EE795: Computer Vision and Intelligent Systems

Spring 2012
TTh 17:30-18:45 FDH 204

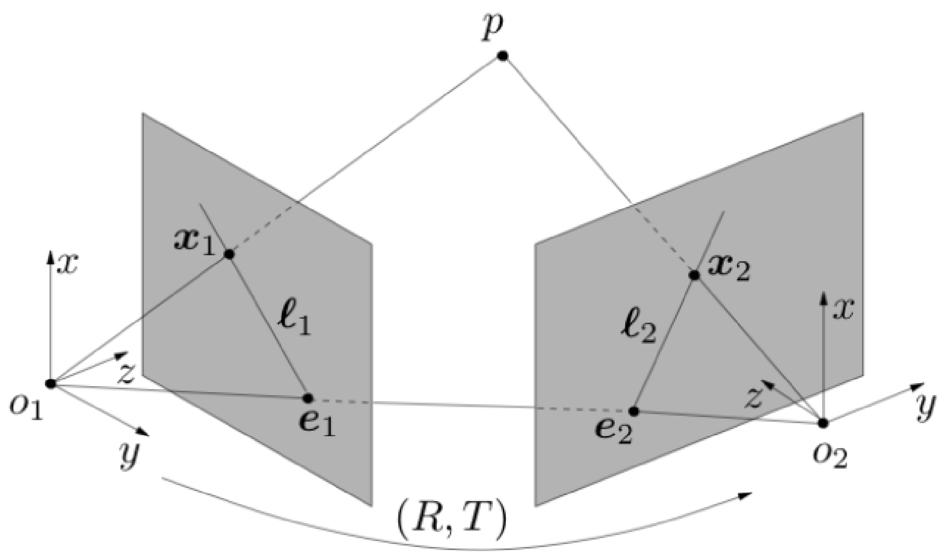
Lecture 13
130305

http://www.ee.unlv.edu/~b1morris/ecg795/

Outline

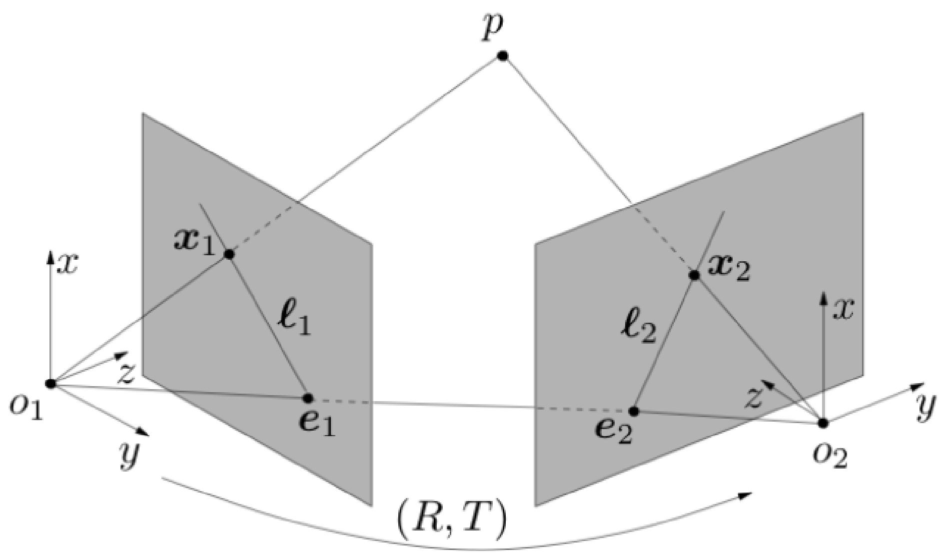
- Review
  - Epipolar Geometry
  - Planar Homography
- Stereo

Two View Geometry



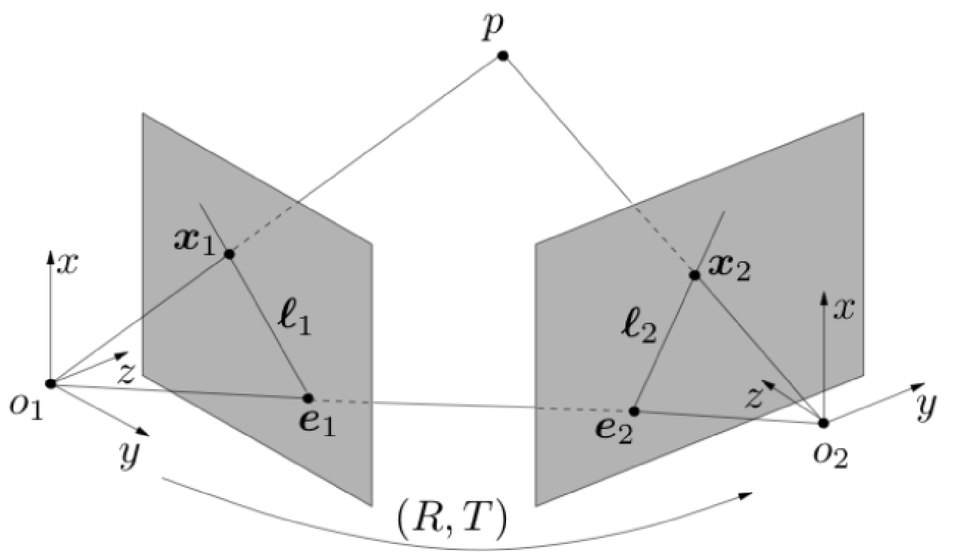
- Basic geometry to relate images of points and their 3d position
  - $X_2 = RX_1 + T$
  - Use triangulation
- Will assume cameras are calibrated
  - Cameras "match"

Epipolar Geometry



- Cameras centered at o_1 and o_2
- Homogeneous vectors e_1, e_2 are known as epipoles
  - Points where baseline pierces the image plane
  - Projection of the other camera's optical center onto the other image plane
  - Translation vector T between cameras

Epipolar Lines



- An point in one image maps to a line in another image

- A plane is spanned by the epipoles, o_1, o_2, and a 3d point p
- l_1, l_2 are epipolar lines
  - Intersection of the p-plane with the image plane
  - Image point x_1 can map anywhere along line l_2
    - Depends on the depth of the point

Rectified Stereo

- Simplest case of two-view geometry
- Camera views are rectified so that there is only a translation between images

- Epipolar lines are horizontal
  - Points in one image map to a horizontal scan line with the same y coordinate in the other image plane

- Simple search and match techniques
  - Can give us disparity (depth) image

Essential Matrix

- Relate 3d world coordinates and image coordinates with epipolar constraints
  - Given 3d relationship
    - $X_2 = RX_1 + T$
  - Image coordinate relationship
    - $X_1 = \lambda_1 x_1$ and $X_2 = \lambda_2 x_2$

