more on stereo;
space-time techniques
rectified stereo pair

find corresponding pixels

"disparity" map

Monday, April 4, 2011
• fast window-based correlation
• diffusion
• energy minimization
• graph cuts
• space-time alternatives
outline

- fast window-based correlation
- diffusion
- energy minimization
- graph cuts
- space-time alternatives
window-based correlation

• for each pixel
  • for each disparity
    • for each pixel in window
    • compute difference
    • find disparity with minimum SSD
reverse order of loops

• for each disparity
  • for each pixel
    • for each pixel in window
      • compute difference
  • find disparity with minimum SSD at each pixel
incremental computation

- given SSD of a window, at some disparity
incremental computation

* want: SSD at next location

---

Image 1

Image 2
incremental computation

- subtract contributions from leftmost column, add contributions from rightmost column:

Image 1

Image 2
selecting window size

- small window: more detail, but more noise
- large window: more robustness, less detail
- example:
selecting window size

3 pixel window

20 pixel window
non-square windows

- compromise: have a larger window, but higher weight near the center
- example: Gaussian
- for each disparity
  - for each pixel
    - compute weighted SSD
outlines

- fast window-based correlation
- diffusion
- energy minimization
- graph cuts
- space-time alternatives
disparity space

* measure of intensity difference at each pixel and for each possible disparity

\[ E_o(x, y, d) = \rho(I_L(x + d, y) - I_R(x, y)) \]

\[ \rho(l - r) = (l - r)^2 \]

\[ d(x, y) = \arg \min_{d \in D} E(x, y, d) \]

helpful to think of computing \( d(x,y) \) as solving a labeling problem
diffusion

for n iterations:

\[ E(i, j, d) \leftarrow (1 - 4\lambda)E(i, j, d) + \lambda \sum_{(k,l) \in N_4} E(i + k, j + l, d) \]
non-linear diffusion

- to prevent blurring even more, only perform diffusion in ambiguous regions
- for each pixel, compute certainty
  - high certainty iff one disparity has low error, all others have high error
- for each pixel, only perform diffusion if certainty goes up
certainty metrics for non-linear diffusion

- winner margin: normalized difference between lowest and second-lowest error

\[
C(i, j) = \frac{E_{\text{min}2} - E_{\text{min}}}{\sum_d E_d}
\]

- entropy:

\[
C(i, j) = -\sum_d p(d) \log p(d) \quad p(d) = \frac{e^{-E_d}}{\sum_{d'} e^{-E_{d'}}}
\]
results

- Scharstein and Szeliski, 1996

3 pixel window  20 pixel window  nonlinear diffusion
outline

• fast window-based correlation
• diffusion
• energy minimization
• graph cuts
• space-time alternatives
energy minimization

• another approach to improve quality of correspondences

• assumption: disparities vary (mostly) smoothly

• minimize energy function:

\[ E_{\text{data}} + \lambda E_{\text{smoothness}} \]

how well does disparity match data

how well does disparity match neighbors (regularization)
energy minimization

• if data and energy terms are nice (continuous, smooth, etc.) can try to minimize via gradient descent, etc.
• in practice: disparities only piecewise smooth
• design smoothness function that doesn’t penalize large jumps too much

\[ E_{\text{smoothness}}(\alpha, \beta) = \min(|\alpha - \beta|, K) \]
energy minimization

- hard to find global minima of non-smooth functions
  - many local minima
  - NP-hard
- practical algorithms look for approximate minima (e.g., simulated annealing)
energy minimization via graph cuts

- Boykov, Veksler, and Zabih, 2001
- define a class of operations
  - e.g., change some of the disparities to “a”
- look for operations that reduce energy
- terminate when no operations of the class being considered reduce energy
energy minimization via graph cuts

- different kinds of operations:

- challenge: how to find the operations that reduce energy the most
energy minimization via graph cuts

- represent possible operations as cuts through graphs
- graph cut: minimal subset of edges that separates two (given) nodes of graph
- fast algorithms for computing minimal-cost cuts
energy minimization via graph cuts

- \( \alpha - \beta \) swap: interchange \( \alpha \) and \( \beta \) labels
energy minimization via graph cuts

• $\alpha$ expansion: add pixels to $\alpha$ label
results

Image

Ground truth

swap algorithm

expansion algorithm
results

image

ground truth

normalized correlation

simulated annealing
energy minimization for image smoothing

apply same principle: image should be close to original image, but piecewise smooth

original image  noise added  local energy minimum with one-pixel changes  local energy minimum with $\alpha$-expansion
outline

- fast window-based correlation
- diffusion
- energy minimization
- graph cuts
- space-time alternatives
standard stereo

calibrated camera rig
“unstructured” light

use same algorithm to find correspondences

calibrated camera rig

projector

Monday, April 4, 2011
“unstructured” light
“unstructured” light

✦ advantages:
  - more robust matches w/ same algorithm
  - don’t have to calibrate projector (as opposed compare to active techniques we’ll see)

✦ disadvantages:
  - requires projector
  - Lambertian surfaces
window size

- recall: trade-off between robustness (larger) and accuracy (smaller)

3 pixel window

20 pixel window

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space-time stereo

• recent technique [Davis et al. 2005] that generalizes “structured light” and classic stereo search methods

• very simple idea:
  - record stereo images over a sequence of different (uncalibrated) lighting conditions
  - consider windows in space and time
space-time stereo

left camera

right camera
space-time stereo

\[ V_{ST}(x_1, t_0) \]

\[ V_{ST}(x_2, t_0) \]
space-time stereo

✦ advantages:
- can use small spatial windows (accuracy)
- can use long time windows (robustness)

✦ disadvantages:
- requires several images of static scene taken with synchronized cameras
- need to select light patterns carefully to avoid ambiguities in matching
space-time stereo

[Davis]
space-time stereo

Spatial Stereo

Temporal Stereo
space-time stereo
space-time stereo
Assignment 4

- explore “disparity space”
  - SSD-based stereo matching
  - diffusion techniques
  - space-time analysis