Image Stitching

Computational Photography
Derek Hoiem, University of Illinois

Photos by Russ Hewett
Project 3 Highlights

For good/interesting blending results: (really, most pages fit here)
• https://web.engr.illinois.edu/~cchen156/cs445/proj3/
• https://web.engr.illinois.edu/~ulzeean2/cs445/proj3/
• https://web.engr.illinois.edu/~bechapm2/cs445/proj3/
• https://web.engr.illinois.edu/~gubatan2/cs445/proj3/
• https://web.engr.illinois.edu/~zli16/cs445/proj3/
• https://web.engr.illinois.edu/~ramados2/cs445/proj3/
• https://web.engr.illinois.edu/~hoskere2/cs445/proj3/
• https://web.engr.illinois.edu/~mwakaba2/cs445/proj3/

For overall correctness of implementation (including the color2gray section):
• https://web.engr.illinois.edu/~yhsu30/cs445/proj3/

For NPR:
• https://web.engr.illinois.edu/~mnmeyer2/cs445/proj3/
• https://web.engr.illinois.edu/~myeh2/cs445/proj3/ (+ other good results)
Project 3 Results

Chen Chen

Ulzee An
Project 3 Results

Blade Chapman

Mark Gubutan + Vivek Ramadoss = Blade Chapman
Michael Meyer (Texture Flattening)

Vedhus Hoskere (Gloss Effect)
Project 5

Input video:
https://www.youtube.com/watch?v=agl5za_gHHU

Aligned frames:
https://www.youtube.com/watch?v=Uahy6kPotaE

Background:
https://www.youtube.com/watch?v=Vt9vv1zCnLA

Foreground:
https://www.youtube.com/watch?v=OlCkKNndEt4
Last Class: Keypoint Matching

1. Find a set of distinctive keypoints
2. Define a region around each keypoint
3. Extract and normalize the region content
4. Compute a local descriptor from the normalized region
5. Match local descriptors

\[ d(f_A, f_B) < T \]
Last Class: Summary

• Keypoint detection: repeatable and distinctive
  – Corners, blobs
  – Harris, DoG

• Descriptors: robust and selective
  – SIFT: spatial histograms of gradient orientation
Today: Image Stitching

• Combine two or more overlapping images to make one larger image

Slide credit: Vaibhav Vaish
Views from rotating camera

Camera Center
Problem basics

• Do on board
Basic problem

- \( x = K [R \ t] \ X \)
- \( x' = K' [R' \ t'] \ X' \)
- \( t=t'=0 \)

- \( x'=Hx \) where \( H = K' \ R' \ R^{-1} K^{-1} \)
- Typically only \( R \) and \( f \) will change (4 parameters), but, in general, \( H \) has 8 parameters
Image Stitching Algorithm Overview

1. Detect keypoints
2. Match keypoints
3. Estimate homography with four matched keypoints (using RANSAC)
4. Project onto a surface and blend
Image Stitching Algorithm Overview

1. Detect/extract keypoints (e.g., DoG/SIFT)
2. Match keypoints (most similar features, compared to 2$^{nd}$ most similar)
Computing homography

Assume we have four matched points: How do we compute homography $H$?

Direct Linear Transformation (DLT)

$$x' = Hx$$

$$x' = \begin{bmatrix} w' \ u' \\ w' \ v' \\ w' \end{bmatrix}$$

$$H = \begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix}$$

$$\begin{bmatrix} -u & -v & -1 & 0 & 0 & 0 & 0 & uu' & vu' & u' \\ 0 & 0 & 0 & -u & -v & -1 & uv' & vv' & v' \end{bmatrix}h = 0$$

$$h = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ h_5 \\ h_6 \\ h_7 \\ h_8 \\ h_9 \end{bmatrix}$$
Computing homography

Direct Linear Transform

\[
\begin{bmatrix}
-u_1 & -v_1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & -u_1 & -v_1 & -1 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & -u_n & -v_n & -1 \\
\end{bmatrix}
\begin{bmatrix}
u_1 u' \\
v_1 v' \\
u_1 \\
u_n v' \\
v_n v' \\
v_n \\
\end{bmatrix}
\]

\[h = 0 \implies Ah = 0\]

- Apply SVD: \(UDV^T = A\)
- \(h = V_{\text{smallest}}\) (column of \(V\) corr. to smallest singular value)

\[
\begin{bmatrix}
h_1 \\
h_2 \\
\vdots \\
h_9 \\
\end{bmatrix}
\begin{bmatrix}
h_1 & h_2 & h_3 \\
h_4 & h_5 & h_6 \\
h_7 & h_8 & h_9 \\
\end{bmatrix}
\]

**Matlab**

\[
[U, S, V] = \text{svd}(A); \\
h = V(:, \text{end});
\]
Computing homography

Assume we have four matched points: How do we compute homography $H$?