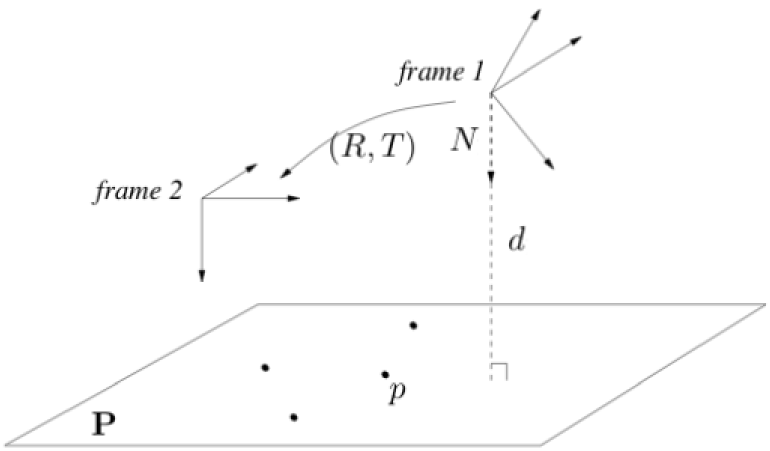
- Map line to a point between images
  - $x_2^T E x_1 = 0$
    - E – 3×3 Essential matrix compactly encodes (R, T)

- Can find the Essential matrix using the 8-point algorithm
  - This gives the camera rotation and translation

Homography

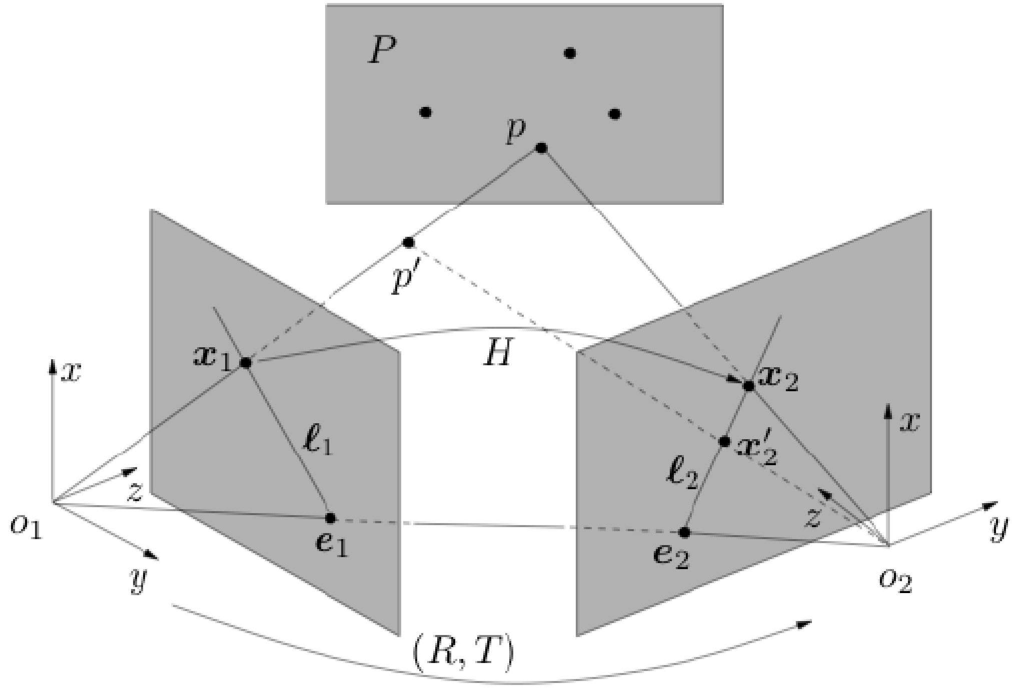
- 8-point algorithm will fail with coplanar points

- Planar relationship
  - $N^T X_1 = n_1 X + n_2 Y + n_3 Z = d$
  - $\frac{1}{d} N^T X_1 = 1$
- 3d relationship
  - $X_2 = R X_1 + T$
  - $X_2 = R X_1 + T \frac{1}{d} N^T X_1$
  - $X_2 = H X_1$
- Homography matrix
  - $H = R + T \frac{1}{d} N^T$
  - 3×3 linear transformation from 3d points



- 2D homography coordinates
  - $X_1 = \lambda_1 x_1$ and $X_2 = \lambda_2 x_2$
  - $\lambda_2 x_2 = H \lambda_1 x_1$
- Homography is a direct mapping between points in the image planes
  - Equality up to a scale factor (universal scale ambiguity)

Induced Homography



- Plane P induces the homography
  - $x_2 \sim H x_1$
- A point *p*' not actually on the plane *P* will get mapped in image 2 as if it were pushed onto P along the ray $\overline{o_1 p'}$

Computing Homography

- Process known as the 4-point algorithm or the Direct Linear Transform (DLT)
- Start from homography constraint
  - $x_2 \sim H x_1$

$$\begin{bmatrix} x'_i \\ y'_i \\ 1 \end{bmatrix} \cong \begin{bmatrix} h_{00} & h_{01} & h_{02} \\ h_{10} & h_{11} & h_{12} \\ h_{20} & h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix}$$

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

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

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

Adapted from R. Szeliski

Solving for Homographies

$$\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x'_1 x_1 & -x'_1 y_1 & -x'_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -y'_1 x_1 & -y'_1 y_1 & -y'_1 \\ & & & & \vdots & & & & \\ x_n & y_n & 1 & 0 & 0 & 0 & -x'_n x_n & -x'_n y_n & -x'_n \\ 0 & 0 & 0 & x_n & y_n & 1 & -y'_n x_n & -y'_n y_n & -y'_n \end{bmatrix} \begin{bmatrix} h_{00} \\ h_{01} \\ h_{02} \\ h_{10} \\ h_{11} \\ h_{12} \\ h_{20} \\ h_{21} \\ h_{22} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}$$

A **h** **0**

2n × 9 **9** **2n**

Defines a least squares problem:

