Stereo

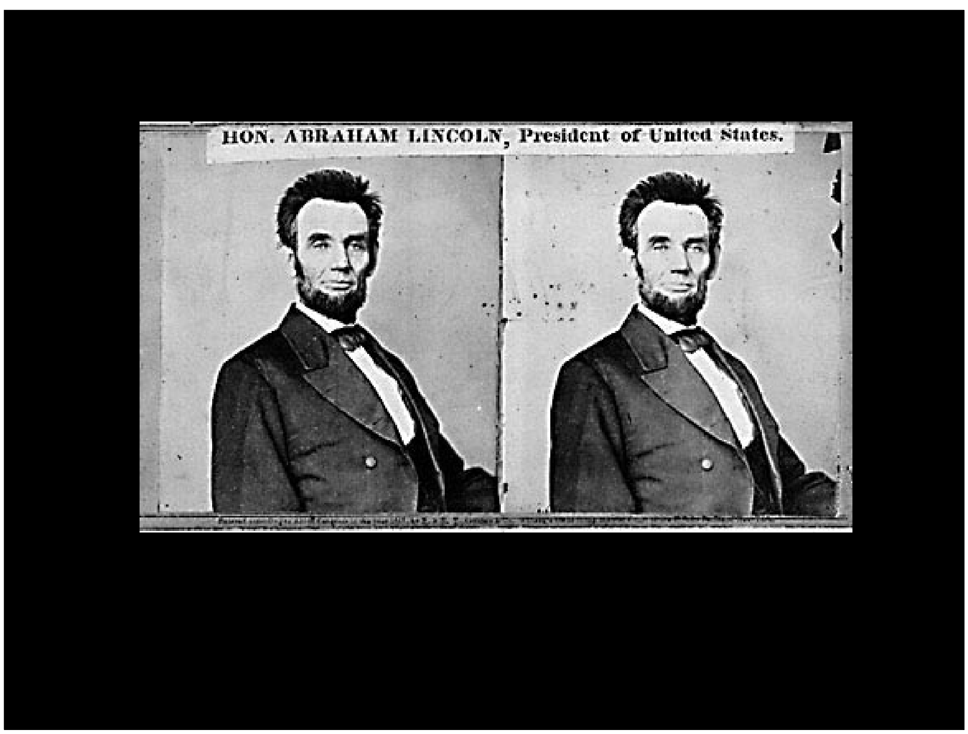
Binocular Stereo

- Motivation
- Epipolar geometry
- Matching
- Depth estimation
- Rectification

Calibration (finish up)

Next Time

- Multiview stereo



Public Library, Stereoscopic Looking Room, Chicago, by Phillips, 1923

Teesta suspension bridge-Darjeeling, India

Mark Twain at Pool Table", no date, UCR Museum of Photography

Woman getting eye exam during immigration procedure at Ellis Island, c. 1905 - 1920 , UCR Museum of Phography

Stereograms online

UCR stereographs
- http://www.cmp.ucr.edu/site/exhibitions/stereo/

The Art of Stereo Photography
- http://www.photostuff.co.uk/stereo.htm

History of Stereo Photography
- http://www.rpi.edu/~ruiz/stereo_history/text/historystereog.html

Double Exposure
- http://home.centurytel.net/s3dcor/index.html

Stereo Photography
- http://www.shortcourses.com/book01/chapter09.htm

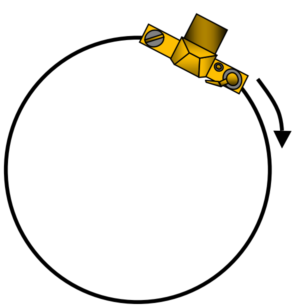
3D Photography links
- http://www.studyweb.com/links/5243.html

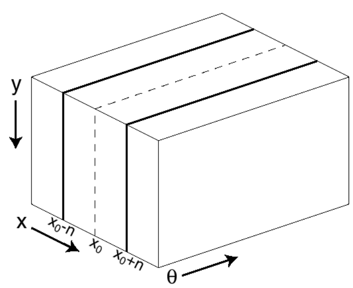
National Stereoscopic Association
- http://204.248.144.203/3dLibrary/welcome.html

