Synthetic aperture photography and illumination using arrays of cameras and projectors

Marc Levoy

Outline

technologies
- large camera arrays
- large projector arrays
- camera-projector arrays

optical effects
- synthetic aperture photography
- synthetic aperture illumination
- synthetic confocal imaging

applications
- partially occluding environments
- weakly scattering media

examples
- foliage
- murky water

Multi-camera systems

- multi-camera vision systems
- omni-directional vision
- 1D camera arrays
- 2D camera arrays

Stanford multi-camera array

- 640 x 480 pixels x 30 fps x 128 cameras ÷ 18:1 MPEG = 512 Mbs

- snapshot or video
- synchronized timing
- continuous streaming
- cheap sensors & optics
- flexible arrangement
Applications for the array

- How are the cameras arranged?
  - tightly packed
  - widely spaced
  - intermediate spacing
  → high-performance imaging
  → light fields
  → synthetic aperture photography

Cameras tightly packed: high-performance imaging

- high-resolution
  → by abutting the cameras’ fields of view
- high speed
  → by staggering their triggering times
- high dynamic range
  → mosaic of shutter speeds, apertures, density filters
- high precision
  → averaging multiple images improves contrast
- high depth of field
  → mosaic of differently focused lenses

Abutting fields of view

Q. Can we align images this well?

A. Yes.
High-speed photography

Harold Edgerton, Stopping Time, 1964

A virtual high-speed video camera

[Wilburn, 2004 (submitted)]

- 52 cameras, each 30 fps
- packed as closely as possible
- staggered firing, short exposure
- result is 1560 fps camera
- continuous streaming
- no triggering needed

Example

A virtual high-speed video camera

[Wilburn, 2004 (submitted)]

- 52 cameras, 30 fps, 640 x 480
- short exposure, staggered firing
- result is 1536 fps camera
- no triggering needed
- scalable to more cameras
- limited by available photons
- overlap exposure times?

100 cameras
3072 fps
Cameras tightly packed: high-X imaging

- high-resolution
  - by abutting the cameras’ fields of view
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High dynamic range (HDR)

- overcomes one of photography’s key limitations
  - negative film = 250:1 (8 stops)
  - paper prints = 50:1
  - [Debevec97] = 250,000:1 (18 stops)
  - hot topic at recent SIGGRAPHs

Seeing through murky water

- scattering decreases contrast
- noise limits perception in low contrast images
- averaging multiple images decreases noise
Seeing through murky water

- scattering decreases contrast, but does not blur
- noise limits perception in low contrast images
- averaging multiple images decreases noise

Cameras tightly packed: high-X imaging

- high-resolution
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High depth-of-field

- adjacent views use different focus settings
- for each pixel, select sharpest view

[Haeberli90]
Synthetic aperture photography

Long-range synthetic aperture photography

Synthetic pull-focus
Synthetic aperture photography using an array of mirrors

- 11-megapixel camera
- 22 planar mirrors
Synthetic aperture illumination

• technologies
  – array of projectors
  – array of microprojectors
  – single projector + array of mirrors

• applications
  – bright display
  – autostereoscopic display [Matusik 2004]
  – confocal imaging [this paper]
Confocal scanning microscopy

light source

pinhole

photocell

Confocal scanning microscopy

light source

pinhole

photocell

Confocal scanning microscopy

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Confocal scanning microscopy

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[UMC SUNY/Stonybrook]
Synthetic confocal scanning

- $\rightarrow$ 5 beams
- $\rightarrow$ 0 or 1 beam

• works with any number of projectors $\geq 2$
• discrimination degrades if $\bullet$ point to left of
• no discrimination for $\bullet$ points to left of
• slow!
• poor light efficiency

Synthetic coded-aperture confocal imaging

• different from coded aperture imaging in astronomy
• [Wilson, Confocal Microscopy by Aperture Correlation, 1996]
100 trials

