CMOS Angle Sensitive SPADs

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Goal: Capture Many Dimensions Of Light

- Sub-sample 8-D “plenoptic function” $I(x,y,z,t,\theta,\phi,p,\lambda)$
  - Standard planar sensors give $x,y$ not $z$.
  - Color filters get $\lambda$ (with less resolution in $x,y$)
  - SPADs are great for getting time, $t$
  - Want to also get angle $\theta,\phi$ and (less so) polarization $p$
Motivation: Lensless nearfield 3-D Imaging

Suspended luminous sources: localization, tracking

Current methods require a microscope and scanned focus

With angle, no microscope needed

Key is to capture local incident angle as well as intensity
Out-of-focus Spatial Structure Encoded in Angle

- Sharp image, undefined angle
- Blurred image, converging angles
- Blurred image, diverging angles

Identical intensity information
Distinct angle information
Outline

• Motivation
• **CMOS-integrated angle-sensitive pixels**
  • Basic structure
  • Angle-sensitive SPADs
• Application: Lensless, filterless 3-D FLIM
  • Localizing sources in 3-D volume w/o a lens
  • Combined with SPADs
• Application: Light-Field
  • 3-D photography: computational refocus, ranging and compression
  • Lensless far-field imaging
• Combining light-field + TOF?
Talbot effect:
Gratings create “self images”

H. F. Talbot (1800 – 1877)

Talbot Depth: \( Z_T = \frac{d^2}{\lambda} \)

Talbot Pattern Shifts With Angle

Goal is to measure this shift

0 degrees

10 degrees

Detector

Detector
Measuring Talbot pattern shifts

Add second grating (analyzer) and use the moire effect

0 degrees

10 degrees
Measuring Talbot patterns

If we sweep the incident angle:

Get a periodic output  \( D_0 = I_0 (1 - m \cos(\beta \theta)) A(\theta) \)
Extracting Angle

\[ D_0 = I_0 (1 - m \cos(\beta \theta)) A(\theta) \]
\[ D_{1/4} = I_0 (1 + m \sin(\beta \theta)) A(\theta) \]
\[ D_{1/2} = I_0 (1 + m \cos(\beta \theta)) A(\theta) \]
\[ D_{3/4} = I_0 (1 - m \sin(\beta \theta)) A(\theta) \]

Intensity

\[ I_0 A(\theta) = \frac{D_{1/2} + D_0}{2} = \frac{D_{1/4} + D_{3/4}}{2} \]

Incident angle

\[ \theta = \frac{1}{\beta} \tan^{-1}\left( \frac{D_{1/4} - D_{3/4}}{D_{1/2} - D_0} \right) \]

Intensity: common mode, angle: differential mode
CMOS Angle Sensitive Pixel (ASP)

- Metal layers used for gratings
- First grating (M6) generates patterns
- Second grating (M3) is analyzer
- Typical CMOS structures below
Describing This Response

• Each curve can be described by:
  \[ I = I_o A(\theta, \phi)[1 - m \cos(\beta(\theta \cos(\psi) + \phi \sin(\psi)) + \alpha)] \]

• Angular offset: \( \alpha \)
• Orientation: \( \psi \)
• Angular frequency: “\( \beta \)”
• Modulation depth: “\( m \)”
  • Impacts SNR especially

\[ \theta \quad \alpha +90 \quad \psi +90 \quad \beta \times 2 \]

\[ 360^\circ / \beta \]
Physical trade-offs

• Angular response (for fixed $\psi$):
  \[ I = I_o A(\theta, \phi)[1 - m\cos(\beta\theta + \alpha)] \]

• $\psi$: set by grating orientation
• $\alpha$: phase set by grating offset
  • $\alpha = 2\pi \frac{\Delta x}{p}$
• $\beta$: Angular “frequency”, set by grating pitch $d$ ($d \sim 2\lambda - 3\lambda$), Talbot order $n$:
  • $\beta \sim 2\pi \frac{d}{\lambda} n$, where $n = \text{round} \left( \frac{d^2}{\lambda} \right)$
• Modulation depth, $m$ want to maximize
  • $m \propto \cos \left( 2\pi \frac{v\lambda}{d^2} \right)$ (how close to Talbot)
  • $m \propto 1 - \frac{n}{\# \text{ gratings}}$
Angle-sensitive SPADS

- Interconnect layers:
  - Diffraction + analyzer gratings
  - Angle information
  - Wave-description