Books on Stereo Photography
- http://userwww.sfsu.edu/~hl/3d.biblio.html

Stereo Panoramas

- [Ishiguro, Yamamoto, Tsuji 92]
- [Peleg and Ben-Ezra 99]
- [Shum, Kalai, Seitz 99]



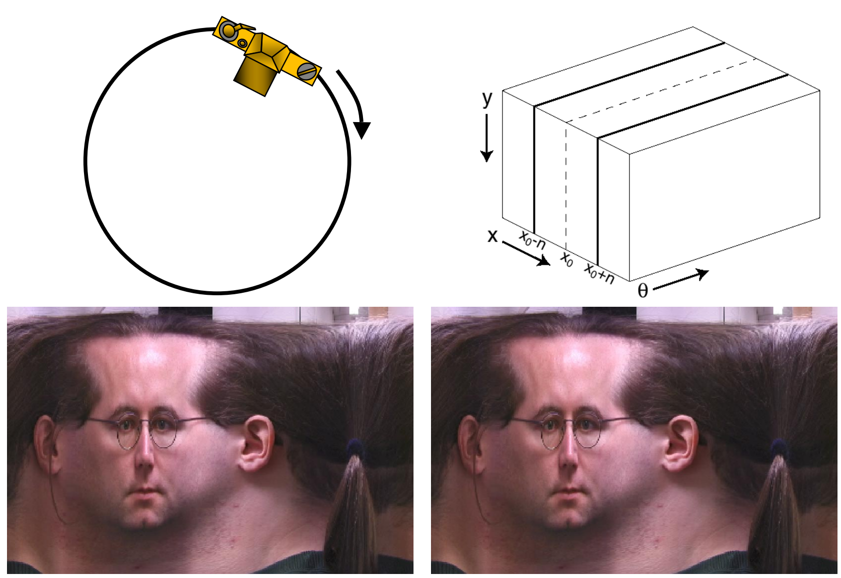


Interactive demo: http://www.cs.columbia.edu/CAVE/

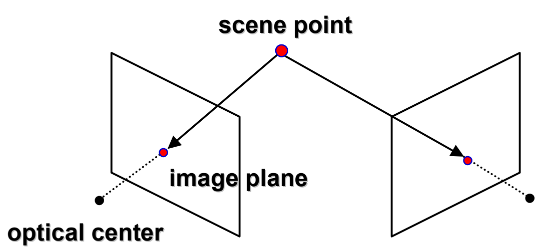
Depth from Stereo Panoramas

Disparity map result

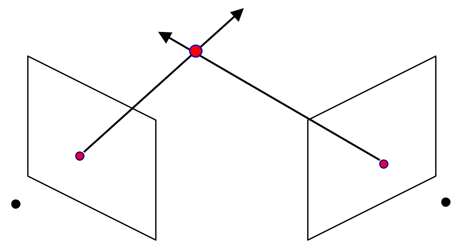
Stereo Cyclographs [Seitz, 2001]



Stereo



Stereo



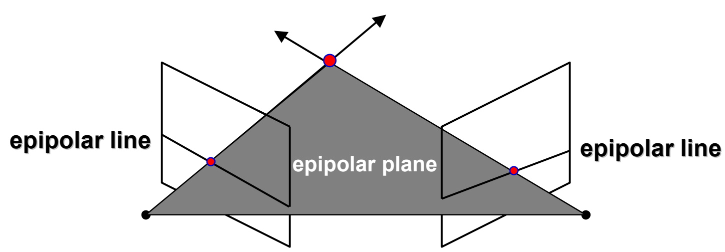
Basic Principle: Triangulation

- Gives reconstruction as intersection of two rays
- Requires
  - calibration
  - ***point correspondence***

Stereo Correspondence

Determine Pixel Correspondence

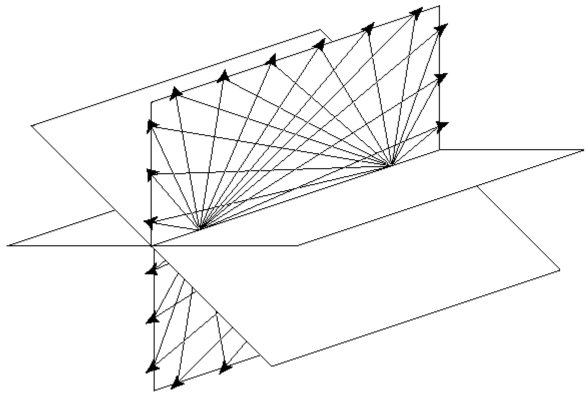
- Pairs of points that correspond to same scene point



