Synthetic aperture photography and illumination using arrays of cameras and projectors

Marc Levoy

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Outline

technologies
- large camera arrays → *synthetic aperture photography*
- large projector arrays → *synthetic aperture illumination*
- camera–projector arrays → *synthetic confocal imaging*

optical effects

applications
- partially occluding environments → foliage
- weakly scattering media → murky water

examples

Multi-camera systems

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

Kang's multi-baseline stereo

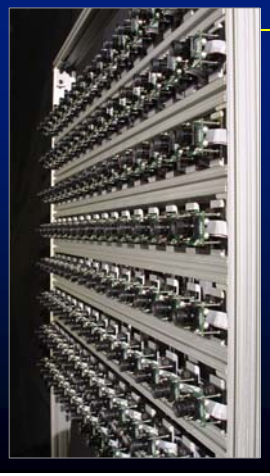
Nayar's Omnicam

Kanade's 3D room

Manex's bullet time array

Immersive Media's dodeca camera

Stanford multi-camera array



- 640 × 480 pixels × 30 fps × 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 → high-performance imaging
  - widely spaced → light fields
  - intermediate spacing → synthetic aperture photography

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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

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Abutting fields of view

Q. Can we align images this well?

A. Yes.

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High-speed photography

Harold Edgerton, Stopping Time, 1964

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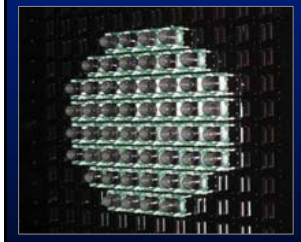
A virtual high-speed video camera

[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

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Example

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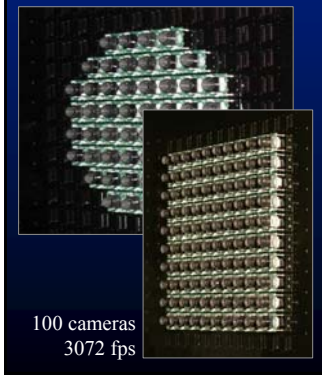
A virtual high-speed video camera

[Wilburn, 2004 (submitted)]



100 cameras
3072 fps

- 52 cameras, 30 fps, 640 × 480
- packed as closely as possible
- short exposure, staggered firing
- result is 1536 fps camera
- continuous streaming
- no triggering needed
- scalable to more cameras
- limited by available photons
- overlap exposure times?

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Cameras tightly packed: high-X imaging

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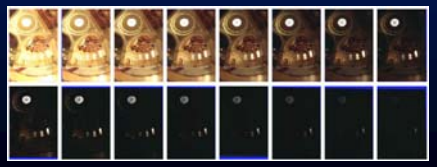
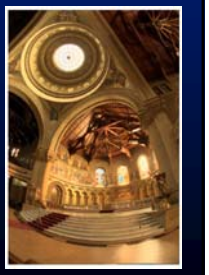
High dynamic range (HDR)

- 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





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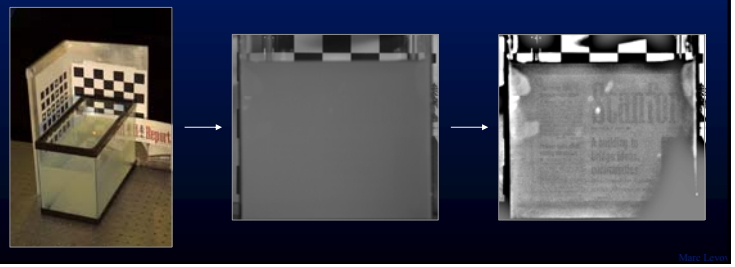
Seeing through murky water

- scattering decreases contrast
- noise limits perception in low contrast images
- averaging multiple images decreases noise



