

Stereo (Part 2)

Introduction to Computer Vision
CSE 152
Lecture 9

Announcements

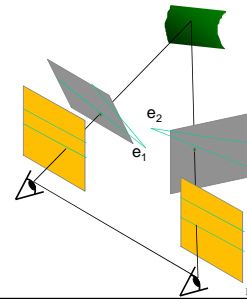
- Homework 2 is due May 4, 11:59 PM
- Reading:
 - Chapter 7: Stereopsis

Stereo Vision Outline

- Offline: Calibrate cameras & determine “epipolar geometry”
- Online
 1. Acquire stereo images
 2. Rectify images to convenient epipolar geometry
 3. Establish correspondence
 4. Estimate depth

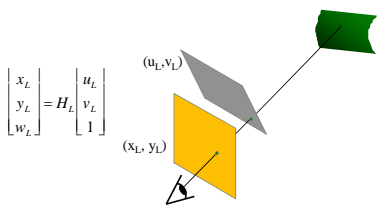
Rectification

Given a pair of images, transform both images so that epipolar lines are scan lines.



Rectification

Under perspective projection, the mapping from a plane to a plane is given by a projective transformation (aka homography).



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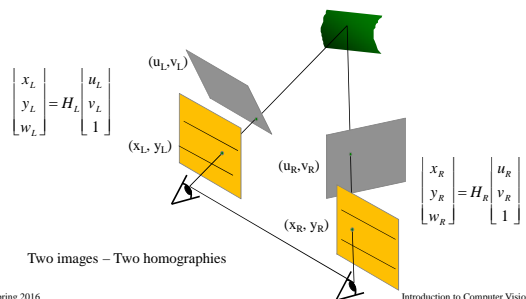


Image pair rectification

Simplify stereo matching by warping the images

Apply projective transformation so that epipolar lines correspond to horizontal scanlines

H should map epipole e to $(1,0,0)$, a point at infinity

H should minimize image distortion

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = He$$

Note that rectified images usually not rectangular
See Text for complete method

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Rectification

Given a pair of images, transform both images so that epipolar lines are scan lines.

Input Images

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Rectification

Given a pair of images, transform both images so that epipolar lines are scan lines.

Rectified Images

See Section 7.2.1 for specific method

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Rectification

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Polar Rectification

Homography-based Rectification

Polar Rectification

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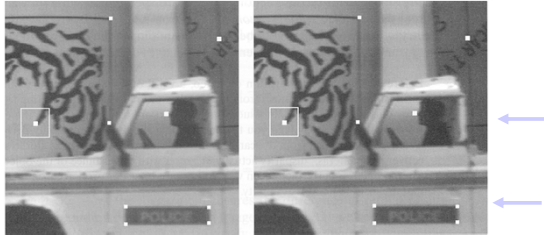
Polar Rectification

Epipoles are in images (white dot on ball)

Homography-based rectification is not possible

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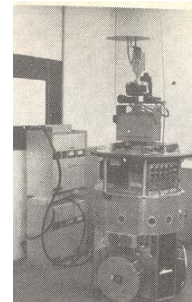
Features on same epipolar line



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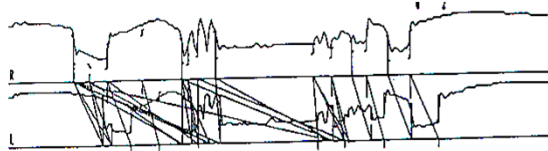
Mobi: Stereo-based navigation



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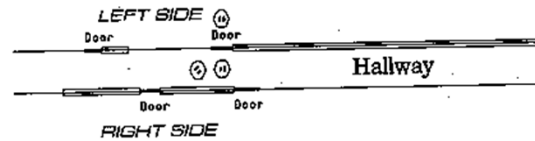
Epipolar correspondence



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Symbolic Map



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Using epipolar & constant Brightness constraints for stereo matching



- For each epipolar line
For each pixel in the left image
- compare with every pixel on same epipolar line in right image
 - pick pixel with minimum match cost
 - This will never work, so:
 - match **windows**

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Finding Correspondences



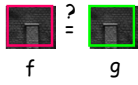
$W(p_l)$

$W(p_r)$

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Comparing Windows:



$$SSD = \sum_{[i,j] \in R} (f(i,j) - g(i,j))^2$$

$$C_{fg} = \sum_{[i,j] \in R} f(i,j)g(i,j)$$

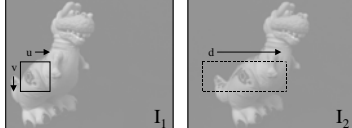
Most popular

For each window, match to closest window on epipolar line in other image.