$$\text{minimize } \|\mathbf{A}\mathbf{h} - \mathbf{0}\|^2$$

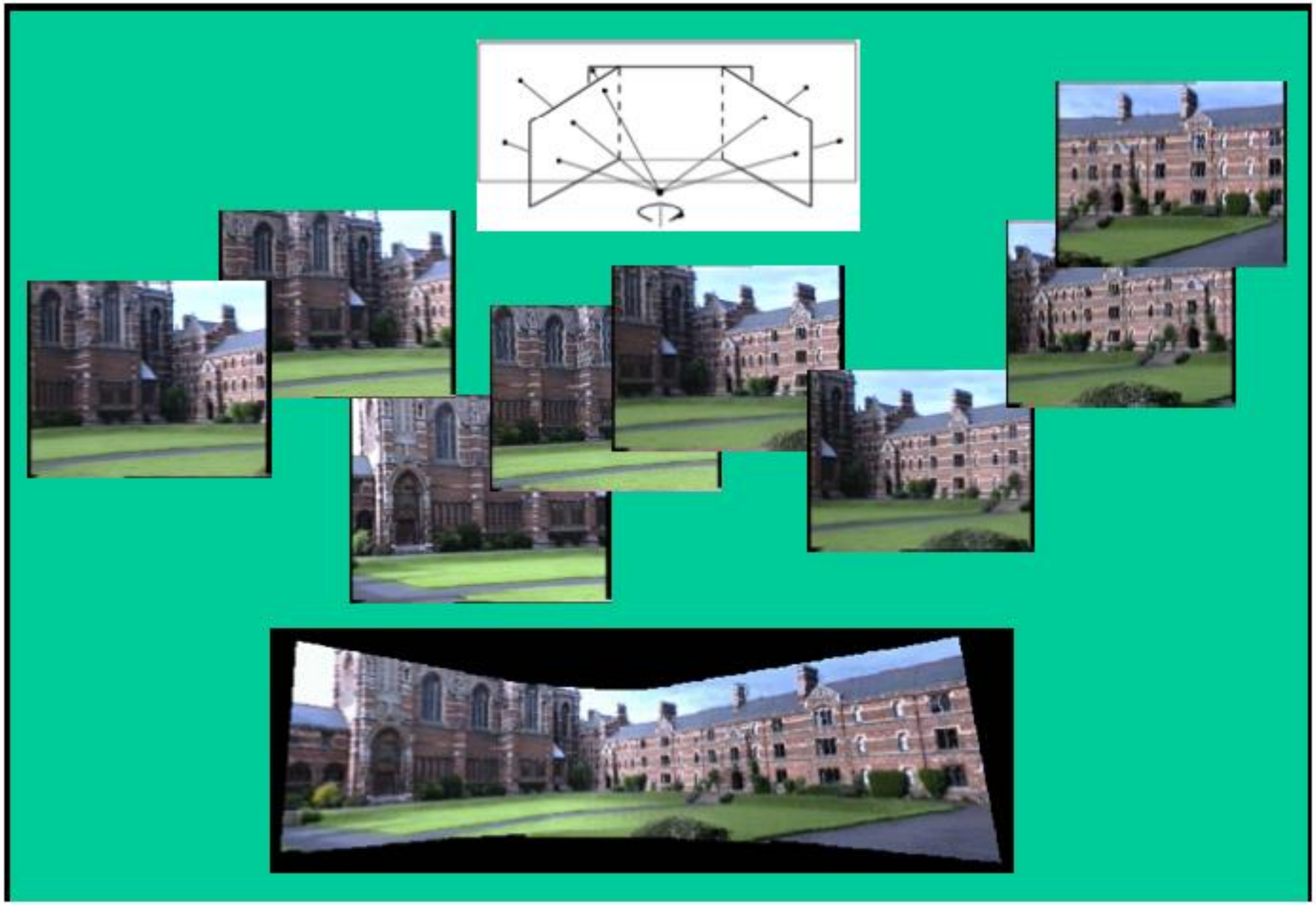
- Since **h** is only defined up to scale, solve for unit vector $\hat{\mathbf{h}}$
- Solution: $\hat{\mathbf{h}}$ = eigenvector of $\mathbf{A}^T\mathbf{A}$ with smallest eigenvalue
- Works with 4 or more points

Adapted from R. Szeliski

Purely Rotating Camera

- No translation between cameras
  - $X_2 = RX_1$
  - $H = R$
- Camera rotating about optical center captures images of a 3d scene as if the scene were on a plane infinitely far away from the camera
- Planar panoramas can be constructed from rotation
  - Select image to be a reference
  - Find corresponding points between overlapping images → derive pairwise homography
  - Blend images together

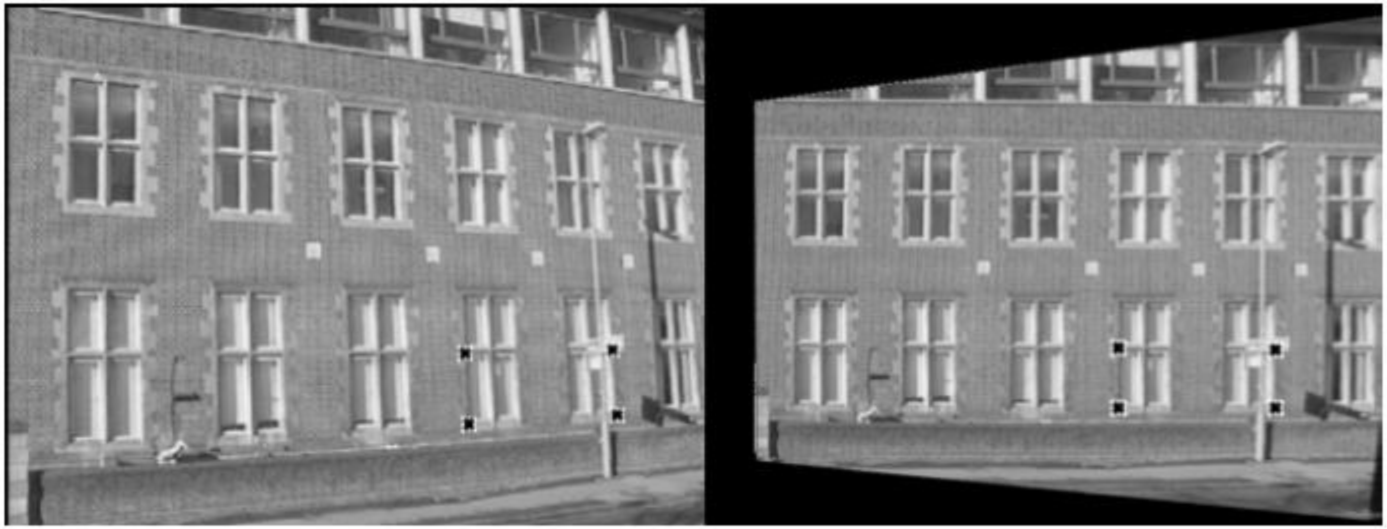
Planar Panorama



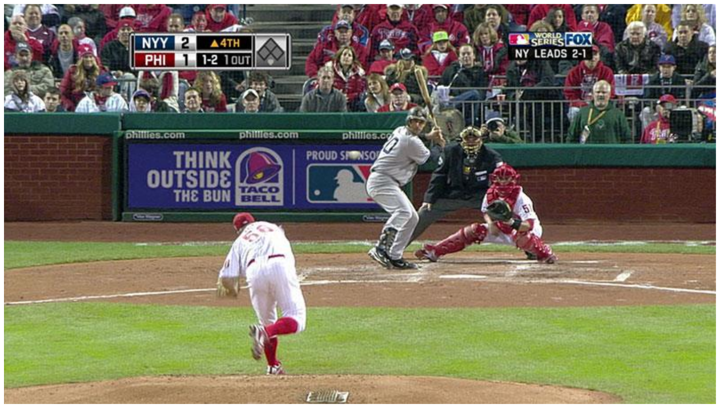
- Notice the bow-tie effect as images further away from the reference are warped outward to fit the homography

Planar Image Rectification

- Given a single perspective image, unwarp it so that a plane has parallel lines
  - Select 4 corners of rectangle, define the output coordinates, compute homography, and warp image



More Fun with Homographies

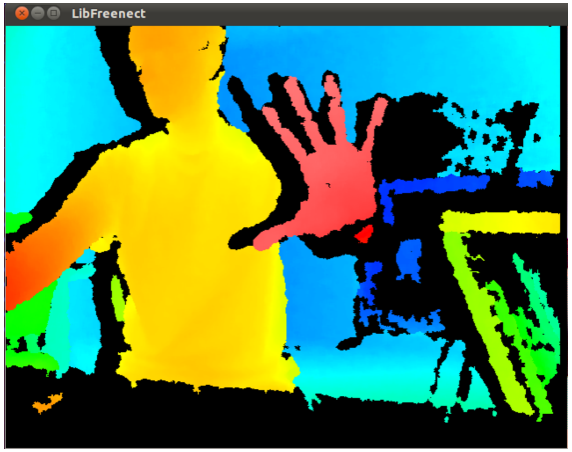


- http://youtu.be/UirmvNktkBc

Stereo Matching

- Given two more images of the same scene or object, compute a representation of its shape

- Common application is generating disparity or depth map
  - Popularized for games recently by Kinect
- What are applications?