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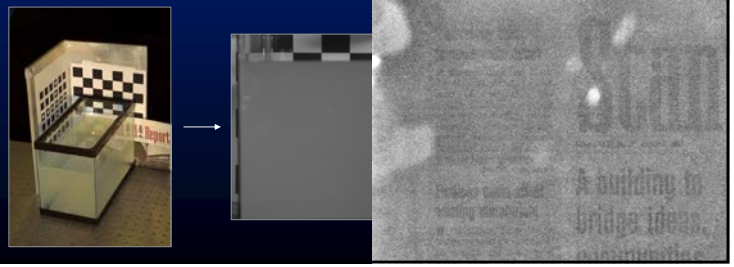
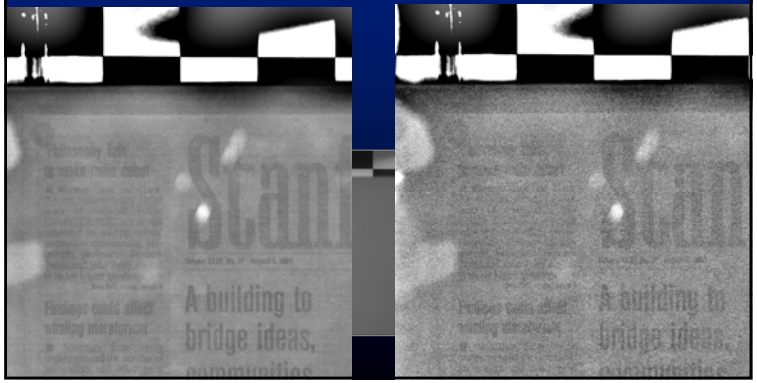
Seeing through murky water

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



Seeing through murky water

16 images 1 image



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High depth-of-field

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

[Haeberli90]

close focus distant focus composite

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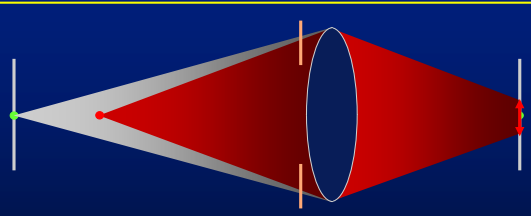
Synthetic aperture photography



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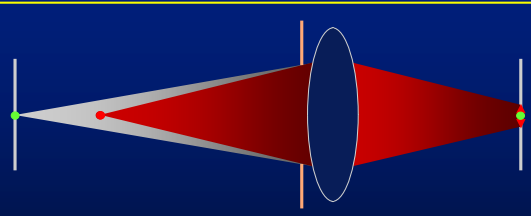
Synthetic aperture photography



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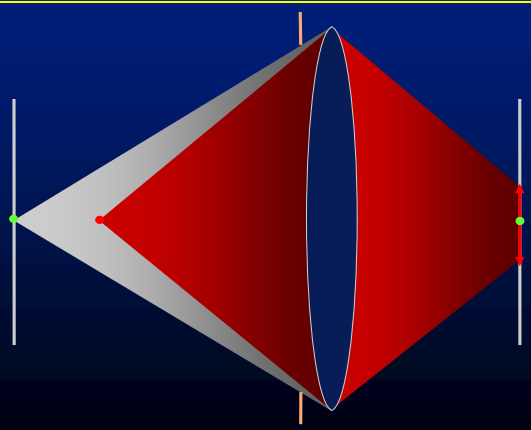
Synthetic aperture photography



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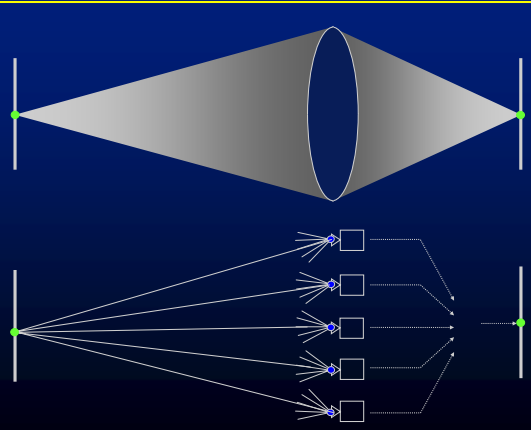
Synthetic aperture photography