(Camps)

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Correspondence Search Algorithm



```

For i = 1:rows
  for j = 1:ncols
    best(i,j) = -1
    for k = mindisparity:maxdisparity
      c = Match_Metric(I1(i,j), I2(i,j+k), winsize)
      if (c > best(i,j))
        best(i,j) = c
        disparities(i,j) = k
      end
    end
  end
end
end

```

$O(\text{rows} * \text{ncols} * \text{disparities} * \text{winx} * \text{winy})$

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Match Metric Summary


MATCH METRIC	DEFINITION
Normalized Cross-Correlation (NCC)	$\frac{\sum_{u,v} (I_1(u,v) - \bar{I}_1)(I_2(u+d,v) - \bar{I}_2)}{\sqrt{\sum_{u,v} (I_1(u,v) - \bar{I}_1)^2 \sum_{u,v} (I_2(u+d,v) - \bar{I}_2)^2}}$
Sum of Squared Differences (SSD)	$\sum_{u,v} (I_1(u,v) - I_2(u+d,v))^2$
Normalized SSD	$\sum_{u,v} \left(\frac{I_1(u,v) - \bar{I}_1}{\sqrt{\sum_{u,v} (I_1(u,v) - \bar{I}_1)^2}} - \frac{I_2(u+d,v) - \bar{I}_2}{\sqrt{\sum_{u,v} (I_2(u+d,v) - \bar{I}_2)^2}} \right)^2$
Sum of Absolute Differences (SAD)	$\sum_{u,v} I_1(u,v) - I_2(u+d,v) $
Zero Mean SAD	$\sum_{u,v} I_1(u,v) - \bar{I}_1 - (I_2(u+d,v) - \bar{I}_2) $
Rank	$I_1(u,v) = \sum_{m,n} I_1(m,n) < I_1(u,v)$ $\sum_{u,v} (I_1(u,v) - I_2(u+d,v))$
Census	$I_1(u,v) = \text{BITSTRING}_{m,n}(I_1(m,n) < I_1(u,v))$ $\sum_{u,v} \text{HAMMING}(I_1(u,v), I_2(u+d,v))$

These two are actually the same

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Stereo results

- Data from University of Tsukuba

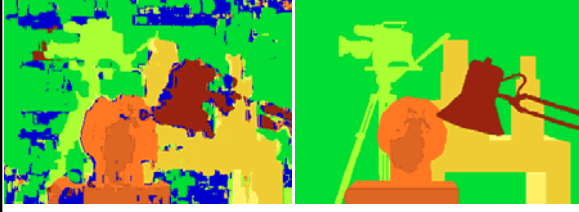


Scene
Ground truth

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Results with window correlation

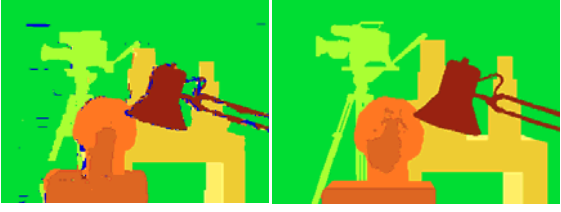


Window-based matching
(best window size)
Ground truth

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Results with better method



Using global optimization
Ground truth

(Seitz)

Boykov et al., <http://www.cs.cmu.edu/~paboiko/papers/01-iccv-3d-obj-segm.pdf>, International Conference on Computer Vision, September 1999.

