Multi-view Reconstruction

CS 600.361/600.461

Instructor: Greg Hager
Outline

- Reminders

- Multi-view reconstruction with calibrated cameras
  - Multi-baseline stereo
  - Volumetric stereo

- Multi-view reconstruction with un-calibrated cameras
  - Affine structure-from-motion
  - Bundle adjustment
Multi-view reconstruction
Calibrated cameras

(Slides adapted from Richard Szeliski)
Beyond two-view stereo

The third view can be used for verification
Multiple-baseline stereo

- Pick a reference image, and slide the corresponding window along the corresponding epipolar lines of all other images, using inverse depth relative to the first image as the search parameter.

Multiple-baseline stereo

- **Pros**
  - Using multiple images reduces the ambiguity of matching

- **Cons**
  - Must choose a reference view
  - Occlusions become an issue for large baseline
  - Cannot rectify without very high precision slider

Alternative is to use a plane sweep algorithm
Volumetric Stereo / Voxel Coloring

**Goal:** Assign RGB values to voxels in $V$ photo-consistent with images
Photo-consistency

• A *photo-consistent scene* is a scene that exactly reproduces your input images from the same camera viewpoints
• You can’t use your input cameras and images to tell the difference between a photo-consistent scene and the true scene
Space Carving

Space Carving Algorithm

- Initialize to a volume $V$ containing the true scene
- Choose a voxel on the current surface
- Project to visible input images
- Carve if not photo-consistent
- Repeat until convergence

Which shape do you get?

The Photo Hull is the UNION of all photo-consistent scenes in V

- It is a photo-consistent scene reconstruction
- Tightest possible bound on the true scene

Source: S. Seitz
Space Carving Results: African Violet

Input Image (1 of 45)

Reconstruction

Reconstruction

Reconstruction

Source: S. Seitz
Space Carving Results: Hand

Input Image
(1 of 100)

Views of Reconstruction
Reconstruction from Silhouettes

- The case of binary images: a voxel is photo-consistent if it lies inside the object’s silhouette in all views.
Reconstruction from Silhouettes

- The case of binary images: a voxel is photostatic consistent if it lies inside the object’s silhouette in all views.

Finding the silhouette-consistent shape (*visual hull*):

- *Backproject* each silhouette
- Intersect backprojected volumes
Volume intersection

Reconstruction Contains the True Scene
- But is generally not the same
Voxel algorithm for volume intersection

Color voxel black if on silhouette in every image
Photo-consistency vs. silhouette-consistency

True Scene

Photo Hull

Visual Hull
Carved visual hulls

- The visual hull is a good starting point for optimizing photo-consistency
  - Easy to compute
  - Tight outer boundary of the object
  - Parts of the visual hull (rims) already lie on the surface and are already photo-consistent

Yasutaka Furukawa and Jean Ponce, 
Carved Visual Hulls for Image-Based Modeling, ECCV 2006.
Multi-view reconstruction
Un-calibrated cameras

(Slides adapted from Svetlana Lazebnik)
Multiple-view geometry questions

- **Scene geometry (structure):** Given 2D point matches in two or more images, where are the corresponding points in 3D?

- **Correspondence (stereo matching):** Given a point in just one image, how does it constrain the position of the corresponding point in another image?

- **Camera geometry (motion):** Given a set of corresponding points in two or more images, what are the camera matrices for these views?
Structure from motion

- Given: $m$ images of $n$ fixed 3D points

\[ x_{ij} = P_i X_j, \quad i = 1, \ldots, m, \quad j = 1, \ldots, n \]

- Problem: estimate $m$ projection matrices $P_i$ and $n$ 3D points $X_j$ from the $mn$ correspondences $x_{ij}$
Structure from motion ambiguity

- If we scale the entire scene by some factor $k$ and, at the same time, scale the camera matrices by the factor of $1/k$, the projections of the scene points in the image remain exactly the same:

$$x = PX = \left(\frac{1}{k}P\right)(kX)$$

It is impossible to recover the absolute scale of the scene!
Structure from motion ambiguity

• If we scale the entire scene by some factor \( k \) and, at the same time, scale the camera matrices by the factor of \( 1/k \), the projections of the scene points in the image remain exactly the same.