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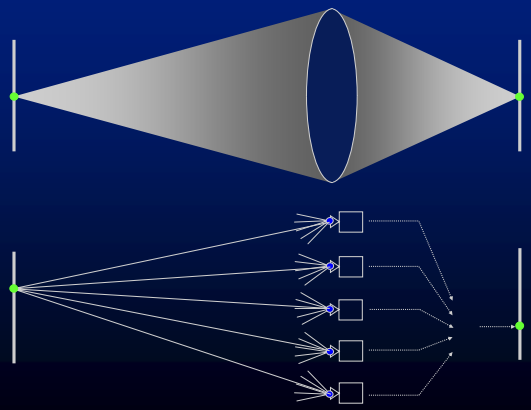
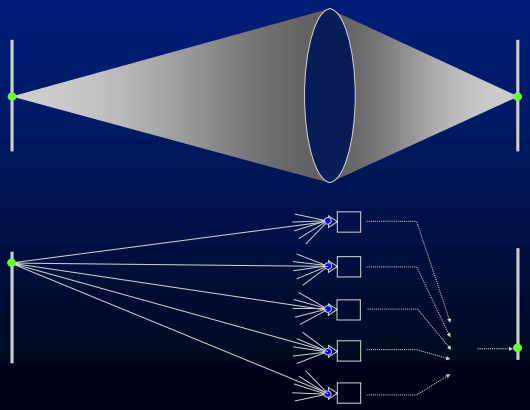
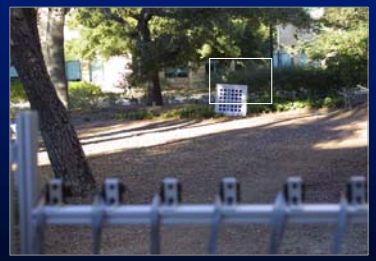
Synthetic aperture photography