Epipolar Constraint

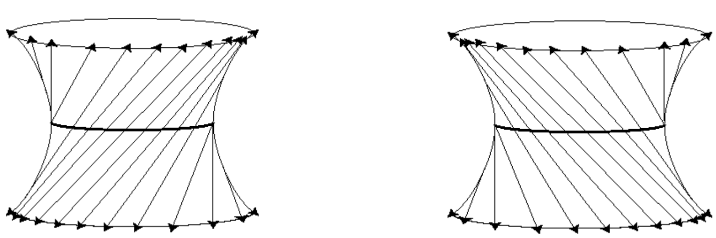
- Reduces correspondence problem to 1D search along *conjugate epipolar lines*
- Java demo: http://www.ai.sri.com/~luong/research/Meta3DViewer/EpipolarGeo.html

Epipolar Geometry

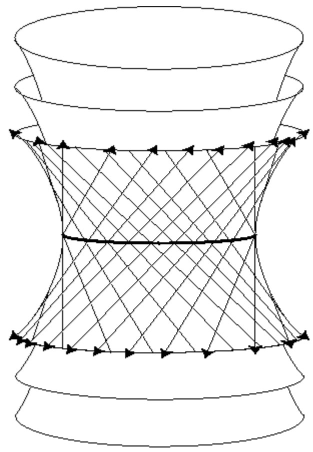


All camera rays lie in a "pencil" of planes

Stereo Panoramas



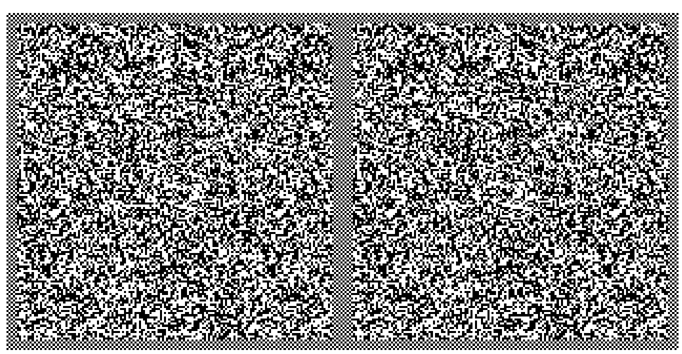
Epipolar Geometry for Stereo Panoramas



Stereo Matching

Features vs. Pixels?

- Do we extract features prior to matching?



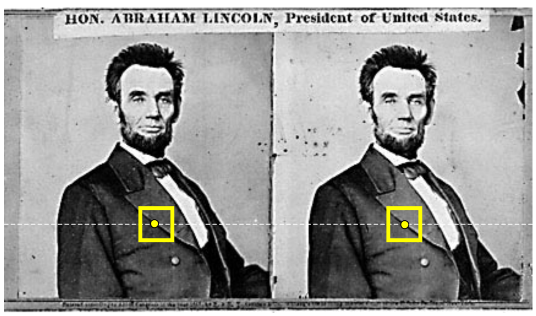
Julesz-style Random Dot Stereogram

Stereo Matching Algorithms

Match Pixels in Conjugate Epipolar Lines

- Assume color of point does not change
- Pitfalls
  - specularities
  - low-contrast regions
  - occlusions
  - image error
  - camera calibration error
- Numerous approaches
  - dynamic programming [Baker 81,Ohta 85]
  - smoothness functionals
  - more images (trinocular, N-ocular) [Okutomi 93]
  - graph cuts [Boykov 00]

Your Basic Stereo Algorithm



For each epipolar line

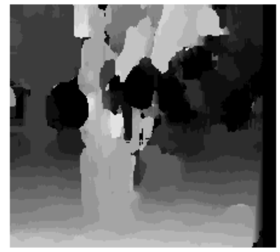
For each pixel in the left image

- compare with every pixel on same epipolar line in right image
- pick pixel with minimum match cost

