New Techniques in Computational photography

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Some (tentative) definitions

• *computational imaging*
  – any image formation method that requires a digital computer
  – first used in medical imaging and remote sensing

• *computational photography*
  – computational imaging techniques that enhance or extend the capabilities of digital photography
  – output is an ordinary photograph, but one that could not have been taken by a traditional camera
19 papers on computational photography at SIGGRAPH 2007

- **Image Analysis & Enhancement**
  - Image Deblurring with Blurred/Noisy Image Pairs
  - Photo Clip Art
  - Scene Completion Using Millions of Photographs

- **Image Slicing & Stretching**
  - Soft Scissors: An Interactive Tool for Realtime High Quality Matting
  - Seam Carving for Content-Aware Image Resizing

- **Light Field & High-Dynamic-Range Imaging**
  - Veiling Glare in High-Dynamic-Range Imaging
  - Ldr2Hdr: On-the-Fly Reverse Tone Mapping of Legacy Video and Photographs

- **Appearance Capture & Editing**
  - Multiscale Shape and Detail Enhancement from Multi-light Image Collections

- **Computational Cameras**
  - Active Refocusing of Images and Videos
  - Multi-Aperture Photography
  - Dappled Photography: Mask-Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing
  - Image and Depth from a Conventional Camera with a Coded Aperture

- **Big Images**
  - Capturing and Viewing Gigapixel Images
  - Efficient Gradient-Domain Compositing Using Quadtrees
  - Image Upsampling via Imposed Edge Statistics
  - Joint Bilateral Upsampling

- **Video Processing**
  - Factored Time-Lapse Video
  - Computational Time-Lapse Video
  - Real-Time Edge-Aware Image Processing With the Bilateral Grid
### Computational Photography

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[Nayar, Tumblin]
Content-aware image resizing
[Avidan SIGGRAPH 2007]

- **to compress**: remove pixels along lowest-energy seams, ordered using dynamic programming
- **to expand**: insert pixels along seams that, if removed in order, would yield the original image
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• **to expand**: insert pixels in order, where seams can be removed

• application to object removal
Content-aware image resizing
[Avidan SIGGRAPH 2007]

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• application to object removal

• **Find the missing shoe!** (original in upper-left)
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• Find the missing shoe! (original in upper-left)
Removing camera shake
[Fergus SIGGRAPH 2006]

- Image with camera shake
- Photoshop Unsharp Mask
- Deconvolution
- Blur kernel
### Computational Photography

#### Computational Processing
- Processing of a set of captured images to create new images.

#### Computational Imaging/Optics
- Capture of optically coded images and computational decoding to produce new images.
- Examples: Mosaicing, Matting, Super-Resolution, Multi-Exposure HDR, Light Field from Multiple View, Structure from Motion, Shape from X.

#### Computational Sensor
- Detectors that combine sensing and processing to create smart pixels.
- Examples: Artificial Retina, Retinex Sensors, Adaptive Dynamic Range Sensors, Edge Detect Chips, Focus of Expansion Chips, Motion Sensors.

#### Computational Illumination
- Adapting and Controlling Illumination to Create revealing image.
- Examples: Flash/no flash, Lighting domes, Multi-flash for depth edges, Dual Photos, Polynomial texture Maps, 4D light source.

### [Nayar, Tumlin]
Gigapixel mosaicing
[xyrez.com]

The camera
Gigapixel mosaicing
[xyrez.com]

A gigapixel image of Half Dome
Gigapixel mosaicing
[xyrez.com]
Gigapixel mosaicing
[xyrez.com]
High dynamic range (HDR) imaging
High dynamic range (HDR) imaging

Too dark
High dynamic range (HDR) imaging

Too bright
High dynamic range (HDR) imaging

Tone mapped combination, but...
High dynamic range (HDR) imaging is still hard to do no cameras automatically take HDR pictures (How much to bracket?) Tone mapped combination, but...
Image stacks
[Agarwala SIGGRAPH 2004]

- multi-shot images
  - shoot until everybody has smiled at least once
Image stacks
[Agarwala SIGGRAPH 2004]