Synthetic aperture photography

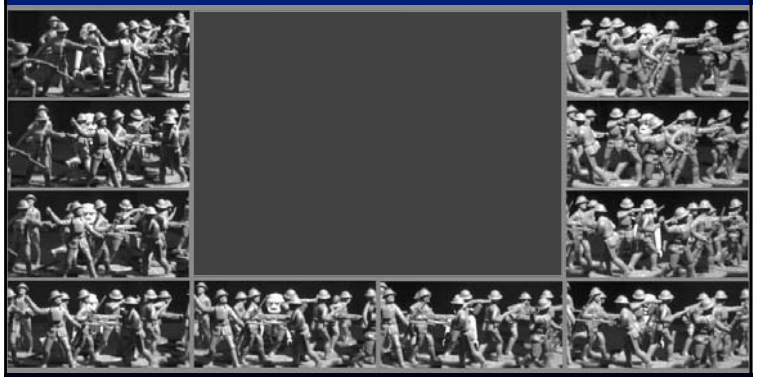


Long-range synthetic aperture photography

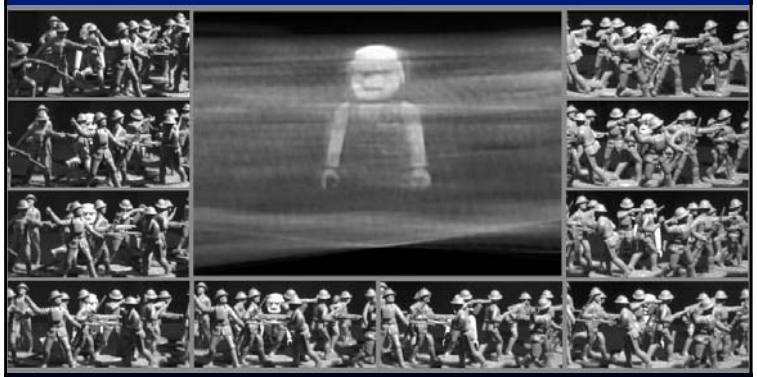


Synthetic pull-focus

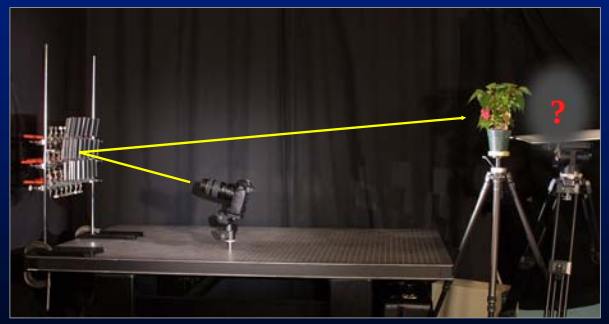
Crowd scene



Crowd scene

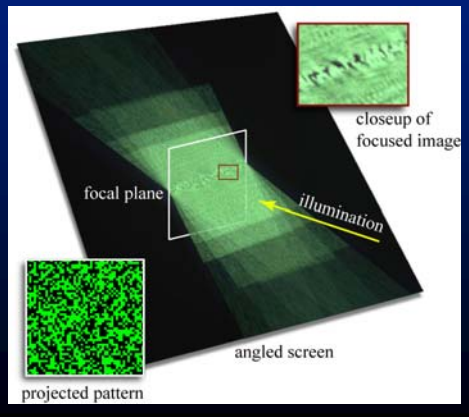


Synthetic aperture photography using an array of mirrors



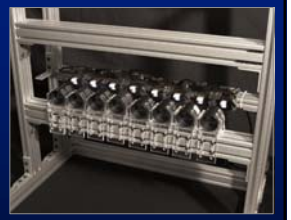
- 11-megapixel camera
- 22 planar mirrors

Synthetic aperture illumation



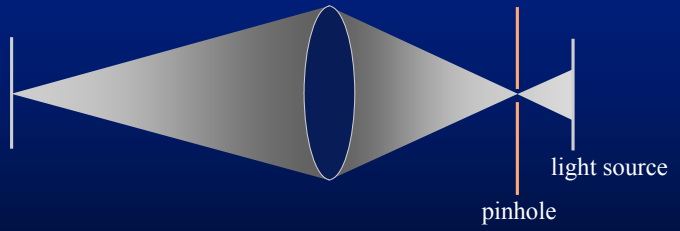
Synthetic aperture illumation

- technologies
  - array of projectors
  - array of microprojectors
  - single projector + array of mirrors

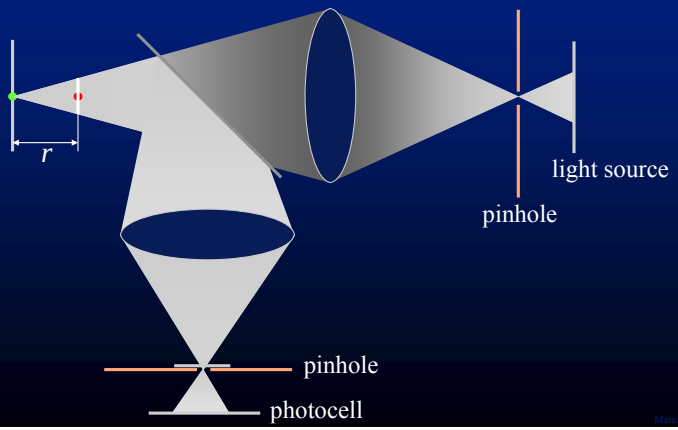


- applications
  - bright display
  - autostereoscopic display [Matusik 2004]
  - confocal imaging [this paper]

Confocal scanning microscopy



Confocal scanning microscopy



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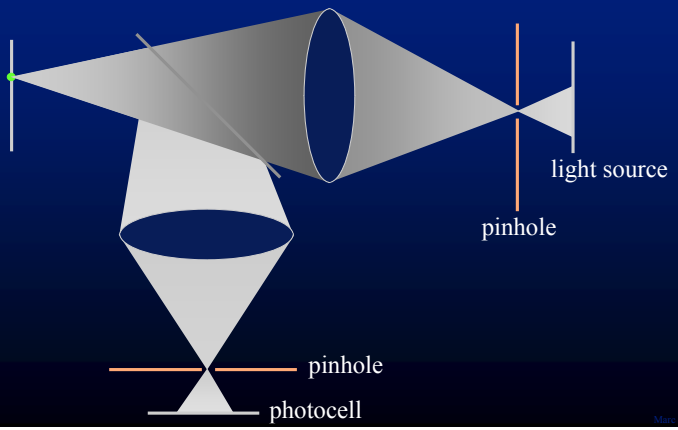