→ 2 beams × ~50/100 trials ≈ 1

→ ~1 beam × ~50/100 trials ≈ 0.5
Synthetic coded-aperture confocal imaging

100 trials
- $\rightarrow$ 2 beams $\times \left\lceil -50/100 \text{ trials} \right\rceil \approx 1$
- $\rightarrow$ 1 beam $\times \left\lceil -50/100 \text{ trials} \right\rceil \approx 0.5$

floodlit
- $\rightarrow$ 2 beams
- $\rightarrow$ 2 beams

trials $- \frac{1}{4} \times$ floodlit
- $\rightarrow 1 - \frac{1}{4} \left( 2 \right) \approx 0.5$
- $\rightarrow 0.5 - \frac{1}{4} \left( 2 \right) \approx 0$

- 50% light efficiency
- any number of projectors $\geq 2$
- no discrimination to left of
- works with relatively few trials (~16)
- needs patterns in which illumination of tiles are uncorrelated

Example pattern
Patterns with less aliasing

(Video available at http://graphics.stanford.edu/papers/confocal/)

Implementation using an array of mirrors

Synthetic aperture confocal imaging

single viewpoint

synthetic aperture image

confocal image

combined
Selective illumination using object-aligned mattes

Confocal imaging in scattering media
- small tank
  - too short for attenuation
  - lit by internal reflections

Experiments in a large water tank
- 50-foot flume at Wood’s Hole Oceanographic Institution (WHOI)
- 4-foot viewing distance to target
- surfaces blackened to kill reflections
- titanium dioxide in filtered water
- transmissometer to measure turbidity
Experiments in a large water tank

- stray light limits performance
- one projector suffices if no occluders

Seeing through turbid water

Other patterns

- sparse grid
- staggered grid
- swept stripe

Other patterns

- floodlit
- scanned tile

- floodlit
- swept stripe
- scanned tile
**Stripe-based illumination**

- if vehicle is moving, no sweeping is needed!
- can triangulate from leading (or trailing) edge of stripe, getting range (depth) for free

**Strawman conclusions on imaging through a scattering medium**

- shaping the illumination lets you see 2-3x further, but requires scanning or sweeping
- use a pattern that avoids illuminating the media along the line of sight
- contrast degrades with increasing total illumination, regardless of pattern

**Application to underwater exploration**

- use a pattern that avoids illuminating the media along the line of sight
- contrast degrades with increasing total illumination, regardless of pattern
The team

- **staff**
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  - Marc Levoy
  - Bennett Wilburn

- **students**
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  - Katherine Chou
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  - Augusto Roman

- **collaborators**
  - Mark Bolas
  - Ian McDowall
  - Guillermo Sapiro

- **funding**
  - Intel
  - Sony
  - Interval Research
  - NSF
  - DARPA

Relevant publications

(in reverse chronological order)

- **Spatiotemporal Sampling and Interpolation for Dense Camera Arrays**
  - Bennett Wilburn, Neel Joshi, Katherine Chou, Marc Levoy, Mark Horowitz
  - ACM Transactions on Graphics (conditionally accepted)

- **Interactive Design of Multi-Perspective Images for Visualizing Urban Landscapes**
  - Augusto Roman, Gaurav Garg, Marc Levoy
  - Proc. IEEE Visualization 2004

- **Synthetic aperture confocal imaging**
  - Marc Levoy, Billy Chen, Vaibhav Vaish, Mark Horowitz, Ian McDowall, Mark Bolas
  - Proc. SIGGRAPH 2004

- **High Speed Video Using a Dense Camera Array**
  - Bennett Wilburn, Neel Joshi, Vaibhav Vaish, Marc Levoy, Mark Horowitz
  - Proc. CVPR 2004

- **The Light Field Video Camera**
  - Bennett Wilburn, Michael Smulski, Hsiao-Heng Kelin Lee, and Mark Horowitz