Normalized DLT

1. Normalize coordinates for each image
   a) Translate for zero mean
   b) Scale so that $u$ and $v$ are $\sim$=1 on average
      \[
      \tilde{x} = T x \quad \tilde{x}' = T' x' 
      \]
      – This makes problem better behaved numerically (see Hartley and Zisserman p. 107-108)

2. Compute $\tilde{H}$ using DLT in normalized coordinates

3. Unnormalize: $H = T^{-1} \tilde{H} T$
   \[
   x'_i = H x_i
   \]
Computing homography

- Assume we have matched points with outliers: How do we compute homography $H$?

Automatic Homography Estimation with RANSAC
RANSAC: RANdom SAample Consensus

Scenario: We’ve got way more matched points than needed to fit the parameters, but we’re not sure which are correct

RANSAC Algorithm
• Repeat N times
  1. Randomly select a sample
     – Select just enough points to recover the parameters
  2. Fit the model with random sample
  3. See how many other points agree
• Best estimate is one with most agreement
  – can use agreeing points to refine estimate
Computing homography

• Assume we have matched points with outliers: How do we compute homography $H$?

Automatic Homography Estimation with RANSAC
1. Choose number of samples $N$
2. Choose 4 random potential matches
3. Compute $H$ using normalized DLT
4. Project points from $x$ to $x'$ for each potentially matching pair: $x'_i = Hx_i$
5. Count points with projected distance $< t$
   – E.g., $t = 3$ pixels
6. Repeat steps 2-5 $N$ times
   – Choose $H$ with most inliers
Automatic Image Stitching

1. Compute interest points on each image

2. Find candidate matches

3. Estimate homography $H$ using matched points and RANSAC with normalized DLT

4. Project each image onto the same surface and blend
Choosing a Projection Surface

Many to choose: planar, cylindrical, spherical, cubic, etc.
1) For red image: pixels are already on the planar surface
2) For green image: map to first image plane
Planar vs. Cylindrical Projection

Photos by Russ Hewett
Planar vs. Cylindrical Projection

Planar
Cylindrical Mapping

1) For red image: compute $h$, theta on cylindrical surface from $(u, v)$
2) For green image: map to first image plane, than map to cylindrical surface
Planar vs. Cylindrical Projection

Cylindrical
Planar vs. Cylindrical Projection

Cylindrical
Simple gain adjustment
Automatically choosing images to stitch
Recognizing Panoramas

Some of following material from Brown and Lowe 2003 talk

Recognizing Panoramas

Input: N images

1. Extract SIFT points, descriptors from all images

2. Find K-nearest neighbors for each point (K=4)

3. For each image
   a) Select M candidate matching images by counting matched keypoints (M=6)
   b) Solve homography $H_{ij}$ for each matched image
Recognizing Panoramas

Input: N images

1. Extract SIFT points, descriptors from all images

2. Find K-nearest neighbors for each point (K=4)

3. For each image
   a) Select M candidate matching images by counting matched keypoints (M=6)
   b) Solve homography $H_{ij}$ for each matched image
   c) Decide if match is valid ($n_i > 8 + 0.3 \ n_f$)

# inliers
# keypoints in overlapping area
RANSAC for Homography

Initial Matched Points
RANSAC for Homography
Verification
RANSAC for Homography
Recognizing Panoramas (cont.)

(now we have matched pairs of images)

4. Find connected components
Finding the panoramas
Finding the panoramas
Finding the panoramas
Recognizing Panoramas (cont.)