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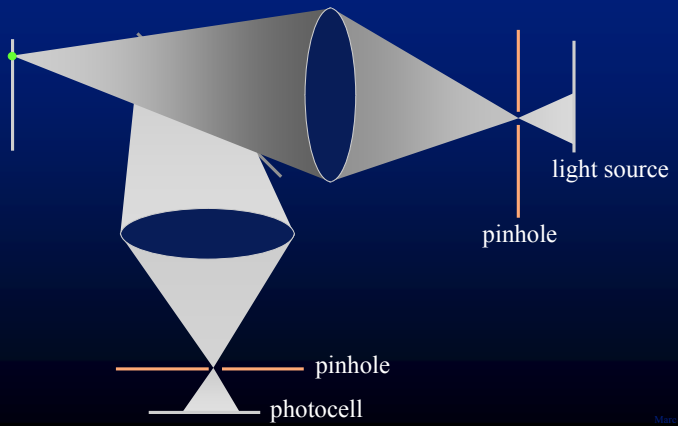
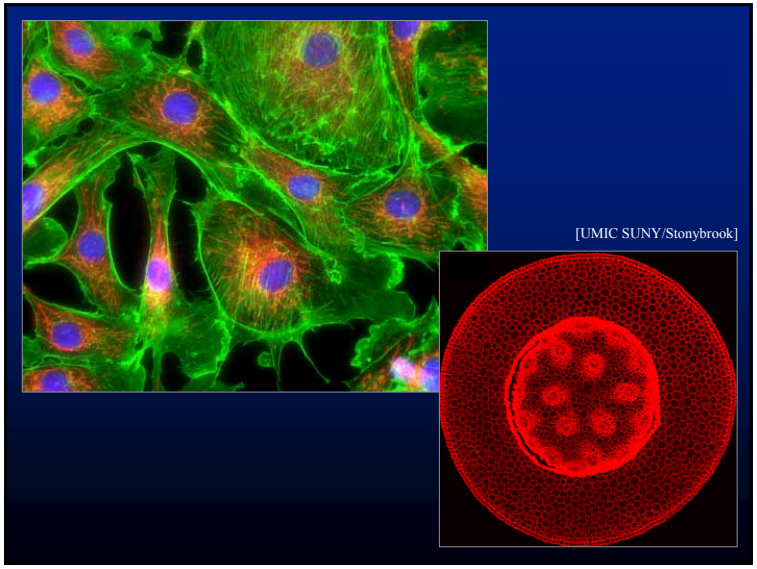
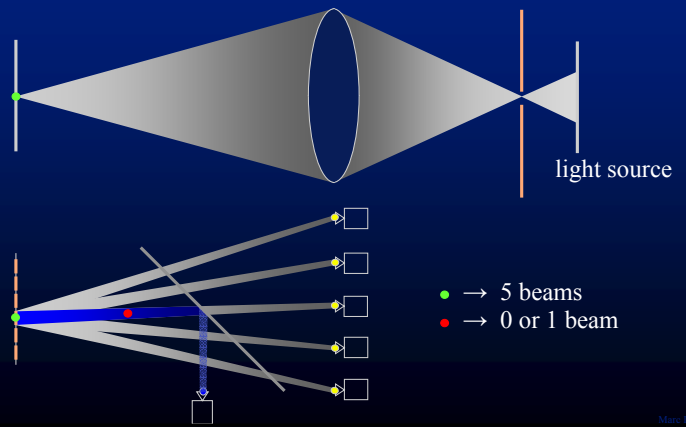