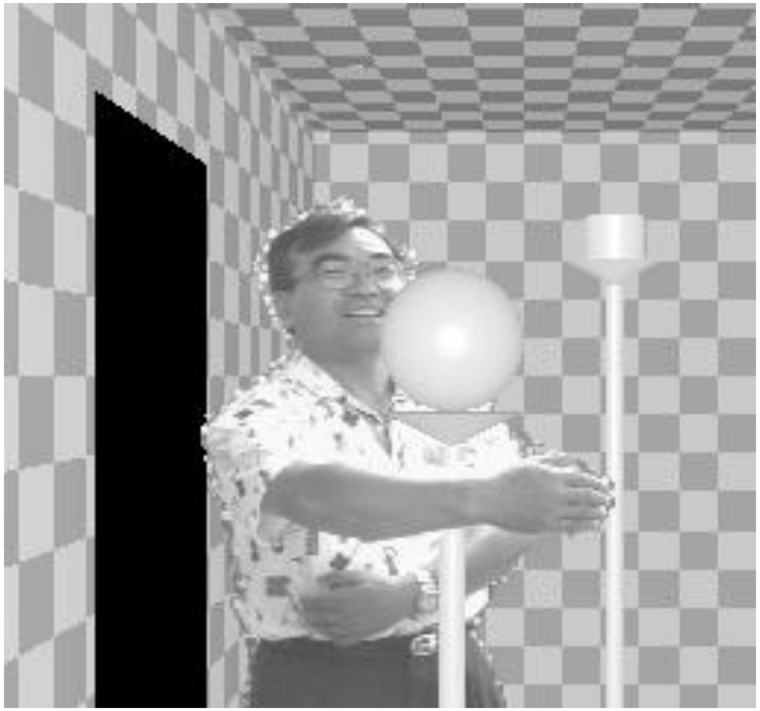
Face modeling

- From one stereo pair to a 3D head model

[Frederic Deverney, INRIA]

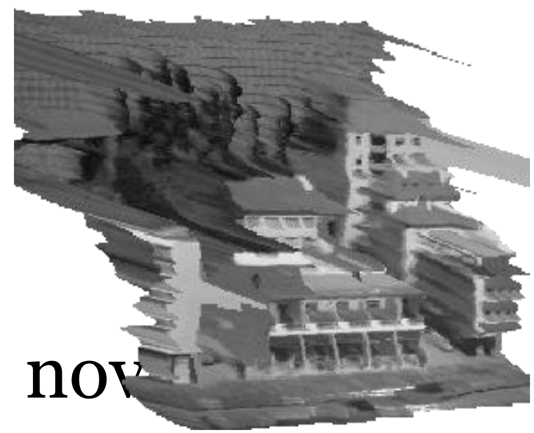
Z-keying: mix live and synthetic

- Takeo Kanade, CMU (Stereo Machine)



View Interpolation

- Given two images with correspondences, *morph* (warp and cross-dissolve) between them [Chen & Williams, SIGGRAPH'93]

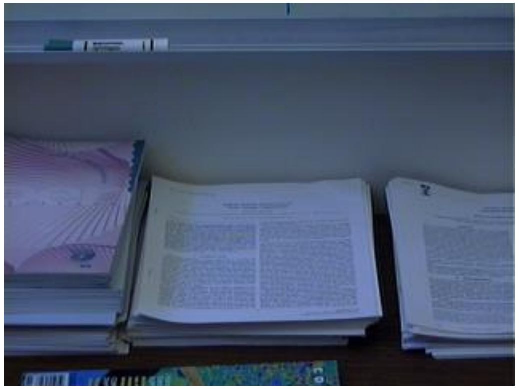


nov

[Matthies,Szeliski,Kanade'88]

More view interpolation

- Spline-based depth map

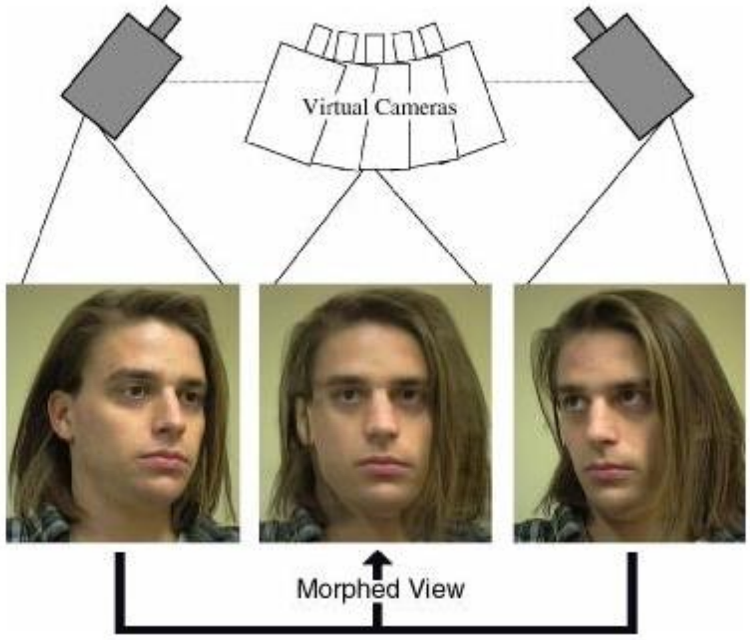


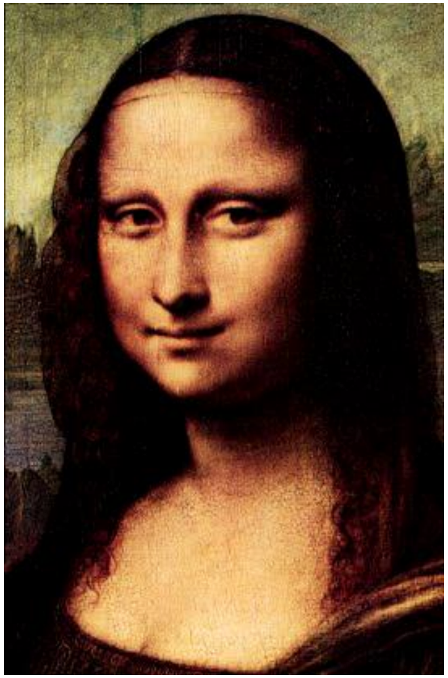
input depth image novel view

- [Szeliski & Kang ‘95]

