### Class: Computational Photography, Advanced Topics
Debevec, Raskar and Tumblin

#### Module 1: 105 minutes

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
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<tbody>
<tr>
<td>1:45</td>
<td>A.1 Introduction and Overview</td>
<td>(Raskar, 15 minutes)</td>
</tr>
<tr>
<td>2:00</td>
<td>A.2 Concepts in Computational Photography</td>
<td>(Tumblin, 15 minutes)</td>
</tr>
<tr>
<td>2:15</td>
<td>A.3 Optics: Computable Extensions</td>
<td>(Raskar, 30 minutes)</td>
</tr>
<tr>
<td>2:45</td>
<td>A.4 Sensor Innovations</td>
<td>(Tumblin, 30 minutes)</td>
</tr>
<tr>
<td>3:15</td>
<td>Q &amp; A</td>
<td>(15 minutes)</td>
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#### 3:30: Break: 15 minutes

#### Module 2: 105 minutes

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<tr>
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<tr>
<td>3:45</td>
<td>B.1 Illumination As Computing</td>
<td>(Debevec, 25 minutes)</td>
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<tr>
<td>4:10</td>
<td>B.2 Scene and Performance Capture</td>
<td>(Debevec, 20 minutes)</td>
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<tr>
<td>4:30</td>
<td>B.3 Image Aggregation &amp; Sensible Extensions</td>
<td>(Tumblin, 20 minutes)</td>
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<td>4:50</td>
<td>B.4 Community and Social Impact</td>
<td>(Raskar, 20 minutes)</td>
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<td>5:10</td>
<td>B.4 Panel discussion</td>
<td>(All, 20 minutes)</td>
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Class Page: [http://ComputationalPhotography.org](http://ComputationalPhotography.org)
Computational Photography: Advanced Topics

A4: Sensor Innovations (30 minutes)

Jack Tumblin
Northwestern University
Film-Like Sensor: Array of Light Meters

Film-like Goals:

- **Instantaneous** measurement
- **Infinite** resolution; arc-min, $\lambda$
- **Infinite** sensitivity, Dyn. Range
- **Zero** noise visible
Film-Like Photo: Photon Arrival Record

- **Snapshot**: ‘flattened’ volume of space time
- **More volume**: more photons → “less noise”
- **Movie**: Repeated snapshots

Ordinary Snapshot

Snapshot with Motion-Blur

‘Motion Picture’ (missing time!)
6 Megapixel 3µm Always Best?

- Independent Lab & Photo Enthusiasts site:
  “The more pixels, the worse the image!”

http://www.6mpixel.org/en/
Noise In Camera Systems

accurate, beautiful analogy:

“Photon Rain”

Small Pixel  Large Pixel

© Roger N. Clark
www.clarkvision.com
Sensor Noise Sources

- **Quantum Noise:** ‘Photon Rain’ (signal dependent)
- **Thermal-dependent noise in semiconductors:**
  - Schott ('shot') noise (electron-hole pairs)
  - Imperfect materials; insulator flaws (temp, voltage, current dependent)
- **Thermal-dependent noise in electronics:**
  - Insulator leakage, phonon effects (temp dependent)
- **RFI/EMI noise in electronics:** ‘crosstalk’ (signal dependent)

Good tutorial: http://www.ph.tn.tudelft.nl/Courses/FIP/noframes/fip-Photon.html
Sensor Noise Sources

- **Quantum Noise**: ‘Photon Rain’ (signal dependent)
- **Thermal-dependent noise in semiconductors**: Schott ('shot') noise (electron-hole pairs), imperfect materials, insulator flaws (temp, voltage, current dependent)
- **Thermal-dependent noise in electronics**: insulator leakage, phonon effects (temp dependent)
- **RFI/EMI noise in electronics**: 'crosstalk' (signal dependent)

"Additive (fixed-strength) vs. Signal Dependent"
Fill Factor

- (Sensing Area / total Area)\%age
- Interconnects, readout transistors
- As low as 20-30%
- Micro-Lenses help

Aptnia (Micron Technologies)
Light-Gathering Microlenses

- Counteracts low fill-factor
- Improved light gathering
- Less Aliasing

- Suitable for color filters
Color Sensing

• 3-chip: vs. 1-chip: quality vs. cost

http://www.cooldictionary.com/words/Bayer-filter.wikipedia
1-Chip Color Sensing: Bayer Grid, De-Mosaicing

• Estimate RGB at ‘G’ cells from neighboring values

http://www.cooldictionary.com/words/Bayer-filter.wikipedia
Microlenses + Color Filters

- Improved light gathering
- Fixed Alignment
- Less Aliasing
Backside Illumination

Advantages:
- Better fill-factor $\rightarrow$ larger pixel sensors
- Less-crammed circuitry (more of it?)
- Seamless Surface $\rightarrow$ less glare, aliasing