Improvement: match ***windows***

Window Size

W = 3



W = 20

Smaller window
- more details
- more noise

Larger window
- less noise
- less detail

Better results with *adaptive window*
- T. Kanade and M. Okutomi, *A Stereo Matching Algorithm with an Adaptive Window: Theory and Experiment*,, Proc. International Conference on Robotics and Automation, 1991.
- D. Scharstein and R. Szeliski. Stereo matching with nonlinear diffusion. International Journal of Computer Vision, 28(2):155-174, July 1998

Stereo as Energy Minimization

Matching Cost Formulated as Energy
- "data" term penalizing bad matches

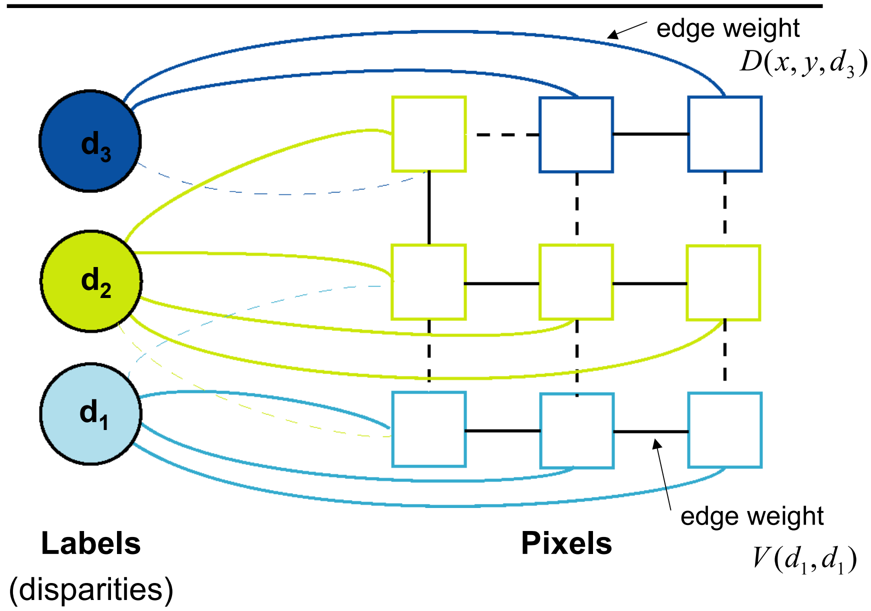
$$D(x,y,d) = \left|\mathbf{I}(x,y) - \mathbf{J}(x+d,y)\right|$$

- "neighborhood term" encouraging spatial smoothness

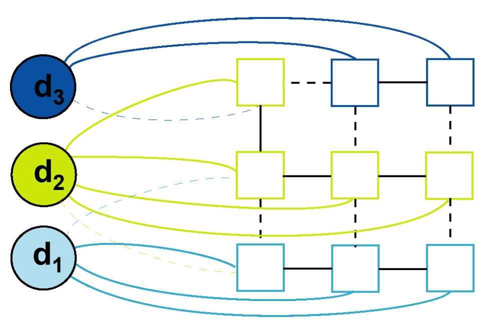
$$V(d_1,d_2) = \text{cost of adjacent pixels with labels d1 and d2}$$
$$= \left|d_1 - d_2\right| \quad \text{(or something similar)}$$

$$E = \sum_{(x,y)} D(x,y,d_{x,y}) + \sum_{neighbors\ (x1,y1),(x2,y2)} V(d_{x1,y1}, d_{x2,y2})$$

Stereo as a Graph Problem [Boykov, 1999]



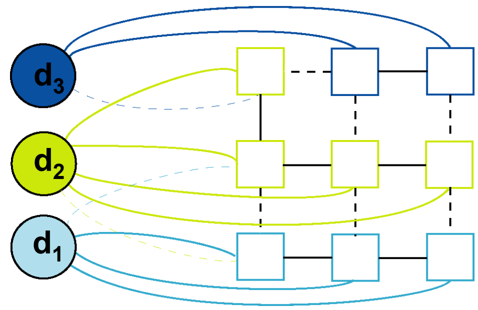
Stereo as a Graph Problem [Boykov, 1999]