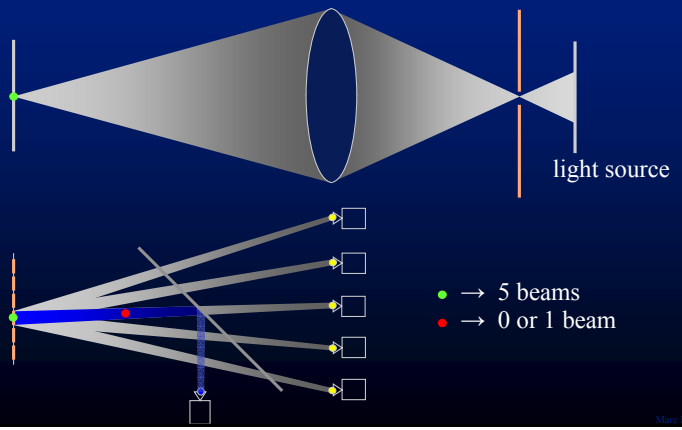


Synthetic confocal scanning



- → 5 beams
- → 0 or 1 beam

Synthetic confocal scanning



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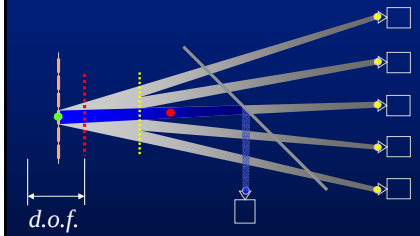
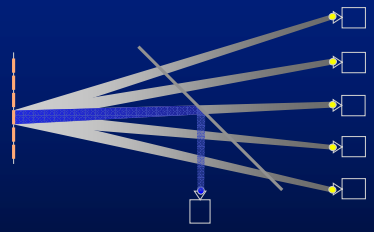


- → 5 beams
- → 0 or 1 beam

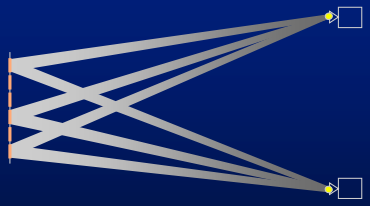
- works with any number of projectors ≥ 2
- discrimination degrades if • point to left of ·····
- no discrimination for • points to left of ·····
- slow!
- poor light efficiency

Synthetic coded-aperture confocal imaging



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

Synthetic coded-aperture confocal imaging



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Synthetic coded-aperture confocal imaging

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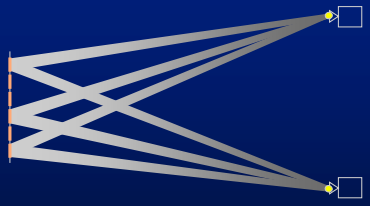

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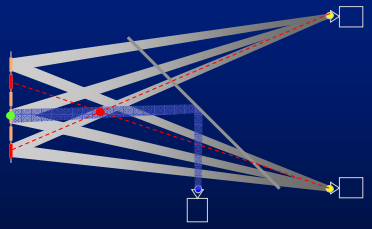

100 trials

- → 2 beams × ~50/100 trials ≈ 1
- → ~1 beam × ~50/100 trials ≈ 0.5

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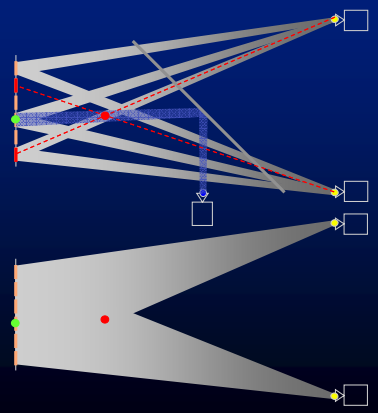
Synthetic coded-aperture confocal imaging



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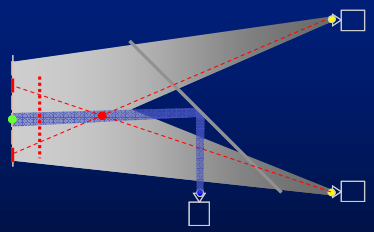
floodlit
- → 2 beams
- → 2 beams

trials – ¼ × floodlit
- → 1 – ¼ (2) ≈ 0.5
- → 0.5 – ¼ (2) ≈ 0

Synthetic coded-aperture confocal imaging



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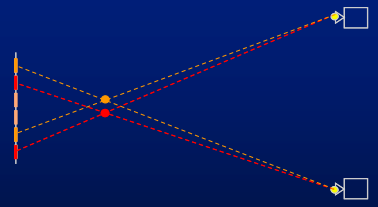
- 50% light efficiency
- any number of projectors ≥ 2
- no discrimination to left of
- works with relatively few trials (~16)

Synthetic coded-aperture confocal imaging



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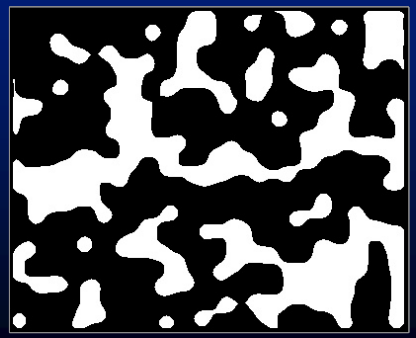
- 50% light efficiency
- any number of projectors ≥ 2
- no discrimination to left of
- works with relatively few trials (~16)
- needs patterns in which illumination of tiles are uncorrelated