Difficulties:
- Fragile: tough to create, mount, connect
- Opacity, Noise, sub-surface scatter
Back-Illuminated CCD

Started ~2000 (micron tech), Now High-Performance

Fairchild 4k x 4k CCD486:
- Thinned to 18microns + anti-reflective coating
- 100% fill factor, 15um pixels,
- 61.4 x 61.4mm sensor area

Back OR Front illumination
Practical Back-Illuminated CMOS

- Difficult ‘Thinning’ -- bulk substrate removal
- Promising preliminary results:
  1.75 μm pixels now → 0.9 μm expected
- (+6dB) sensitivity (~2x)
- (-2db) noise

Sony Corp. Prototype
Color Estimation: RGBW Method

- 2007: Kodak ‘Panchromatic’ Pixels
- Outperforms Bayer Grid
  - 2X-4X sensitivity (W: no filter loss)
  - May improve dynamic range (W >> RGB sensitivity)
  - Colorimetry: Direct luminance, not computed
- Drawbacks? de-mosaicing more difficult; earlier 4-color systems (JVC: CMYW, Canon: CMGY) earned shrugs
Assorted Pixels (Nayar et al.)

- Color mosaic:
Assorted Pixels (Nayar et al.)

- Intensity mosaic:
Assorted Pixels (Nayar et al.)

- Intensity-and-color mosaic:
Assorted Pixels (Nayar et al.)

- Intensity-and-color-and-polarization mosaic:
- Other dimensions:
  - IR? UV?
  - Temporal? (frameless rendering)
  - Viewpoint? (camera arrays, epipolar imaging)
Assorted Pixels (Nayar et al.)

Sony Prototype...
Demosaicking Difficulties

- Under-sampling, esp. in red, blue → Loss of detail, aliasing, zippering:
- Many good methods, no perfect answer

“Demosaicing by Smoothing along 1D Features”, Ajdin et al., CVPR 2008

FOVEON Sensor

- Multi-layer sensor, no color filter mosaic
- Senses wavelength by absorption depth

FOVEON Sensor

- No under-sampling for any color,
- No de-mosaicking

Hyper-Acuity Hints & SuperResolution

Human Eye:

- Foveal receptors: 2.5 μm, \( \sim 28 \) arc-sec (Curcio et al, 1990)
- “Hyper-Acuity” can detect \( \sim 1 \) arc-sec displacement
- Ocular tremor contributes...

Superresolution:

- Multiple photos subpixel shifts:
- Assemble dense sample grid:
Penrose Pixels for SuperResolution

ICCV 2007, Ben-Ezra et al., “Penrose Pixels: Super-Resolution in the Detector Layout Domain”

**Periodic:** sub-pixel shifts

**Non-Periodic:** any shift ok

8X super-res; same Back-Projection Reconstruction Method;

5.78 RMS error

2.78 RMS error
How can we choose What Matters?

- Image== ‘flattened’ spatio-temporal volume
- Choose Integration limits to fit the task
- More volume $\rightarrow$ less noise? Not always…
Take it all: Very Long Exposure

18 Months
Postdamer Platz, Berlin

26 Months
Note sun track breaks, ‘ghost’ buildings

http://www.wesely.org/wesely/index.php
Perfect Timing: Casio EXLIM Pro EX F-1

- Sports: the right *instant* to click the shutter?

**Time bracketing:**

- burst buffer: 6Mpix x 60 frames up to 60 Hz
- Data-rate limited: at 336 x 96 res up to 1,200 Hz
Flash + Light-Source Blur

- Lighting Integration Tricks:
  - Draw light paths in darkness
  - Flash captures one instant

1949 AP: Pablo Picasso, Time Magazine ‘Top 100 Artists’
See also: http://www.vpphotogallery.com/photog_mili_picasso.htm

“Lighting Doodle Projects”

http://tochka.jp/pikapika/
2006/06/report_pikapika_in_kitajo.html
Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

Users may edit Lighting, Shadows, Reflectance, NPR

SIGGRAPH 2007 “Factored Time Lapse Video” Sunkavalli et al.
Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

- Sky-only lighting, and
- Whole-Day, Sun-only lighting

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Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

- Whole-Day, Sun-only lighting
- Sky-only lighting, and
- Shadow Amount vs time

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Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

Sky-only lighting, and
Whole-Day, Sun-only lighting
Shadow Amount vs time
Edit Scene Lighting

Users may edit Lighting, Shadows, Reflectance, NPR

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Factor Whole-Day Video Seq. into:

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Sky-only lighting, and
Whole-Day, Sun-only lighting
Shadow Amount vs time
Edit Scene Lighting
NPR efx and more …
Spectral Range: Silicon >> Eye

