Announcements

- Midterm went out on Tuesday (due next Tuesday)
- Project 3 out today

Recovering 3D from images

So far, we've relied on a human to provide depth cues
- parallel lines, reference points, etc.

How might we do this automatically?
- What cues in the image provide 3D information?

Visual cues

Shading

Merle Norman Cosmetics, Los Angeles

Visual cues

Shading

Texture

The Visual Cliff, **by William Vandivert, 1960**

Visual cues

Shading

Texture

Focus

From *The Art of Photography*, Canon

Visual cues

Shading

Texture

Focus

Motion

Visual cues

Shading

Texture

Focus

Motion

Others:
- Highlights
- Shadows
- Silhouettes
- Inter-reflections
- Symmetry
- Light Polarization
- ...

Shape From X
- X = shading, texture, focus, motion, ...
- In this class we'll focus on the motion cue

Stereo

Single image stereogram, by Niklas Een

Readings
- Trucco & Verri, Chapter 7
  - Read through 7.3.2, also 7.3.7 and 7.4, 7.4.1. The rest is optional.

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

Teesta suspension bridge-Darjeeling, India

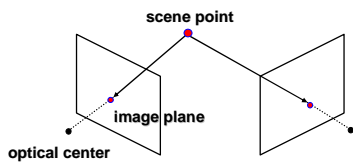Mark Twain at Pool Table", no date, UCR Museum of Photography

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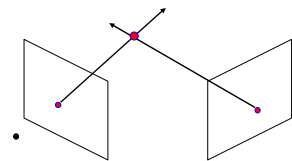Island, c. 1905 - 1920 , UCR Museum of Phography

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

A free pair of red-blue stereo glasses can be ordered from Rainbow Symphony Inc
- http://www.rainbowsymphony.com/freestuff.html

Stereo
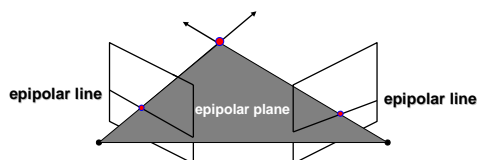

scene point
image plane
optical center

Stereo

Basic Principle: Triangulation
- Gives reconstruction as intersection of two rays
- Requires
  - calibration
  - *point correspondence*
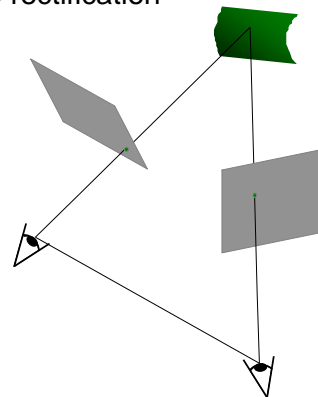
Stereo correspondence

Determine Pixel Correspondence
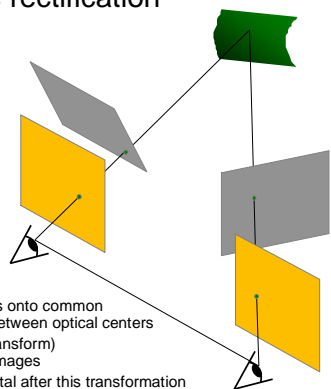- Pairs of points that correspond to same scene point

epipolar line **epipolar plane** **epipolar line**

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

Stereo image rectification

Stereo 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
- pixel motion is horizontal after this transformation
- C. Loop and Z. Zhang. Computing Rectifying Homographies for Stereo Vision. IEEE Conf. Computer Vision and Pattern Recognition, 1999.

Stereo matching algorithms

Match Pixels in Conjugate Epipolar Lines
- Assume brightness constancy
- This is a tough problem
- Numerous approaches
    - dynamic programming [Baker 81,Ohta 85]
    - smoothness functionals
    - more images (trinocular, N-ocular) [Okutomi 93]
    - graph cuts [Boykov 00]
- A good survey and evaluation: http://www.middlebury.edu/stereo/

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...
- Can use Lukas-Kanade or discrete search (latter more common)