View Morphing

- Morph between pair of images using epipolar geometry [Seitz & Dyer, SIGGRAPH'96]





Video view interpolation

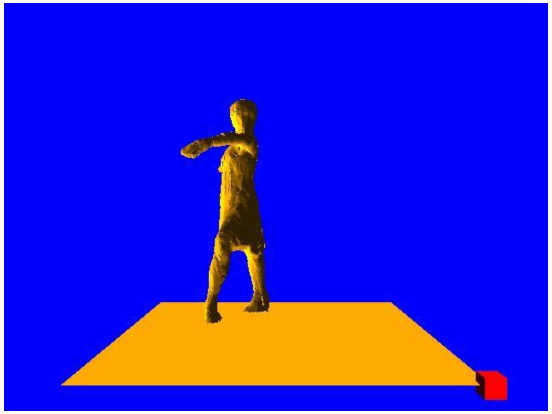
[Zitnick et. al 2004]

- http://research.microsoft.com/en-us/um/people/larryz/MassiveArabesque.wmv
- http://www.youtube.com/watch?v=uqKTbyNoaxE

Virtualized Reality™

- [Takeo Kanade *et al.*, CMU]
  - collect video from 50+ stream
  - reconstruct 3D model sequences





  - steerable version used for SuperBowl XXV "eye vision"

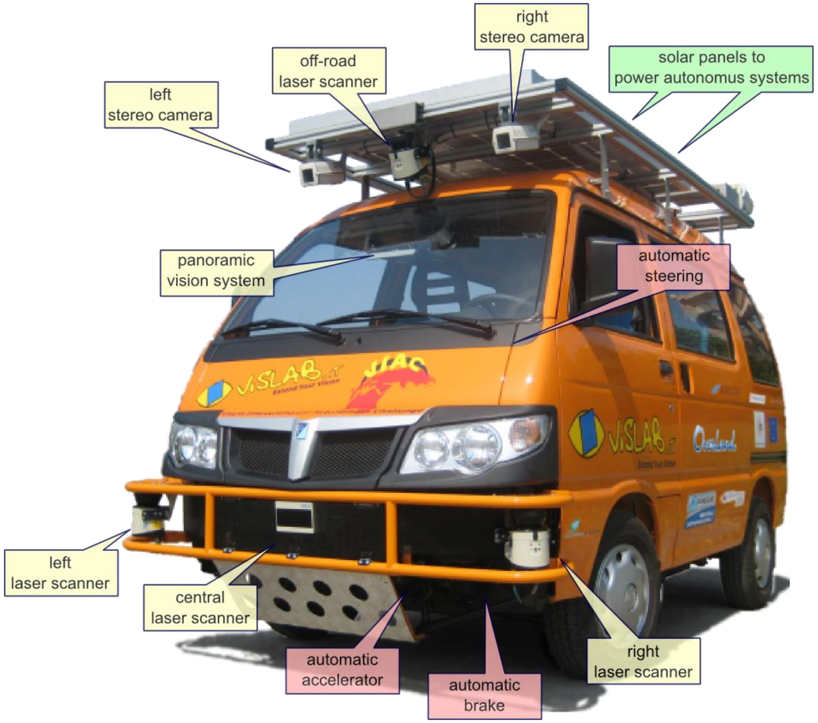
Real-time stereo

Nomad robot searches for meteorites in Antartica
http://www.frc.ri.cmu.edu/projects/meteorobot/index.html

- Used for robot navigation (and other tasks)
  - Software-based real-time stereo techniques

Driver Assistance Systems

- Environment sensing and autonomous control
- http://youtu.be/_imrrzn8NDk?t=12s
- http://youtu.be/-MWVbfia3Dk



http://vislab.it/automotive/
Autonomous drive from Parma, Italy to Shanghai, China

Additional applications

- Real-time people tracking (systems from Pt. Gray Research and SRI)
- “Gaze” correction for video conferencing [Ott,Lewis,Cox InterChi’93]
- Other ideas?

Stereo Matching

- Given two or more images of the same scene or object, compute a representation of its shape

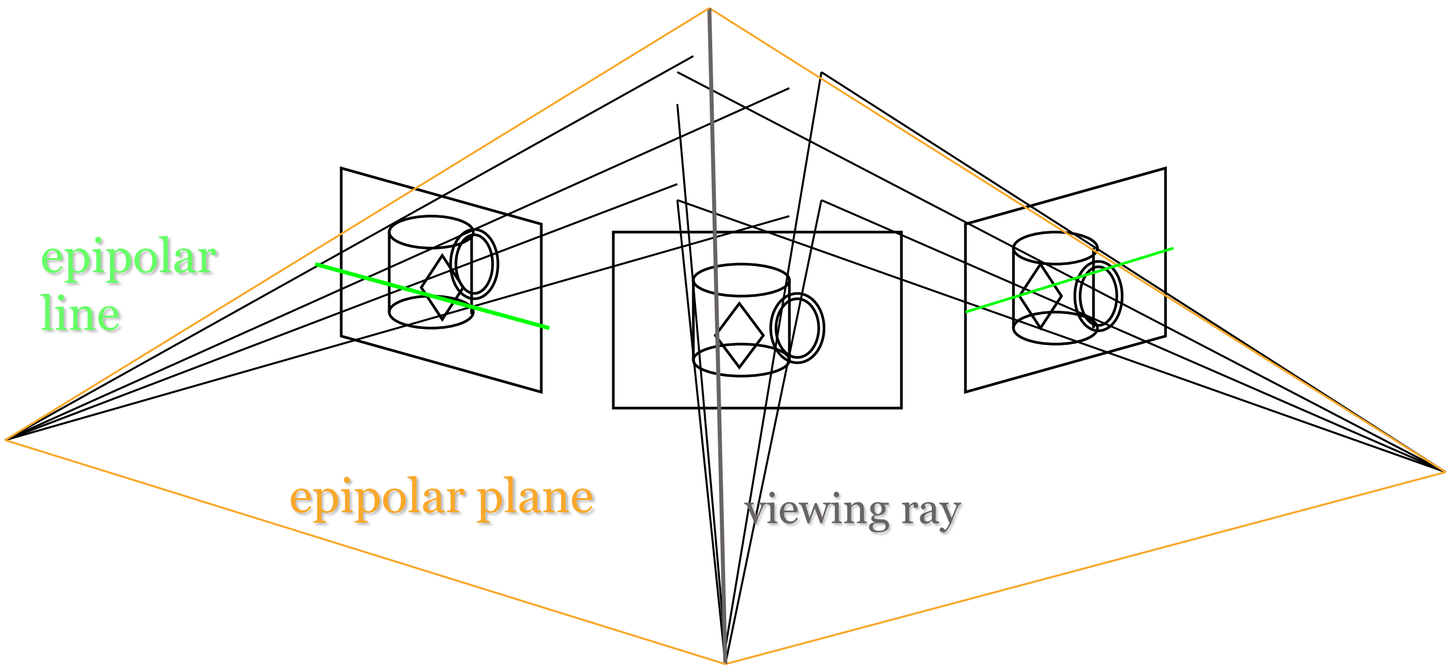
- What are some possible representations?
  - depth maps
  - volumetric models
  - 3D surface models
  - planar (or offset) layers