- Semiconductor layers:
  - SPAD + support circuits
  - Time information
  - Particle description
Angle-sensitive SPADS

Caveat: Metal blocks light

• Bare minimum:
  • Each grating blocks ~ ½ of light
  • So QE<25% before get to sensor

• Reality even worse:
  • Gratings block light within ~ \( \lambda/4 \)
  • Measured QE ~ 12-15%
Enhanced ASPs for Quantum Efficiency: Less Metal

Interleaved diodes: 50% higher QE, 2x better density

Phase Gratings: ~ 2.5x better QE

Better QE but worse modulation depth
Other Caveats

• Wavelength:
  • Tends to degrade modulation depth away from optimum
  • Low angular frequency ASPs work from blue-orange (450-650nm)
  • All pictures will be with white light

• Pixel size:
  • Limited to >3 grating periods (more=better) → ~3μm
  • Can “share” gratings to be better

• Spatial gradients confuse with angle
  • Use “common-centroid” ASPs
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  • 3-D photography: computational refocus, ranging and compression
  • Lensless far-field imaging
• Combining light-field + TOF?
Lensless Localization

• “Angle” not defined
• But:
  • ASP responds best to light from certain parts of space
  • If a given ASP shows a strong response, light must come from that region
• Correlate actual responses to predicted values at each location.
\( \beta \) sets resolution, ambiguity

\[
\Delta x, y = \frac{z \cdot \pi}{\beta} \\
\Delta z = \frac{z \cdot \pi}{\beta \cos(\theta_{\text{max}})}
\]
High $\beta$: better resolution, worse ambiguity
Diversity: much better

- 2 Fluorescent sources (over a 32x32 array)
- Multiple ASP types ($\beta = 12, 20$)
- Localized based on correlation+ threshold

General, formal description

- Matrix description:
  - each ASP output ($y_i$) is a weighted sum of inputs ($x_j$) from different locations in space:
  - can describe as matrix operation: $y = Ax$

- Want $A^{-1}$
  - But $\dim(y) \propto N^2$ (plane),
  - $\dim(x) \propto N^3$ (volume)
  - $A$ is not square $\rightarrow$ can’t invert.
  - Need more constraints
Assume Sparseness:

- i.e. fluorescent cells in biology, imaged without a lens
- Use tricks from compressive sensing.
- Look for estimated input $x$ that minimizes: $\|y - Ax\|_2^2 + \lambda \|x\|_1$

Lensless 3-D Fluorescent Imaging?

Current methods require a microscope with “filter cube”

Fluorescence requires stimulation light that is MUCH brighter

With ASP arrays, no filter

Use time instead of wavelength to isolate signals
Angle-Sensitive SPAD Array

• 72x60 Array of A-SPADs
  • Includes multiple DTCs, windowing (~75ps LSB)
  • Rolling read-out
Actual Angle Sensitive SPAD Array

- Local 10b counter
- 35μm pitch

- Three phases ($\alpha$): $0^\circ$, $\pm 120^\circ$
- Two orientations, V, H
- Two “frequencies” ($\beta$): 8, 15

$\alpha = 180^\circ$
$\alpha = 60^\circ$
$\alpha = -60^\circ$
Lensless 3-D Fluorescent Lifetime Imaging

Can (imperfectly) extract two different time histograms of fluorophores using SPADs

Angular info provides 3-D reconstruction: localizes two sources

3-D Fluorescent microscope on a chip!
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Modeling the pixel

Intensity: CM

\[ I_0 A(\theta) = \frac{D_{1/2} + D_0}{2} = \frac{D_{1/4} + D_{3/4}}{2} \]

Incident angle: DM

\[ \theta = \frac{1}{\beta} \tan^{-1} \left( \frac{D_{1/4} - D_{3/4}}{D_{1/2} - D_0} \right) \]

\[
D_0 = I_0 (1 - m \cos(\beta \theta)) A(\theta)
\]

\[
D_{1/4} = I_0 (1 - m \cos(\beta \theta + 90)) A(\theta)
\]

\[
D_{1/2} = I_0 (1 - m \cos(\beta \theta + 180)) A(\theta)
\]

\[
D_{3/4} = I_0 (1 - m \cos(\beta \theta - 270)) A(\theta)
\]
ASPs as band-pass filters