– segment
Digital Photomontage
[Agarwala SIGGRAPH 2004]

– assemble
Digital Photomontage
[Agarwala SIGGRAPH 2004]

• remove foreground objects that don’t appear in all shots as the camera translates (based on median filter)
Removing camera shake (again)

- deconvolve long-exposure (blurred) image, using short-exposure (noisy) image as prior
  [Yuan SIGGRAPH 2007]
Stanford Multi-Camera Array
[Wilburn SIGGRAPH 2005]

- 640 × 480 pixels × 30 fps × 128 cameras
- synchronized timing
- continuous streaming
- flexible arrangement
Synthetic aperture photography
Example using 45 cameras
[Vaish CVPR 2004]
one camera’s view  
synthetic aperture view

(movie is available at http://graphics.stanford.edu/projects/array)
Digital Photography

Image processing applied to captured images to produce better images.


Computational Processing

Processing of a set of captured images to create new images.

Examples: Mosaicing, Matting, Super-Resolution, Multi-Exposure HDR, Light Field from Mutiple View, Structure from Motion, Shape from X.

Computational Imaging/Optics

Capture of optically coded images and computational decoding to produce new images.

Examples: Coded Aperture, Optical Tomography, Diaphanography, SA Microscopy, Integral Imaging, Assorted Pixels, Catadioptric Imaging, Holographic Imaging.

Computational Sensor

Detectors that combine sensing and processing to create smart pixels.

Examples: Artificial Retina, Retinex Sensors, Adaptive Dynamic Range Sensors, Edge Detect Chips, Focus of Expansion Chips, Motion Sensors.

Computational Illumination

Adapting and Controlling Illumination to Create revealing image

Examples: Flash/no flash, Lighting domes, Multi-flash for depth edges, Dual Photos, Polynomial texture Maps, 4D light source.

[Nayar, Tumblin]
Light field photography using a handheld plenoptic camera

Ren Ng, Marc Levoy, Mathieu Brédif, Gene Duval, Mark Horowitz and Pat Hanrahan

(Proc. SIGGRAPH 2005 and TR 2005-02)
Plenoptic camera

[Ng SIGGRAPH 2005]
Prototype camera

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array

125 µ square-sided microlenses

\[ 4000 \times 4000 \text{ pixels} \div 292 \times 292 \text{ lenses} = 14 \times 14 \text{ pixels per lens} \]
Typical image captured by camera (show here at low res)
Digital refocusing
Example of digital refocusing
Example of digital refocusing
Example of digital refocusing
Example of digital refocusing
Example of digital refocusing
Refocusing portraits

(movie is available at http://refocusimaging.com)
Light Field Microscopy

Marc Levoy, Ren Ng, Andrew Adams, Matthew Footer, and Mark Horowitz

(Proc. SIGGRAPH 2006)
A traditional microscope

eyepiece

intermediate image plane

objective

specimen
A light field microscope (LFM)
Example light field micrograph

ordinary microscope

light field microscope

movies are available at http://graphics.stanford.edu/projects/lfmicroscope

focal stack

panning sequence
Other examples

- **ferm spore** (60x, autofluorescence)
- **Golgi-stained neurons** (40x, transmitted light)
- **zebrafish optic tectum** (calcium imaging of neural activity)

(movies are available at http://graphics.stanford.edu/projects/lfmicroscope)
Alternatives to microlenses

- heterodyning using structured masks
  [Veeraraghavan & Raskar SIGGRAPH 2007]
Alternatives to microlenses

- heterodyning using structured masks
  [Veeraraghavan & Raskar SIGGRAPH 2007]
Controlling focus using coded or structured apertures

- binary mask at the aperture plane
  [Levin & Fergus SIGGRAPH 2007]

Fourier transforms of blur patterns for different amounts of defocus
(note locations of zeros)
Controlling focus using coded or structured apertures

- binary mask at the aperture plane
  [Levin & Fergus SIGGRAPH 2007]
Controlling focus using coded or structured apertures

- multiple concentric annulus apertures
  [Green & Durand SIGGRAPH 2007]
Controlling focus using coded or structured apertures

- Binary mask at the aperture plane
  - Levin & Fergus SIGGRAPH 2007
- Multiple concentric annulus apertures
  - Green & Durand SIGGRAPH 2007
Wavefront coding
[Dowski 1995]

profile of cubic phase plate

ray trace through a normal lens
lens plus cubic phase plate

MTFs through lens and cubic phase plate
Wavefront coding
[Dowski 1995]

- normal lens
- stopped down
- wavefront coded
- after processing

- normal
- wavefront
- processed
# Computational Photography

**Digital Photography**

Image processing applied to captured images to produce better images.