Stereo Matching

- What are some possible algorithms?
  - match “features” and interpolate
  - match edges and interpolate
  - match all pixels with windows (coarse-fine)
  - use optimization:
    - iterative updating
    - dynamic programming
    - energy minimization (regularization, stochastic)
    - graph algorithms

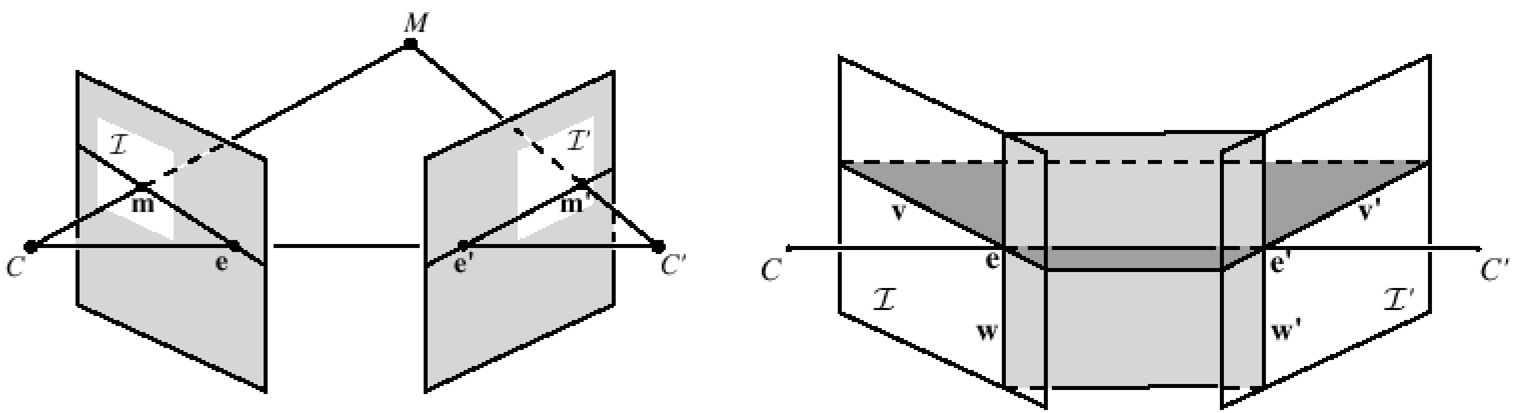
Stereo: epipolar geometry

- Match features along epipolar lines



- **Rectification:** warping the input images (perspective transformation) so that epipolar lines are horizontal

Rectification

- Project each image onto same plane, which is parallel to the epipole
- Resample lines (and shear/stretch) to place lines in correspondence, and minimize distortion
- 

- [Loop and Zhang, CVPR’99]

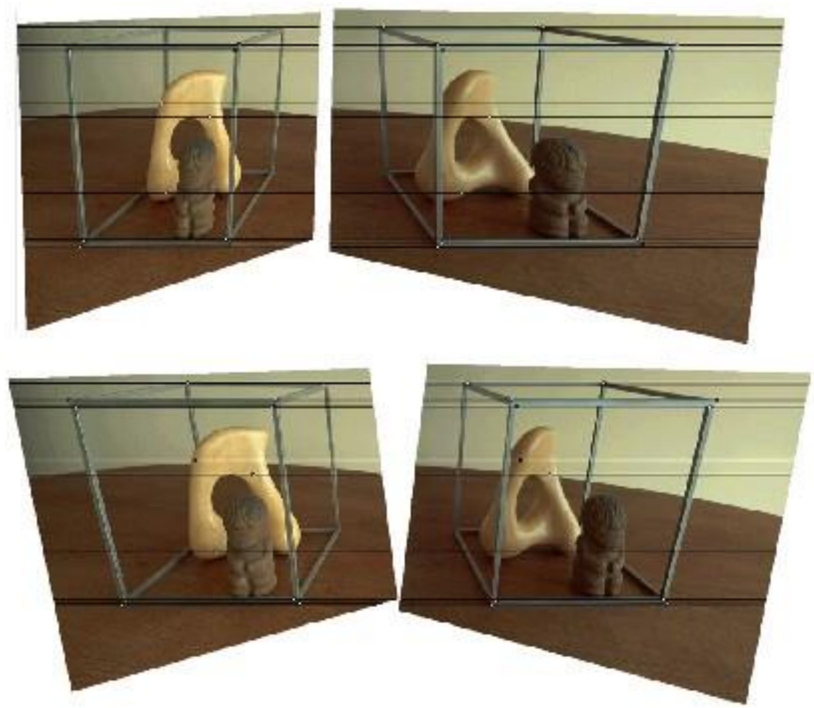
Rectification

(a) Original image pair overlayed with several epipolar lines.

(b) Image pair transformed by the specialized projective mapping $\mathbf{H}_p$ and $\mathbf{H}'_p$. Note that the epipolar lines are now parallel to each other in each image.

BAD!

Rectification



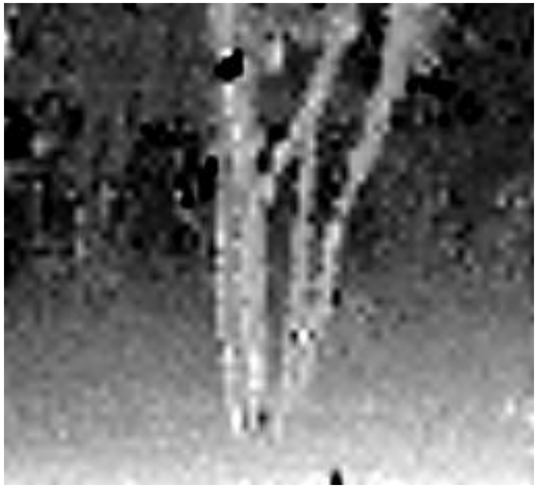
(c) Image pair transformed by the similarity $\mathbf{H}_r$ and $\mathbf{H}'_r$. Note that the image pair is now rectified (the epipolar lines are horizontally aligned).

(d) Final image rectification after shearing transform $\mathbf{H}_s$ and $\mathbf{H}'_s$. Note that the image pair remains rectified, but the horizontal distortion is reduced.