Angular frequency response

Spatial frequency $\Omega$

$V(\Omega)$

$W(\Omega)$

$\beta/z'$

$\Omega$

Impulse response

Low pass

Band pass

Bank of Band pass filters
500 kASP array

Low frequency
Mid frequency
High frequency

Similar to a 2-D Fourier transform
Light-Field Implications

• Entries in a 2-D Fourier transform form a basis set: fully describe angle (up to limit of resolution) → invertible

• Orthogonal → linearly independent, so easily invertible

• Well characterized for natural scenes → they are “good”

• 1-to-1 mapping to more standard light-field (ie micro-lens)
Fourier is its own inverse

Intensity (DC)  \[ \beta = 12, \text{ here } n = 1 \]

\[ \sum_{k=1}^{8} \text{out}(k) \ast \text{wavelet}(k) \]

\[ \beta = 24, \text{ here } n = 2 \]
Complex scene, compute refocus

This Also Allows for a Range Map

Use quadrature nature of data with trig. functions

\[ P = W \cos \left( \beta \frac{x'}{z'} \right) \]

\[ Q = W \sin \left( \beta \frac{x'}{z'} \right) \]

\[ \frac{dQ}{dx'} P - \frac{dP}{dx'} Q = \frac{M}{C} = \frac{z'}{\beta} \]

Albert Wang, Sheila Hemami, Alyosha Molnar, “Angle-sensitive pixels: a new paradigm for low-power, low-cost 2D and 3D sensing”, IS&T/SPIE Electronic Imaging 2012, Burlingame Ca
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ASPs are Polarization Sensitive

- Want to capture as many dimensions as possible:
  - \( I(x,y,z,t,\theta,\phi,p,\lambda) \)
  - Gratings provide some polarizations: larger pitch than ideal wire-grid polarizer.
- Use the “common mode” of different orientations:
- This can help with specular reflection

Spatial band-pass for image compression

Image capture → Convolution → Filter bank → rounding

Pixel Histogram

Transform Histogram

Coefficient value

Pixel value

Count
ASPs compress images

Low frequency (8x)

Mid frequency (8x)

High frequency (8x)

Transform inversion

Σ

Image Recovery

Transform inversion

24 channel recovery

Data: 90Kbits (All 24 channels)

Full reconstruction

Averaged intensity

Data: 27Kbits (subsampled)

Bitmap image

117Kbits (10:1 reduction)

1.2Mbits (150Kpixel, 8 bit)
Taking this to an extreme: no lens at all!

• Can make lots of ASPs with $\beta$ up to $\sim$50 in 180nm CMOS $\rightarrow$ so make a “full set”
• Every harmonic frequency from $\beta=4$ to $\beta=48$ (4000 ASP)
Taking this to another extreme

- Each ASP captures one component 2-D FFT (really, Hartley)
- Provide ~400 independent readings about a scene.
- This is invertible
Taking this to another extreme

- So take pictures in the Fourier-domain
- Invert
- Get a tiny (bad) camera with no lens

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Why Combine ASPs + SPADs?

• Lensless, ultra-compact lensless range-finder with (some) spatial resolution
• Optical compression on SPAD signals? \(\rightarrow\) less data
• Complementary capabilities of Light Field, TOF:
  • Light Field:
    • Passive
    • Good at short range
    • Bad at long range (set by baseline)
    • Needs contrast to work
  • Time of Flight:
    • Active
    • Not so good at short range
    • WAY better at “long” range.
    • Does not need contrast
Example combo: “depth fields”

- Use TOF to find depth
- Use light-field to computationally refocus
- Benefit: can use larger aperture for TOF without losing depth of field
Depth Fields Can help with Occlusion

Example Scene: plant occludes monkey

Can focus on the monkey

But depth is corrupted

Count

Can see both in depth histogram of rays

Use just “monkey” rays

Now, much better
Summary: Angle Sensitive Pixels and SPADs

- Pixels sensitive to incident angle, polarization and time.
- Arrays able to capture in 3D image information
- Information in format useful for image processing
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Combining three viewpoints

Light-Field imaging:
• 3-D scenes generate distributions of light rays \( I(x,y,z,\theta,\phi) \)
• Need to capture enough of this to reconstruct: both angle and space

Frequency-domain image analysis:
• Real scene features easily analyzed in frequency domain
• Gabor filters and FFTs common

Solid-state light capture and analysis:
• Want to build small sensors (<10\( \mu \)m/side): diffractive domain
• Want in standard CMOS