• More generally: if we transform the scene using a transformation \( Q \) and apply the inverse transformation to the camera matrices, then the images do not change.

\[ x = PX = \left( PQ^{-1} \right)(QX) \]
Types of ambiguity

- Projective 15dof: \[
\begin{bmatrix}
A & t \\
v^T & v
\end{bmatrix}
\]
  Preserves intersection and tangency

- Affine 12dof: \[
\begin{bmatrix}
A & t \\
o^T & 1
\end{bmatrix}
\]
  Preserves parallelism, volume ratios

- Similarity 7dof: \[
\begin{bmatrix}
sR & t \\
o^T & 1
\end{bmatrix}
\]
  Preserves angles, ratios of length

- Euclidean 6dof: \[
\begin{bmatrix}
R & t \\
o^T & 1
\end{bmatrix}
\]
  Preserves angles, lengths

- With no constraints on the camera calibration matrix or on the scene, we get a projective reconstruction
- Need additional information to upgrade the reconstruction to affine, similarity, or Euclidean
Projective ambiguity

\[ x = PX = (PQ_P^{-1})(Q_PX) \]
Projective ambiguity
Affine ambiguity

\[ x = PX = \left( PQ^{-1}_A \right) \left( Q_A x \right) \]
Affine ambiguity
Similarity ambiguity

\[ x = PX = \left( PQ^{-1}_S \right)(Q_S X) \]
Similarity ambiguity
Structure from motion

- Let’s start with *affine cameras* (the math is easier)
Recall: Orthographic Projection

Special case of perspective projection

- Distance from center of projection to image plane is infinite

![Diagram of orthographic projection]

- Projection matrix:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \Rightarrow (x, y)$$

Slide by Steve Seitz
Affine cameras

Orthographic Projection

Parallel Projection
Affine cameras

- A general affine camera combines the effects of an affine transformation of the 3D space, orthographic projection, and an affine transformation of the image:

\[
P = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
[4 \times 4 \text{ affine}]
= \begin{bmatrix}
a_{11} & a_{12} & a_{13} & b_1 \\
a_{21} & a_{22} & a_{23} & b_2 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
= \begin{bmatrix}
A & b \\
0 & 1 \\
\end{bmatrix}
\]

- Affine projection is a linear mapping + translation in inhomogeneous coordinates

\[
x = \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
\end{bmatrix}\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = AX + b
\]

Projection of world origin
Affine structure from motion

• Given: $m$ images of $n$ fixed 3D points:
  \[ x_{ij} = A_i X_j + b_i, \quad i = 1, \ldots, m, \quad j = 1, \ldots, n \]

• Problem: use the $mn$ correspondences $x_{ij}$ to estimate $m$ projection matrices $A_i$ and translation vectors $b_i$, and $n$ points $X_j$

• The reconstruction is defined up to an arbitrary affine transformation $Q$ (12 degrees of freedom):
  \[
  \begin{bmatrix}
  A & b \\
  0 & 1
  \end{bmatrix} \rightarrow \begin{bmatrix}
  A & b \\
  0 & 1
  \end{bmatrix} Q^{-1}, \quad \begin{bmatrix}
  X \\
  1
  \end{bmatrix} \rightarrow Q \begin{bmatrix}
  X \\
  1
  \end{bmatrix}
  \]

• We have $2mn$ knowns and $8m + 3n$ unknowns (minus 12 dof for affine ambiguity)

• Thus, we must have $2mn \geq 8m + 3n - 12$

• For two views, we need four point correspondences
Affine structure from motion

• Centering: subtract the centroid of the image points

\[
\hat{x}_{ij} = x_{ij} - \frac{1}{n} \sum_{k=1}^{n} x_{ik} = A_i X_j + b_i - \frac{1}{n} \sum_{k=1}^{n} (A_i X_k + b_i)
\]

\[
= A_i \left( X_j - \frac{1}{n} \sum_{k=1}^{n} X_k \right) = A_i \hat{X}_j
\]

• For simplicity, assume that the origin of the world coordinate system is at the centroid of the 3D points