Examples:
- Interpolation, Filtering
- Enhancement, Dynamic Range Compression
- Color Management, Morphing, Hole Filling
- Artistic Image Effects
- Image Compression, Watermarking.

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**Film-like Photography with bits**

Computational Camera

**Computational Illumination**

Smart Light

[Nayar, Tumblin]
Coded-exposure photography
[Raskar SIGGRAPH 2006]

Continuous shutter

Fluttered shutter

Fourier transforms
Coded-exposure photography
[Raskar SIGGRAPH 2006]
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Flash-noflash photography
[Agrawal SIGGRAPH 2005]

- compute ambient + flash – features in sum that don’t appear in ambient alone (as determined from image gradients) (except where ambient image is nearly black)
Separation of direct and global reflections
[Nayar SIGGRAPH 2006]
Separation of direct and global reflections
[Nayar SIGGRAPH 2006]
Other applications of structured masks conjugate to the scene (not the aperture)

- using structured illumination to separate singly from multiply scattered light in 3D scenes [Nayar SIGGRAPH 2006]
- using a structured mask to reduce veiling glare in cameras, i.e. scattering in the camera body & optics [Talvala SIGGRAPH 2007]

before and after glare removal
Large online photo collections

- Facebook
  - 3 billion photos
- Flickr
  - 9 billion photos
- Google Library Project
  - 50 million books × 300 pages = 15 billion images
- Google Earth
- Google StreetView Project
  - formerly the Stanford CityBlock Project
Computational photography using online photograph collections

- scene completion
- texture synthesis
- image-based image search
Image inpainting / image completion

- extrapolation along isophotes
  + anisotropic diffusion
  to prevent crossings
  [Bertalmio & Sapiro SIGGRAPH 2000]
Image inpainting / image completion

• extrapolation along isophotes + anisotropic diffusion to prevent crossings [Bertalmio & Sapiro SIGGRAPH 2000]

• extrapolation for structure (from edge-preserving smoothing) + texture synthesis for the rest [Bertalmio & Sapiro CVPR 2003]
Image inpainting / image completion

- extrapolation along isophotes + anisotropic diffusion to prevent crossings [Bertalmio & Sapiro SIGGRAPH 2000]
- extrapolation for structure (from edge-preserving smoothing) + texture synthesis for the rest [Bertalmio & Sapiro CVPR 2003]
- search for matches from a large database + seam finding using graph-cut algorithm + gradient blending & integration [Hays & Efros SIGGRAPH 2007]
App #2 for large image collections: texture synthesis

• tiling from exemplar with overlaps (“quilting”) + seam-finding using graph-cut algorithm
  [Efros & Freeman SIGGRAPH 2001]
App #2 for large image collections: texture synthesis

- tiling from exemplar with overlaps (“quilting”) + seam-finding using graph-cut algorithm [Efros & Freeman SIGGRAPH 2001]
- neighborhood search from 3D exemplar + histogram matching to enforce appearance [Kopf et al. SIGGRAPH 2007]

useful for 3D models and volume data
App #3: image-based image search

- search on text tags + feature-based classification using categories learned from manually tagged training sets [hot topic in CVPR community]
App #3: image-based image search

- segmentation of “photo clip art” from background
- estimation of object size, orientation, and lighting
- gradient blending & integration

[Lalonde & Efros SIGGRAPH 2007]
Other applications of image-based image-search

• Tell me about this building/painting.
• Where have I seen this person before?
• Find this (broken part) in an online catalog.
• Show me an online review of this restaurant.