Window size

$W = 3$ $W = 20$

Effect of window size
- Smaller window
  - +
  - –
- Larger window
  - +
  - –

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 results

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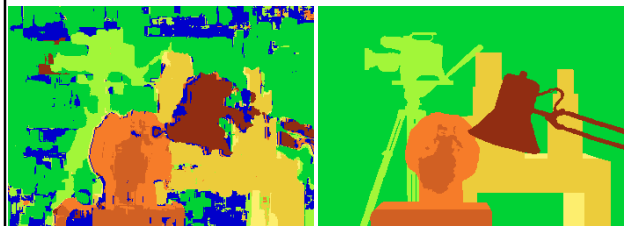- Similar results on other images without ground truth

Scene   Ground truth

Results with window correlation

Window-based matching   Ground truth
(best window size)

Results with better method

State of the art method   Ground truth

Boykov et al., Fast Approximate Energy Minimization via Graph Cuts.
International Conference on Computer Vision, September 1999.
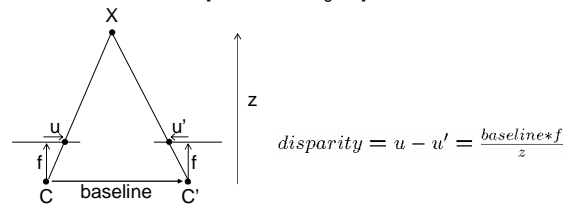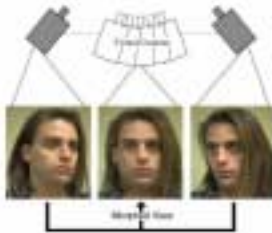
Depth from disparity

input image (1 of 2)   depth map   3D rendering
                              [Szeliski & Kang '95]

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

Image-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.

Stereo reconstruction pipeline

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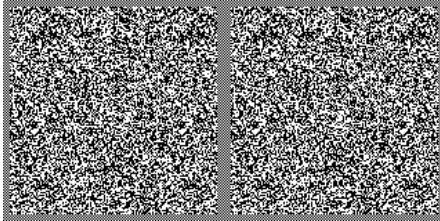- Rectify images
- Compute disparity
- Estimate depth

What will cause errors?
- Camera calibration errors
- Poor image resolution
- Occlusions
- Violations of brightness constancy (specular reflections)
- Large motions
- Low-contrast image regions

Stereo matching

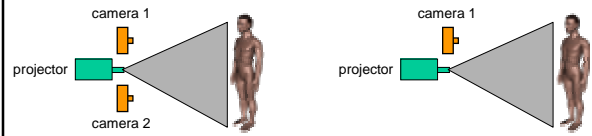Features vs. Pixels?
- Do we extract features prior to matching?

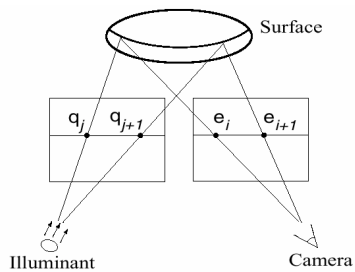Julesz-style Random Dot Stereogram

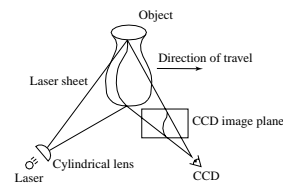## Active stereo with structured light

Li Zhang's one-shot stereo

camera 1

projector

camera 2

camera 1

projector

Project "structured" light patterns onto the object
- simplifies the correspondence problem

Active stereo with structured light

Surface

q_j q_{j+1} e_i e_{i+1}

Illuminant

Camera

Laser scanning

Object

Direction of travel

Laser sheet

CCD image plane

Cylindrical lens

Laser

CCD

Digital Michelangelo Project
http://graphics.stanford.edu/projects/mich/

Optical triangulation
- Project a single stripe of laser light
- Scan it across the surface of the object
- This is a very precise version of structured light scanning

Portable 3D laser scanner (this one by Minolta)

Real-time stereo

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

real-time
stereo video

Used for robot navigation (and other tasks)
- Several software-based real-time stereo techniques have been developed (most based on simple discrete search)

Summary

Things to take away from this lecture
- Cues for 3D inference, shape from X
- Epipolar geometry
- Stereo image rectification
- Stereo matching
  - window-based epipolar search
  - effect of window size
  - sources of error
- Active stereo
  - structured light
  - laser scanning