Graph showing the relative response of the Human Eye and Silicon across different wavelengths (nm). The graph indicates that silicon has a lower response across the visible spectrum compared to the human eye.
Thermographic Cameras

Two classes: Near-IR and Bolometer
Thermal IR Camera

Uncooled Bolometer Arrays:
Temperature-Dependent Conductance

320 x 240 pixels typical
Slow Temporal Response
Often Shutter-free
Millimeter Wave Imaging (Radiometry)

- Sensitive to Temperature AND material’s reflectance
- High reflectance from water, metals, etc.
- See thru clouds and weather at some wavelengths
- High sensitivity, phase-sensitive (optical? RF? (1/r, not 1/r^2))
1-2mm Imaging Radiometry: Security

- At 1-2mm humans ‘glow’ very faintly ($10^{-14}$ joule)
- Metals, conductors, occlude; but clothes don’t
- Passive-only imaging: 40-60 ft camera range
- Weapons: Strong Silhouettes
ZCam (3Dvsystems), Shuttered Light Pulse

Resolution: 1cm for 2-7 meters

Figure 1: A light pulse of duration $T$ radiates an object and is reflected back to the sensor. The signal is shuttered at the head, center and tail of the signal. The measured intensities $I_h$ and $I_t$ are functions of the distance travelled by the pulse, while the intensity $I'_n$ is a constant fraction of the unshuttered value $I_n$. 

- 16x16 pixel overlapped sub-images
- Disjoint apertures, uniform spacing
- Many correspondences $\rightarrow$ 3D depth
A Bit of Metrology History

How do I weigh many small parts accurately?

random error $\varepsilon$, zero mean

- **Tedious:**
  Measure N items, one-at-a-time: $\sigma$

- **Extra-Tedious:**
  Measure N items, M times. $\frac{\sigma}{\sqrt{M}}$

- **Tolerable:**
  Measure N SETS of ($\sim N/2$) items. $\frac{2\sigma}{\sqrt{N}}$
OLD: Hadamard Transform Imaging

- N sensors, N pixels, but
- Sensors get unique SUMS of pixels
- Each pixel is part of \(~N/2\) measurements

\[
\begin{bmatrix}
L_0 \\
L_1 \\
L_2 \\
L_3
\end{bmatrix} = \begin{bmatrix}
A \\
B \\
C \\
D
\end{bmatrix}
\]

\[
\begin{bmatrix}
A \\
B \\
C \\
D
\end{bmatrix} = \begin{bmatrix}
p_0 \\
p_1 \\
p_2 \\
p_2
\end{bmatrix}
\]

- Compute pixels using \textit{inverse} matrix;
Compressive Sensing: “Single Pixel Cam”

- Sense large sums of pixels, not N pixels
- Key notion: number of pixel sums $\ll N$
- **Support:** several ground-breaking proofs

Diagram:
- Low-cost, fast, sensitive optical detection
- Image encoded by DMD and random basis
- Compressed, encoded image data sent via RF for reconstruction
- A/D, Xmtr, Rcvr, DSP
Bio-Inspired Single-Photon Detectors

Mohseni, Memis: Bio-Inspired sensor

- Large photon-absorption region (rhodopsin)
- Nano-scale hole detection (1-electron injector)
- Extremely small, low noise, HDR, no cooling req’d
Single-Photon Detectors

- **Quantum Wells / Quantum Dots**
  - ‘traps’ 1 electron/hole pair, from 1 absorbed photon
  - No noisy ‘avalanche’ effect

- **Applications:**
  - Medical imaging
  - ‘Ghost Imaging’?
  - Secure Quantum communications?
Single-Photon ‘Ghost’ Imaging

- Create two entangled photons: one to keep, one for scanning
- Kept photon tells direction, scanned photon: reflectance
- Covert Sensing: Interceptor can’t identify entangled photon

Shih, Y., Univ Maryland: Physical Review A (DOI: 10.1103/PhysRevA.77.041801)
Flexible-Array Sensor

- John Rogers et al. (Beckman Institute, U of Illinois) (EECS, Northwestern Univ.)
Sensor Fabrics?

- Camera-Scale projects in that direction:

Other Free-Form Choices?

Andrew Davidhazy, RIT: http://www.rit.edu/~andpph/
What is **ABSOLUTELY MANDATORY** here?

- **One** sample-time? Spatial, Temporal Uniformity?
  Why not many? [Flutter Shutter, 2005 Raskar]? …
- **Perfect Sync, Non-adaptive, all at once?**
  rolling shutter? Adaptive Frameless Render[2005 Dayal]? …
- **No Spatial Overlap?**
  Why not sinusoids? Wavelets? Gabor functions? …
**Common Thread:**

Existing Film-like Camera quality is **VERY HIGH**, despite low cost.

Existing sensors and cameras are just now escaping film-like assumptions,

?what can we compute with them?