Graph Cost

- Matching cost between images
- Meighborhood matching term
- Goal: figure out which labels are connected to which pixels

Stereo Matching by Graph Cuts



Graph Cut

- Delete enough edges so that
  - each pixel is (transitively) connected to exactly one label node
- Cost of a cut: sum of deleted edge weights
- Finding min cost cut equivalent to finding global minimum of energy function

Computing a multiway cut

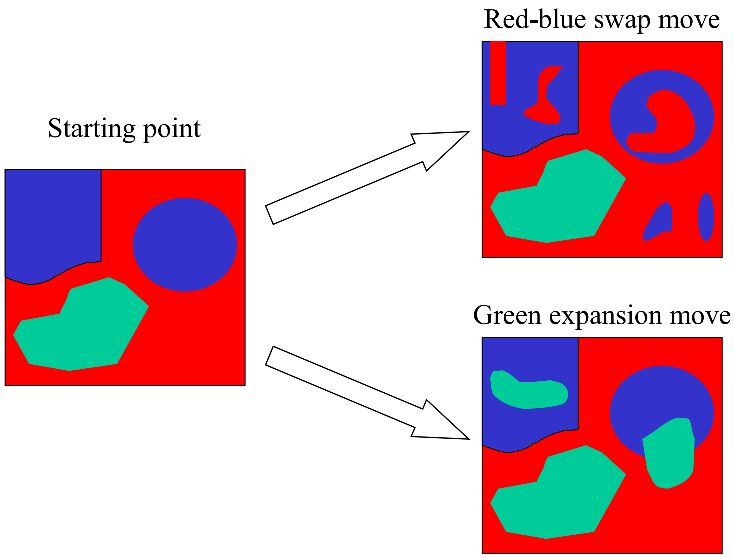
With 2 labels: classical min-cut problem

- Solvable by standard flow algorithms
  - polynomial time in theory, nearly linear in practice
- More than 2 terminals: NP-hard
  [Dahlhaus *et al.*, STOC '92]

Efficient approximation algorithms exist

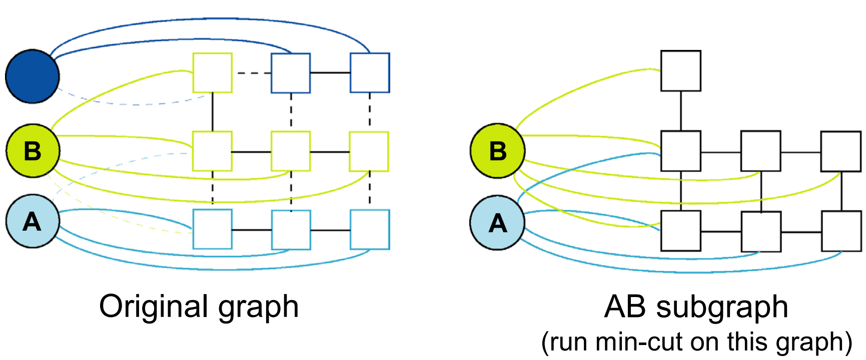
- Within a factor of 2 of optimal
- Computes local minimum in a strong sense
  - even very large moves will not improve the energy
- Yuri Boykov, Olga Veksler and Ramin Zabih, Fast Approximate Energy Minimization via Graph Cuts, International Conference on Computer Vision, September 1999.

Move Examples



The Swap Move Algorithm

1. Start with an arbitrary labeling
2. Cycle through every label pair *(A,B)* in some order
   - 2.1 Find the lowest *E* labeling within a single *AB*-swap
   - 2.2 Go there if it's lower *E* than the current labeling
3. If *E* did not decrease in the cycle, we're done
   Otherwise, go to step 2