(now we have matched pairs of images)

4. Find connected components

5. For each connected component
   a) Perform bundle adjustment to solve for rotation $(\theta_1, \theta_2, \theta_3)$ and focal length $f$ of all cameras
   b) Project to a surface (plane, cylinder, or sphere)
   c) Render with multiband blending
Bundle adjustment for stitching

- Non-linear minimization of re-projection error

\[ \hat{\mathbf{x}}' = \mathbf{Hx} \text{ where } \mathbf{H} = \mathbf{K'} \mathbf{R'} \mathbf{R}^{-1} \mathbf{K}^{-1} \]

- Solve non-linear least squares (Levenberg-Marquardt algorithm)
  - See paper for details

\[ \mathbf{R}_i = e^{[\theta_i]_x}, [\theta_i]_x = \begin{bmatrix} 0 & -\theta_{i3} & \theta_{i2} \\ \theta_{i3} & 0 & -\theta_{i1} \\ -\theta_{i2} & \theta_{i1} & 0 \end{bmatrix} \]

\[ \mathbf{K}_i = \begin{bmatrix} f_i & 0 & 0 \\ 0 & f_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

\[ \text{error} = \sum_{1}^{N} \sum_{j}^{M} \sum_{k}^{N} \text{dist}(\mathbf{x}', \hat{\mathbf{x}}') \]
Bundle Adjustment

New images initialized with rotation, focal length of the best matching image
Bundle Adjustment

New images initialized with rotation, focal length of the best matching image
Blending

• Gain compensation: minimize intensity difference of overlapping pixels

• Blending
  – Pixels near center of image get more weight
  – Multiband blending to prevent blurring
Multi-band Blending (Laplacian Pyramid)

- Burt & Adelson 1983
  - Blend frequency bands over range $\propto \lambda$
Multiband blending

(a) Original images and blended result

(b) Band 1 (scale 0 to $\sigma$)

(c) Band 2 (scale $\sigma$ to $2\sigma$)

(d) Band 3 (scale lower than $2\sigma$)
Blending comparison (IJCV 2007)

(a) Linear blending

(b) Multi-band blending
Blending Comparison

(b) Without gain compensation

(c) With gain compensation

(d) With gain compensation and multi-band blending
Straightening

Rectify images so that “up” is vertical
Further reading

Harley and Zisserman: Multi-view Geometry book

- DLT algorithm: HZ p. 91 (alg 4.2), p. 585
- Normalization: HZ p. 107-109 (alg 4.2)
- RANSAC: HZ Sec 4.7, p. 123, alg 4.6

- **Recognising Panoramas**: Brown and Lowe, IJCV 2007 (also bundle adjustment)
Tips and Photos from Russ Hewett
Capturing Panoramic Images

• Tripod vs Handheld
  • Help from modern cameras
  • Leveling tripod
  • Gigapan
  • Or wing it

• Image Sequence
  • Requires a reasonable amount of overlap (at least 15-30%)
  • Enough to overcome lens distortion

• Exposure
  • Consistent exposure between frames
  • Gives smooth transitions
  • Manual exposure
  • Makes consistent exposure of dynamic scenes easier
  • But scenes don’t have constant intensity everywhere

• Caution
  • Distortion in lens (Pin Cushion, Barrel, and Fisheye)
  • Polarizing filters
  • Sharpness in image edge / overlap region
Pike’s Peak Highway, CO

Photo: Russell J. Hewett

Nikon D70s, Tokina 12-24mm @ 16mm, f/22, 1/40s
Pike’s Peak Highway, CO

Photo: Russell J. Hewett
Howth, Ireland

Photo: Russell J. Hewett

(See Photo On Web)
Les Diablerets, Switzerland

Photo: Russell J. Hewett

(See Photo On Web)
Side of Laptop

Photo: Russell J. Hewett & Bowen Lee
Considerations For Stitching

• Variable intensity across the total scene

• Variable intensity and contrast between frames

• Lens distortion
  • Pin Cushion, Barrel, and Fisheye
  • Profile your lens at the chosen focal length (read from EXIF)
  • Or get a profile from LensFun

• Dynamics/Motion in the scene
  • Causes ghosting
  • Once images are aligned, simply choose from one or the other

• Misalignment
  • Also causes ghosting
  • Pick better control points

• Visually pleasing result
  • Super wide panoramas are not always ‘pleasant’ to look at
  • Crop to golden ratio, 10:3, or something else visually pleasing
Ghosting and Variable Intensity

Photo: Russell J. Hewett

Nikon D70s, Tokina 12-24mm @ 12mm, f/8, 1/400s
Ghosting From Motion

Photo: Bowen Lee
Things to remember

• Homography relates rotating cameras
  – Homography is plane to plane mapping

• Recover homography using RANSAC and normalized DLT

• Can choose surface of projection: cylinder, plane, and sphere are most common

• Lots of room for tweaking (blending, straightening, etc.)
Next class

- Object recognition and retrieval