANSAC loop

  1. Get four point correspondences (randomly)
  2. Compute H using DLT
  3. Count inliers
  4. Keep H if
Estimating homography using RANSAC

• RANSAC loop

  1. Get four point correspondences (randomly)
  2. Compute H using DLT
  3. Count inliers
  4. Keep H if largest number of inliers

• Recompute H using all inliers
Useful for...
The image correspondence pipeline

1. Feature point detection
   • Detect corners using the Harris corner detector.

2. Feature point description
   • Describe features using the Multi-scale oriented patch descriptor.

3. Feature matching and homography estimation
   • Do both simultaneously using RANSAC.
Basic reading:
• Szeliski textbook, Sections 6.1.

Additional reading:
  as usual when it comes to geometry and vision, this book is the best reference; Sections 2 and 4 in particular discuss everything about homography estimation