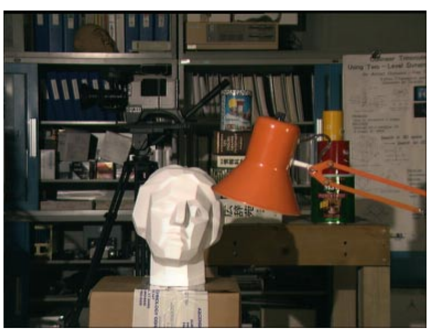


The expansion move algorithm

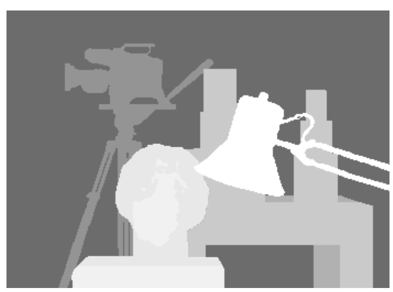
1. Start with an arbitrary labeling
2. Cycle through every label *A* in some order
   2.1 Find the lowest *E* labeling within a single *A*-expansion
   2.2 Go there if it's lower *E* than the current labeling
3. If *E* did not decrease in the cycle, we're done Otherwise, go to step 2

Stereo Results

- Data from University of Tsukuba
- Similar results on other images without ground truth

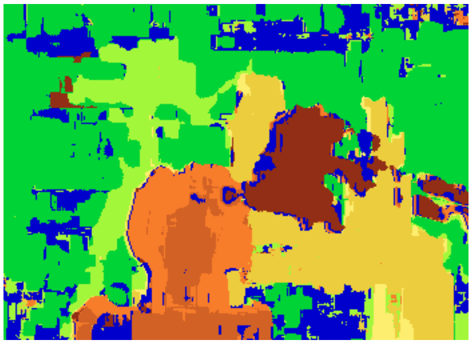


Scene



Ground truth

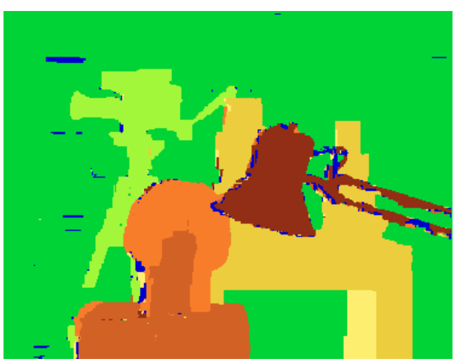
Results with Window Correlation



Normalized correlation
(best window size)

Ground truth

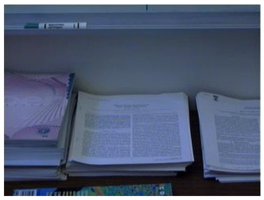
Results with Graph Cuts



Graph Cuts
(Potts model *E,*
expansion move algorithm)

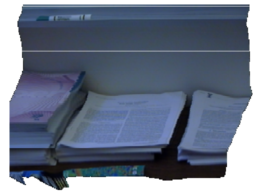
Ground truth

Depth from Disparity

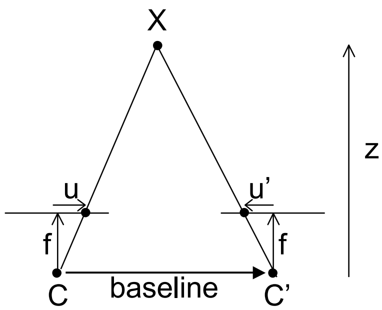


input image (1 of 2)

depth map
[Szeliski & Kang '95]

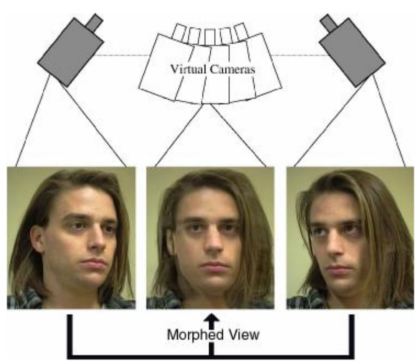


3D rendering



$$disparity = u - u' = \frac{baseline * f}{z}$$

Disparity-Based Rendering



Render new views from raw disparity

- S. M. Seitz and C. R. Dyer, View Morphing, *Proc. SIGGRAPH 96*, 1996, pp. 21-30.
- L. McMillan and G. Bishop. Plenoptic Modeling: An Image-Based Rendering System, *Proc. of SIGGRAPH 95*, 1995, pp. 39-46.