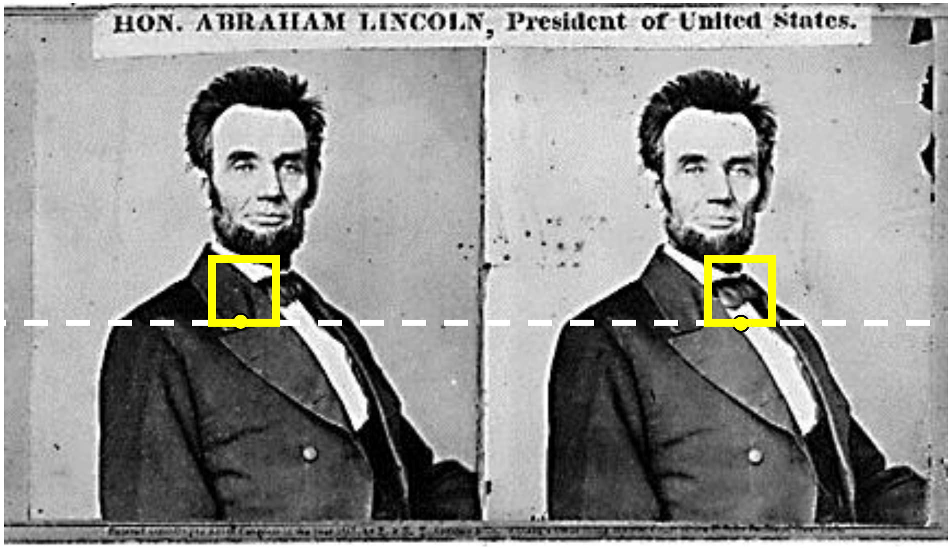
GOOD!

Finding correspondences

- apply feature matching criterion (e.g., correlation or Lucas-Kanade) at *all* pixels simultaneously
- search only over epipolar lines (many fewer candidate positions)



Your basic stereo algorithm



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

Improvement: match ***windows***

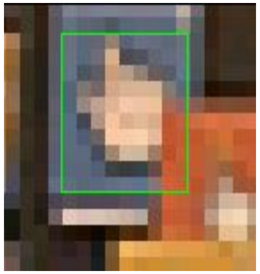
- This should look familar...

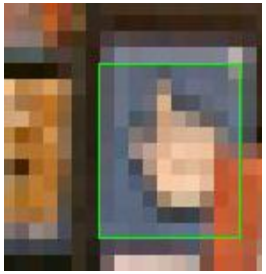
Image registration (revisited)

- How do we determine correspondences?
  - *block matching* or *SSD* (sum squared differences)

$$E(x, y; d) = \sum_{(x',y') \in N(x,y)} [I_L(x'+d, y') - I_R(x', y')]^2$$

d is the *disparity* (horizontal motion)

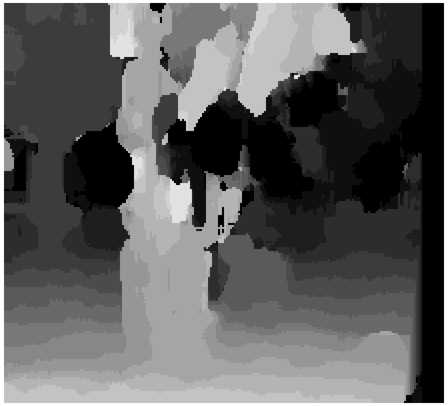


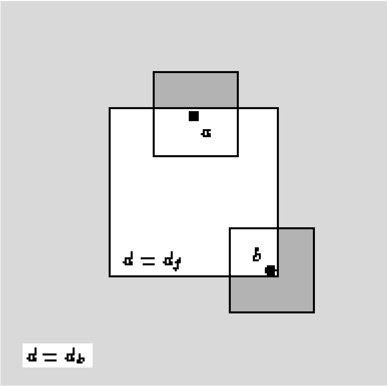


- How big should the neighborhood be?

Neighborhood size

- Smaller neighborhood: more details
- Larger neighborhood: fewer isolated mistakes





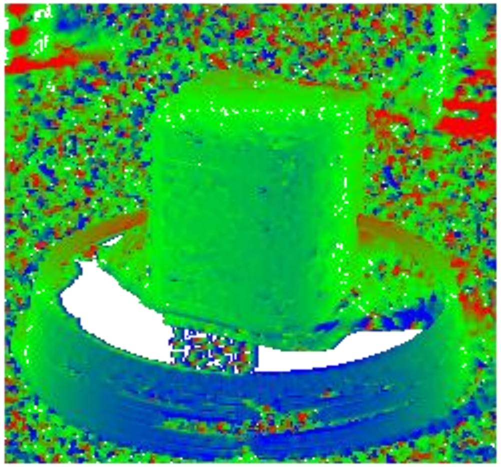
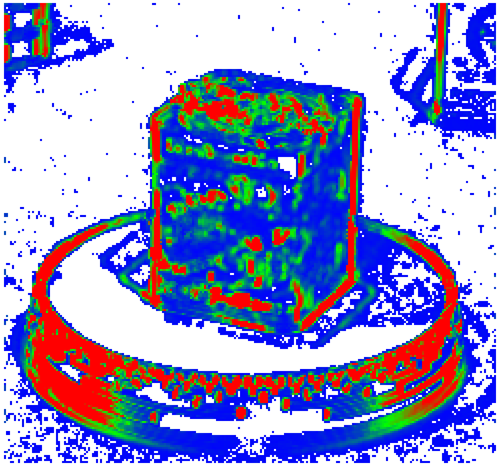
- w = 3 w = 20

Matching criteria

- Raw pixel values (correlation)
- Band-pass filtered images [Jones & Malik 92]
- “Corner” like features [Zhang, …]
- Edges [many people…]
- Gradients [Seitz 89; Scharstein 94]
- Rank statistics [Zabih & Woodfill 94]

Stereo: certainty modeling

- Compute certainty map from correlations

- input depth map certainty map

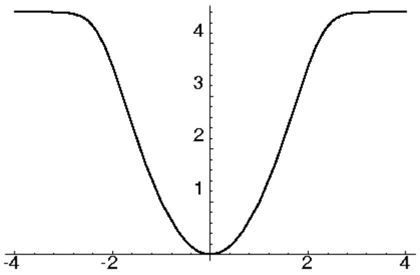
Stereo matching framework

1. For every disparity, compute *raw* matching costs

$$E_0(x, y; d) = \rho(I_L(x' + d, y') - I_R(x', y'))$$

Why use a robust function?

- occlusions, other outliers



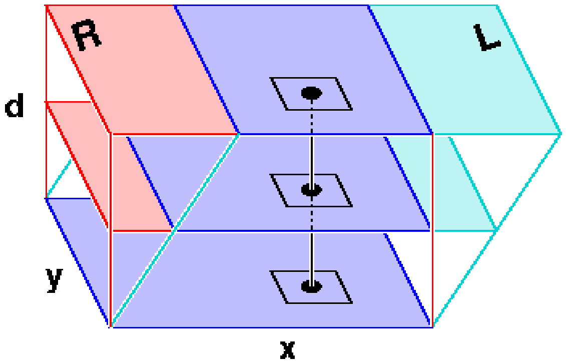
- Can also use alternative match criteria

Stereo matching framework

2. Aggregate costs spatially

$$E(x,y;d) = \sum_{(x',y') \in N(x,y)} E_0(x',y',d)$$

- Here, we are using a *box filter* (efficient moving average implementation)
- Can also use weighted average, [non-linear] diffusion…