• After centering, each normalized point \( x_{ij} \) is related to the 3D point \( X_j \) by

\[
\hat{X}_{ij} = A_i X_j
\]
Affine structure from motion

- Let’s create a $2m \times n$ data (measurement) matrix:

$$
\mathbf{D} =
\begin{bmatrix}
\hat{\mathbf{x}}_{11} & \hat{\mathbf{x}}_{12} & \cdots & \hat{\mathbf{x}}_{1n} \\
\hat{\mathbf{x}}_{21} & \hat{\mathbf{x}}_{22} & \cdots & \hat{\mathbf{x}}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\hat{\mathbf{x}}_{m1} & \hat{\mathbf{x}}_{m2} & \cdots & \hat{\mathbf{x}}_{mn}
\end{bmatrix}
$$

Cameras ($2m$)  \hspace{1cm}  Points ($n$)

Affine structure from motion

- Let’s create a $2m \times n$ data (measurement) matrix:

$$\mathbf{D} = \begin{bmatrix}
\hat{\mathbf{X}}_{11} & \hat{\mathbf{X}}_{12} & \cdots & \hat{\mathbf{X}}_{1n} \\
\hat{\mathbf{X}}_{21} & \hat{\mathbf{X}}_{22} & \cdots & \hat{\mathbf{X}}_{2n} \\
\cdots & \cdots & \cdots & \cdots \\
\hat{\mathbf{X}}_{m1} & \hat{\mathbf{X}}_{m2} & \cdots & \hat{\mathbf{X}}_{mn}
\end{bmatrix} = \begin{bmatrix}
\mathbf{A}_1 \\
\mathbf{A}_2 \\
\vdots \\
\mathbf{A}_m
\end{bmatrix} \begin{bmatrix}
\mathbf{X}_1 \\
\mathbf{X}_2 \\
\cdots \\
\mathbf{X}_n
\end{bmatrix}
$$

- The measurement matrix $\mathbf{D} = \mathbf{MS}$ must have rank 3!

Factorizing the measurement matrix

$$2m \text{ Measurements} = \text{Motion} \times \text{Shape}$$

$$D = MS$$

Source: M. Hebert
Factorizing the measurement matrix

• Singular value decomposition of $D$:

\[
D = U W V^T
\]

\[
D = U_3 W_3 V_3^T
\]

Source: M. Hebert
Factorizing the measurement matrix

- Singular value decomposition of D:

\[ D = U W V^T \]

To reduce to rank 3, we just need to set all the singular values to 0 except for the first 3.
Factorizing the measurement matrix

• Obtaining a factorization from SVD:

\[ \begin{array}{c}
2m \\
\downarrow
\end{array} \begin{array}{c}
\text{D}
\end{array} = \begin{array}{c}
\text{U}_3
\end{array} \times 3 \begin{array}{c}
\text{W}_3
\end{array} \times \begin{array}{c}
\text{V}_3^T
\end{array} \]

Source: M. Hebert
Factorizing the measurement matrix

- Obtaining a factorization from SVD:

\[ D = U_3 W_3^{1/2} V_3^T \]

This decomposition minimizes \(|D-MS|^2\)

Source: M. Hebert
Affine ambiguity

The decomposition is not unique. We get the same $D$ by using any $3 \times 3$ matrix $C$ and applying the transformations $M \rightarrow MC$, $S \rightarrow C^{-1}S$

That is because we have only an affine transformation and we have not enforced any Euclidean constraints (like forcing the image axes to be perpendicular, for example)

Source: M. Hebert
Eliminating the affine ambiguity

- Orthographic: image axes are perpendicular and scale is 1

\[ \mathbf{a}_1 \cdot \mathbf{a}_2 = 0 \]
\[ |\mathbf{a}_1|^2 = |\mathbf{a}_2|^2 = 1 \]

- This translates into \(3m\) equations in \( \mathbf{L} = \mathbf{CC}^T \):
  \[ \mathbf{A}_i \mathbf{L} \mathbf{A}_i^T = \mathbf{Id}, \quad i = 1, \ldots, m \]