Image Rectification

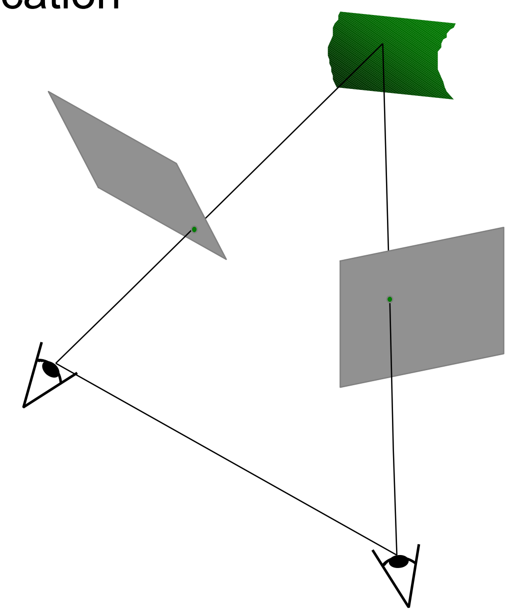


Image Rectification

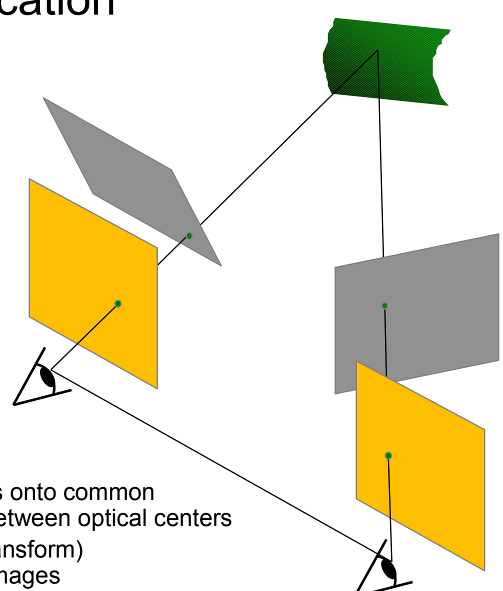


Image Reprojection

- reproject image planes onto common plane parallel to line between optical centers
- a homography (3x3 transform) applied to both input images
- C. Loop and Z. Zhang. Computing Rectifying Homographies for Stereo Vision. IEEE Conf. Computer Vision and Pattern Recognition, 1999.

Stereo Reconstruction Pipeline

Steps

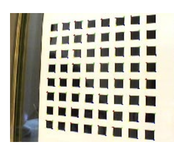
- Calibrate cameras
- Rectify images
- Compute disparity
- Estimate depth

Calibration from (unknown) Planes

What's the image of a plane under perspective?

- a homography (3x3 projective transformation)

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \sim \begin{bmatrix} * & * & * \\ * & * & * \\ * & * & * \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \mathbf{H} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$



- preserves lines, incidence, conics

H depends on camera parameters (**A**, **R**, **t**)

$$\mathbf{H} = \mathbf{A}\begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix}$$

where $\mathbf{A} = \begin{bmatrix} fa & c & u_c \\ 0 & f & v_c \\ 0 & 0 & 1 \end{bmatrix}$ $\mathbf{R} = \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{r}_3 \end{bmatrix}$

Given 3 homographies, can compute A, R, t

- Z. Zhang. A flexible new technique for camera calibration. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 22(11):1330-1334, 2000.
- http://research.microsoft.com/~zhang/Calib/

Calibration from Planes

1. Compute homography $\mathbf{H}^i$ for 3+ planes
   - Doesn't require knowing 3D
   - Does require mapping between at least 4 points on plane and in image (both expressed in 2D plane coordinates)
2. Solve for **A, R, t** from $\mathbf{H}^1, \mathbf{H}^2, \mathbf{H}^3$
   - 1plane if only *f* unknown
   - 2 planes if (f, u_c, v_c) unknown
   - 3+ planes for full $\boldsymbol{K}$
3. Introduce radial distortion model

$$\begin{aligned} \hat{u} &= u + u(\kappa_1 r^2 + \kappa r^4) \\ \hat{v} &= v + v(\kappa_1 r^2 + \kappa r^4) \end{aligned}$$

where

$$r = \sqrt{(u - u_c)^2 + (v - v_c)^2}$$

Solve for **A**, **R**, **t**, κ_1, κ_2

- nonlinear optimization (using Levenberg-Marquardt)