Example pattern

Patterns with less aliasing



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Implementation using an array of mirrors

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Synthetic Aperture Confocal Imaging

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

Synthetic aperture confocal imaging

single viewpoint

synthetic aperture image

confocal image

combined

Selective illumination using object-aligned mattes

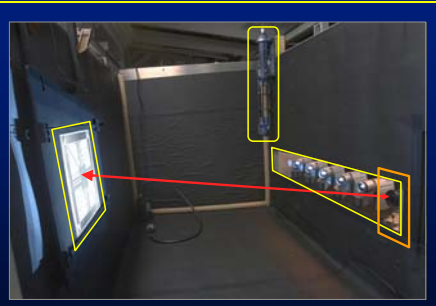
Confocal imaging in scattering media

- 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)

Experiments in a large water tank

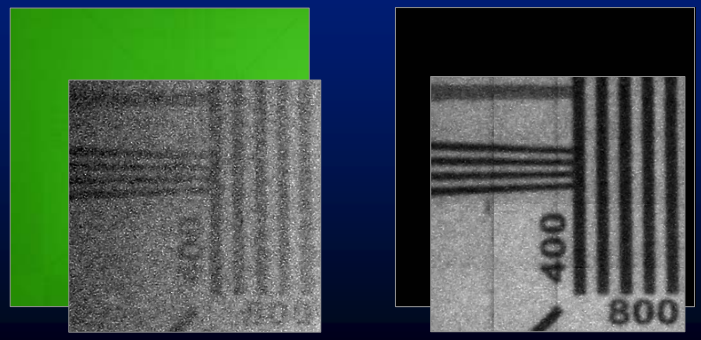


- 4-foot viewing distance to target
- surfaces blackened to kill reflections
- titanium dioxide in filtered water
- transmissometer to measure turbidity

Experiments in a large water tank

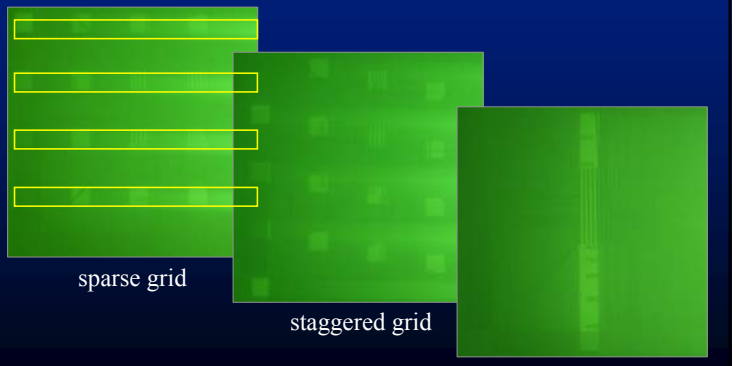
- stray light limits performance
- one projector suffices if no occluders