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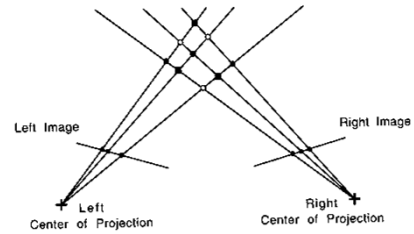
Some Issues

- Epipolar ordering
- Ambiguity
- Window size
- Window shape
- Lighting
- Half occluded regions

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A challenge: Multiple Interpretations

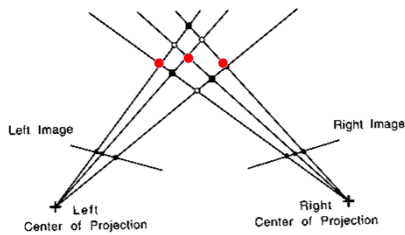


Each feature on left epipolar line match one and only one feature on right epipolar line.

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Multiple Interpretations

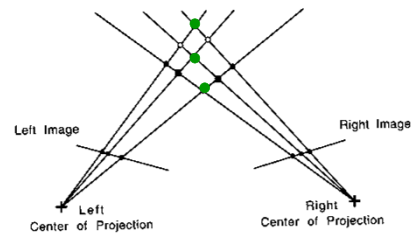


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Multiple Interpretations

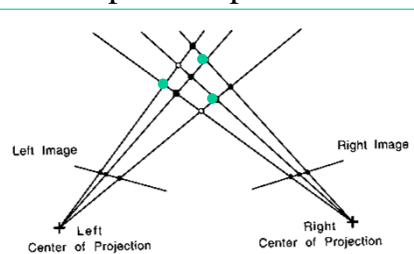


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Multiple Interpretations



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Some Issues

- Epipolar ordering
- **Ambiguity**
- Window size
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Ambiguity

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Some Issues

- Epipolar ordering
- Ambiguity
- **Window size**
- Window shape
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- Half occluded regions

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Window size

W = 3 W = 20

- Effect of window size

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Some Issues

- Epipolar ordering
- Ambiguity
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- Half occluded regions

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Window Shape and Forshortening

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Window Shape: Fronto-parallel Configuration

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Some Issues

- Epipolar ordering
- Window size
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- **Lighting**
- Half occluded regions

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Lighting Conditions (Photometric Variations)



$W(P_l)$



$W(P_r)$

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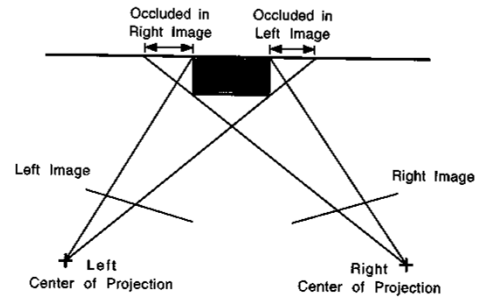
Some Issues

- Epipolar ordering
- Ambiguity
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- Lighting
- **Half occluded regions**

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Half occluded regions



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Summary of Stereo Constraints

CONSTRAINT	BRIEF DESCRIPTION
1-D Epipolar Search	Arbitrary images of the same scene may be rectified based on epipolar geometry such that stereo matches lie along one-dimensional scanlines. This reduces the computational complexity and also reduces the likelihood of false matches.
Monotonic Ordering	Points along an epipolar scanline appear in the same order in both stereo images, assuming that all objects in the scene are approximately the same distance from the cameras.
Image Brightness Constancy	Assuming Lambertian surfaces, the brightness of corresponding points in stereo images are the same.
Match Uniqueness	For every point in one stereo image, there is at most one corresponding point in the other image.
Disparity Continuity	Disparities vary smoothly (i.e. disparity gradient is small) over most of the image. This assumption is violated at object boundaries.
Disparity Limit	The search space may be reduced significantly by limiting the disparity range, reducing both computational complexity and the likelihood of false matches.
Fronto-Parallel Surfaces	The implicit assumption made by area-based matching is that objects have fronto-parallel surfaces (i.e. depth is constant within the region of local support). This assumption is violated by sloping and creased surfaces.
Feature Similarity	Corresponding features must be similar (e.g. edges must have roughly the same length and orientation).
Structural Grouping	Corresponding feature groupings and their connectivity must be consistent.

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(From G. Hager) Introduction to Computer Vision

Next Lecture

- Early vision: multiple images
 - Structure from motion
- Reading:
 - Chapter 8: Structure from Motion

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