- Solve for \( \mathbf{L} \)
- Recover \( \mathbf{C} \) from \( \mathbf{L} \) by Cholesky decomposition: \( \mathbf{L} = \mathbf{CC}^T \)
- Update \( \mathbf{M} \) and \( \mathbf{S} \): \( \mathbf{M} = \mathbf{MC}, \mathbf{S} = \mathbf{C}^{-1}\mathbf{S} \)

Source: M. Hebert
Algorithm summary

- Given: $m$ images and $n$ features $x_{ij}$
- For each image $i$, center the feature coordinates
- Construct a $2m \times n$ measurement matrix $D$:
  - Column $j$ contains the projection of point $j$ in all views
  - Row $i$ contains one coordinate of the projections of all the $n$ points in image $i$
- Factorize $D$:
  - Compute SVD: $D = U W V^T$
  - Create $U_3$ by taking the first 3 columns of $U$
  - Create $V_3$ by taking the first 3 columns of $V$
  - Create $W_3$ by taking the upper left $3 \times 3$ block of $W$
- Create the motion and shape matrices:
  - $M = U_3 W_3^{\frac{1}{2}}$ and $S = W_3^{\frac{1}{2}} V_3^T$ (or $M = U_3$ and $S = W_3 V_3^T$)
- Eliminate affine ambiguity

Source: M. Hebert
Reconstruction results

The Results
Dealing with missing data

• So far, we have assumed that all points are visible in all views
• In reality, the measurement matrix typically looks something like this:
Dealing with missing data

- Possible solution: decompose matrix into dense sub-blocks, factorize each sub-block, and fuse the results
  - Finding dense maximal sub-blocks of the matrix is NP-complete (equivalent to finding maximal cliques in a graph)

- Incremental bilinear refinement

1. Perform factorization on a dense sub-block
2. Solve for a new 3D point visible by at least two known cameras (linear least squares)
3. Solve for a new camera that sees at least three known 3D points (linear least squares)

F. Rothganger, S. Lazebnik, C. Schmid, and J. Ponce.
Segmenting, Modeling, and Matching Video Clips Containing Multiple Moving Objects. PAMI 2007.
Sequential structure from motion

• Initialize motion from two images using fundamental matrix

• Initialize structure by triangulation

• For each additional view:
  • Determine projection matrix of new camera using all the known 3D points that are visible in its image – *calibration*
Sequential structure from motion

• Initialize motion from two images using fundamental matrix

• Initialize structure by triangulation

• For each additional view:
  • Determine projection matrix of new camera using all the known 3D points that are visible in its image – calibration
  • Refine and extend structure: compute new 3D points, re-optimize existing points that are also seen by this camera – triangulation
Sequential structure from motion

• Initialize motion from two images using fundamental matrix

• Initialize structure by triangulation

• For each additional view:
  • Determine projection matrix of new camera using all the known 3D points that are visible in its image – *calibration*
  
  • Refine and extend structure: compute new 3D points, re-optimize existing points that are also seen by this camera – *triangulation*

• Refine structure and motion: bundle adjustment
Projective structure from motion

• Given: $m$ images of $n$ fixed 3D points

$$z_{ij} \mathbf{x}_{ij} = \mathbf{P}_i \mathbf{X}_j, \; i = 1, \ldots, m, \; j = 1, \ldots, n$$

• Problem: estimate $m$ projection matrices $\mathbf{P}_i$ and $n$ 3D points $\mathbf{X}_j$ from the $mn$ correspondences $\mathbf{x}_{ij}$
Projective structure from motion

• Given: \( m \) images of \( n \) fixed 3D points

\[
z_{ij} x_{ij} = P_i X_j, \quad i = 1, \ldots, m, \quad j = 1, \ldots, n
\]

• Problem: estimate \( m \) projection matrices \( P_i \) and \( n \) 3D points \( X_j \) from the \( mn \) correspondences \( x_{ij} \)

• With no calibration info, cameras and points can only be recovered up to a 4x4 projective transformation \( Q \):

\[
X \rightarrow QX, \quad P \rightarrow PQ^{-1}
\]

• We can solve for structure and motion when

\[
2mn \geq 11m + 3n - 15
\]

• For two cameras, at least 7 points are needed
Projective SFM: Two-camera case

- Compute fundamental matrix $F$ between the two views.
- First camera matrix: $[I|0]$
- Second camera matrix: $[A|b]$
- Then $b$ is the epipole ($F^T b = 0$), $A = -[b \times] F$
General Perspective and Motion

• There are iterative methods for differential motion (see book); we will not cover these.
  – In general, any motion and structure method is extremely sensitive for small motion (i.e. in the optical flow case).