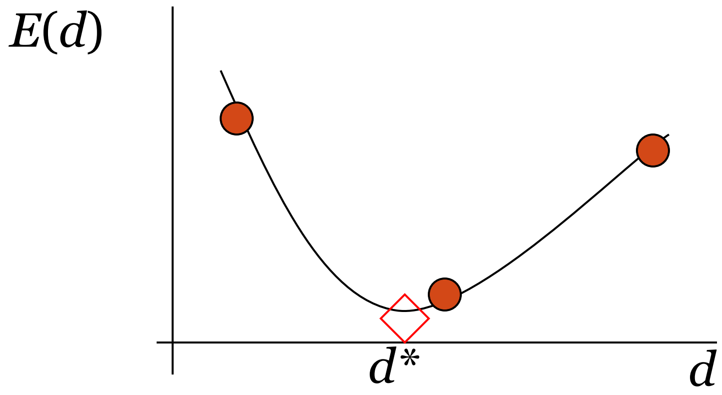


Stereo matching framework

3. Choose winning disparity at each pixel

$$d(x,y) = \arg\min_d E(x,y;d)$$

4. Interpolate to *sub-pixel* accuracy

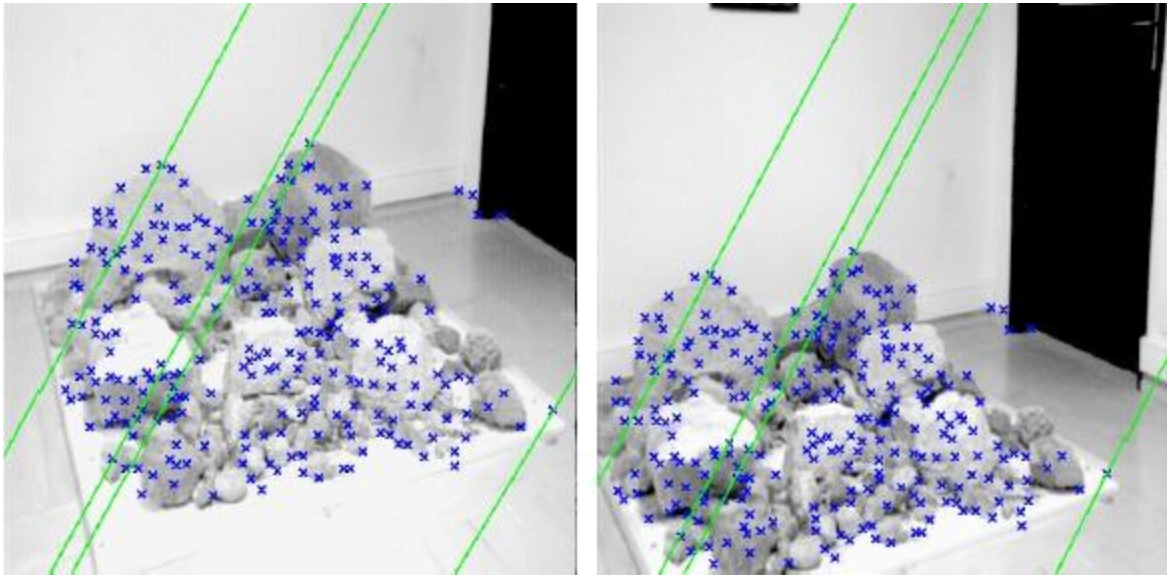


Traditional Stereo Matching

- Advantages:
  - gives detailed surface estimates
  - fast algorithms based on moving averages
  - sub-pixel disparity estimates and confidence
- Limitations:
  - narrow baseline $\Rightarrow$ noisy estimates
  - fails in textureless areas
  - gets confused near occlusion boundaries

Feature-based stereo

- Match “corner” (interest) points



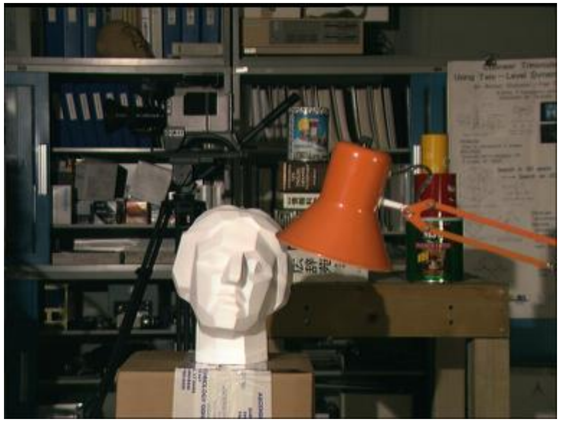
- Interpolate complete solution

Data interpolation

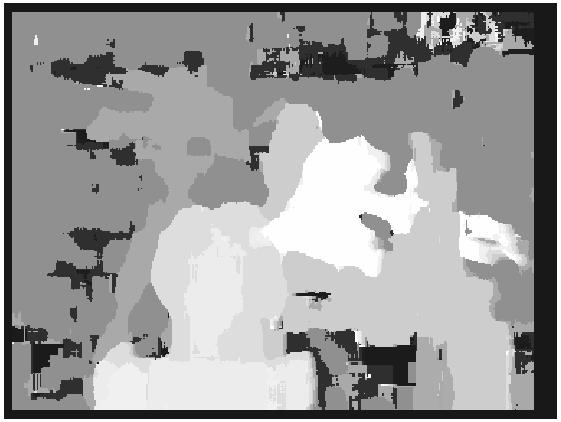
- Given a sparse set of 3D points, how do we *interpolate* to a full 3D surface?
- Scattered data interpolation [Nielson93]
- triangulate
- put onto a grid and fill (use pyramid?)
- place a *kernel function* over each data point
- minimize an energy function

- Lots of more advanced stereo matching options and algorithms exist

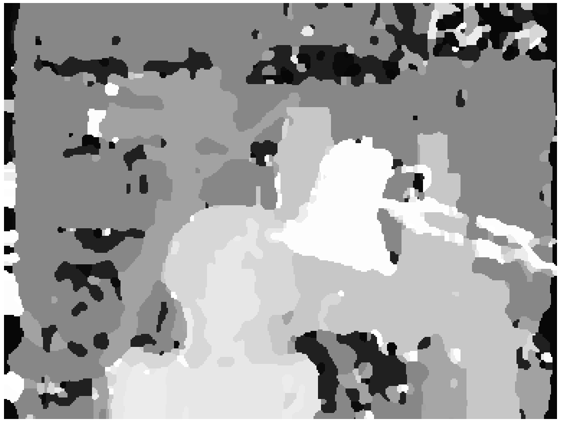
Depth Map Results



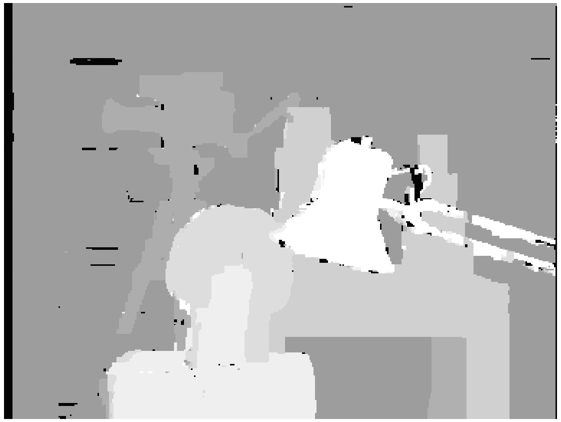
- Input image



Sum Abs Diff



- Mean field



Graph cuts