Seeing through turbid water



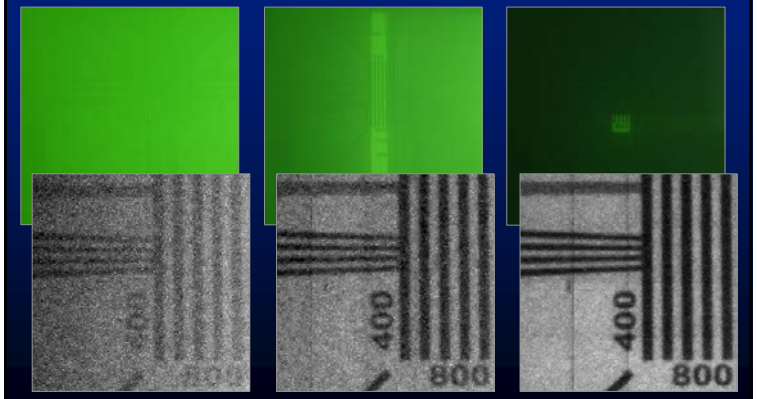
floodlit scanned tile

Other patterns



sparse grid staggered grid swept stripe

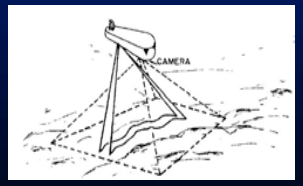
Other patterns



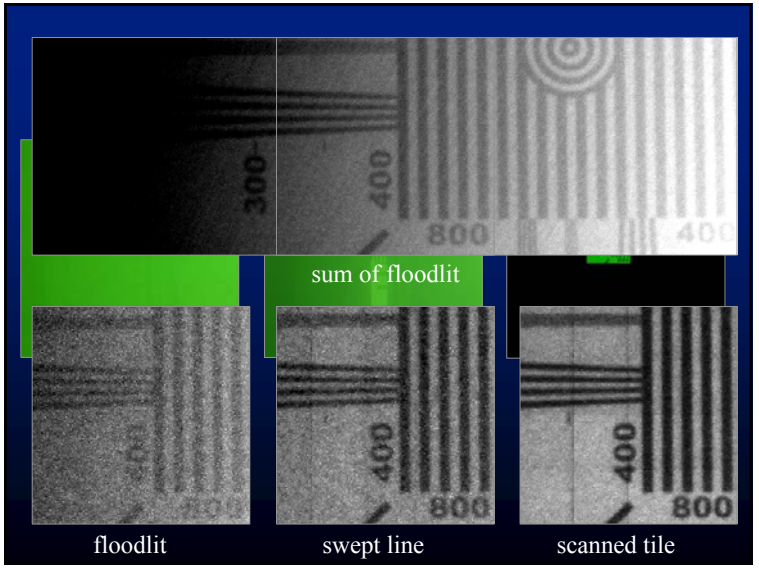
floodlit swept stripe scanned tile

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



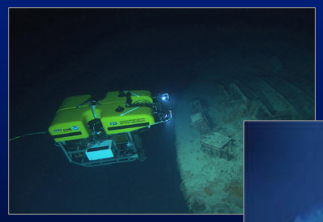
[Jaffe90]



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



[Ballard/IFE 2004]

[Ballard/IFE 2004]

The team

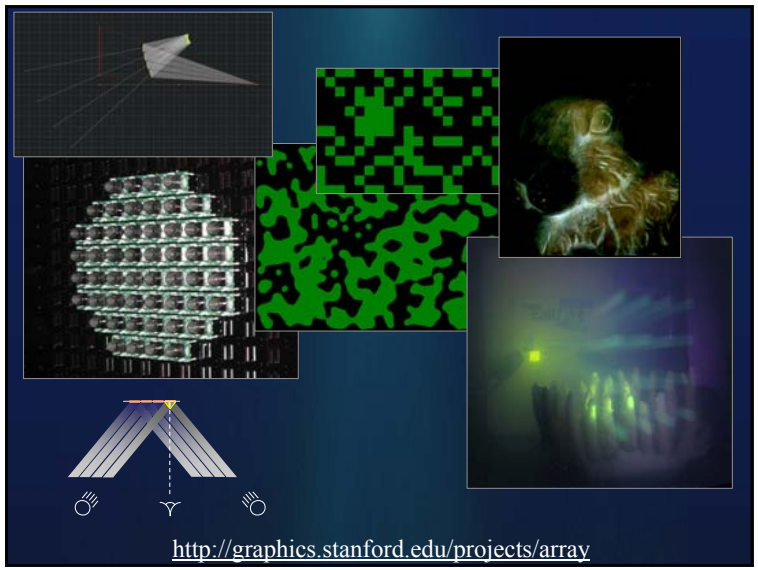
- staff
  - Mark Horowitz
  - Marc Levoy
  - Bennett Wilburn
- students
  - Billy Chen
  - Vaibhav Vaish
  - Katherine Chou
  - Monica Goyal
  - Neel Joshi
  - Hsiao-Heng Kelin Lee
  - Georg Petschnigg
  - Guillaume Poncin
  - Michael Smulski
  - Augusto Roman
- collaborators
  - Mark Bolas
  - Ian McDowall
  - Guillermo Sapiro
- funding
  - Intel
  - Sony
  - Interval Research
  - NSF
  - DARPA

Marc Levoy

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 Román, 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
- 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
  Proc. Media Processors 2002, SPIE Electronic Imaging 2002



http://graphics.stanford.edu/projects/array