• There are extensions of factorization to the perspective case; the method (see Ponce and Forsyth)

• For large motions, E-matrix computation and stereo-like methods are reasonable solutions to get dense estimates of depth

• Motion segmentation (multiple motions) is an important problem. GPCA-like methods have recently been developed (Vidal, Ma) as a way of describing the generalized epipolar constraints that arise in this case.
Perspective Motion Factorization
(Courtesy Marc Pollefeys)
Bundle adjustment

• Non-linear method for refining structure and motion
• Minimizing reprojection error

\[ E(P, X) = \sum_{i=1}^{m} \sum_{j=1}^{n} D(x_{ij}, P_iX_j)^2 \]
Self-calibration

• Self-calibration (auto-calibration) is the process of determining intrinsic camera parameters directly from uncalibrated images
• For example, when the images are acquired by a single moving camera, we can use the constraint that the intrinsic parameter matrix remains fixed for all the images
  • Compute initial projective reconstruction and find 3D projective transformation matrix $Q$ such that all camera matrices are in the form $P_i = K [R_i \mid t_i]$
• Can use constraints on the form of the calibration matrix: zero skew
Some Things We Aren’t Covering in Detail
The BRDF

The Bidirectional Reflection Distribution Function

- Given an incoming ray \((\theta_i, \phi_i)\) and outgoing ray \((\theta_e, \phi_e)\), what proportion of the incoming light is reflected along outgoing ray?

Answer given by the BRDF: \(\rho(\theta_i, \phi_i, \theta_e, \phi_e)\)
Photometric stereo

Can write this as a matrix equation:

\[
\begin{bmatrix}
    I_1 & I_2 & I_3 \\
\end{bmatrix}
= k_d N^T \begin{bmatrix}
    L_1 & L_2 & L_3 \\
\end{bmatrix}
\]

\[
I_1 = k_d N \cdot L_1 \\
I_2 = k_d N \cdot L_2 \\
I_3 = k_d N \cdot L_3
\]
Active stereo – color coded stripes

- Dense reconstruction
- Correspondence problem again
- Get around it by using color codes

L. Zhang, B. Curless, and S. M. Seitz 2002
S. Rusinkiewicz & Levoy 2002
Reminder - What is stereo vision?

• Generic problem formulation: given several images of the same object or scene, compute a representation of its 3D shape
• “Images of the same object or scene”
  • Arbitrary number of images (from two to thousands)
  • Arbitrary camera positions (isolated cameras or video sequence)
  • Cameras can be calibrated or uncalibrated
• “Representation of 3D shape”
  • Depth maps
  • Meshes
  • Point clouds
  • Patch clouds
  • Volumetric models
  • Layered models
What is stereo vision?

- Generic problem formulation: given several images of the same object or scene, compute a representation of its 3D shape
Review: Structure from motion

- Ambiguity
- Affine structure from motion
  - Factorization
- Dealing with missing data
  - Incremental structure from motion
- Projective structure from motion
  - Bundle adjustment
  - Self-calibration
Summary: 3D geometric vision

• Single-view geometry
  • The pinhole camera model
    – Variation: orthographic projection
  • The perspective projection matrix
  • Intrinsic parameters
  • Extrinsic parameters
  • Calibration

• Multiple-view geometry
  • Triangulation
  • The epipolar constraint
    – Essential matrix and fundamental matrix
  • Stereo
    – Binocular, multi-view
  • Structure from motion
    – Reconstruction ambiguity
    – Affine SFM
    – Projective SFM
Conclusion

• Today
  • Multi-view reconstruction with calibrated cameras
    – Multi-baseline stereo
    – Volumetric stereo
  • Multi-view reconstruction with un-calibrated cameras
    – Affine structure-from-motion
    – Bundle adjustment

• Tuesday
  • Texture synthesis
  • Review
  • Information about final exam