Sensors & noise

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Camera pixel pipeline

• every camera uses different algorithms
• the processing order may vary
• most of it is proprietary
Example pipeline

Sensor → analog to digital conversion (ADC) → processing: demosaicing, tone mapping & white balancing, denoising & sharpening, compression → storage

Canon 21 Mpix CMOS sensor → Canon DIGIC 4 processor → Compact Flash card

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Example

Canon 21 Mpix CMOS sensor

Canon DIGIC 4 processor

Compact Flash card
Outline (1st half of lecture)

- converting photons to charge
- getting the charge off the sensor
  - CCD versus CMOS
  - analog to digital conversion (ADC)
- supporting technology
  - microlenses
  - antialiasing filters
- noise
The photoelectric effect

- when a photon strikes a material, an electron may be emitted
  - depends on wavelength, not intensity

$$E_{\text{photon}} = \frac{h \times c}{\lambda}$$
Quantum efficiency

- not all photons will produce an electron
  - depends on quantum efficiency of the device

\[
QE = \frac{\# \text{electrons}}{\# \text{photons}}
\]

- human vision: ~15%
- typical digital camera: < 50%
- best back-thinned CCD: > 90%
the current from one electron is small (10-100 fA)
• so integrate over space and time (pixel area × exposure time)
• larger pixel × longer exposure means more accurate measure

typical pixel sizes
• casio EX-F1: 2.5μ × 2.5μ = 6μ²
• Canon 5D II: 6.4μ × 6.4μ = 41μ²
Full well capacity

- too many photons causes saturation
  - larger capacity leads to higher dynamic range
  - but the noise floor is also a factor, as we’ll see
Blooming

- charge spilling over to nearby pixels
  - can happen on CCD and CMOS sensors
  - don’t confuse with glare or other image artifacts
Image artifacts can be hard to diagnose

Q. Is this blooming?
**CMOS versus CCD sensors**

- **CMOS** = complementary metal-oxide semiconductor
  - an amplifier per pixel converts charge to voltage
  - low power, but noisy (but getting better)

- **CCD** = charge-coupled device
  - charge shifted along columns to an output amplifier
  - oldest solid-state image sensor technology
  - highest image quality, but not as flexible or cheap as CMOS
Gratuitous animation showing a CCD “bucket brigade” readout

\[ \Phi_1 \quad +10V \quad \Phi_2 \quad +0V \quad \Phi_3 \quad 0V \quad \Phi_1 \quad +10V \quad \Phi_2 \quad +0V \quad \Phi_3 \quad +0V \]

P-substrate

\[ T=0 \]
Gratuitous animation showing a CCD “bucket brigade” readout

\[ \Phi_1 \quad \Phi_2 \quad \Phi_3 \quad \Phi_1 \quad \Phi_2 \quad \Phi_3 \]

\[ +10V \quad -10V \quad 0V \quad +10V \quad +10V \quad +0V \]

P-substrate

\[ v \quad T=1 \]
Gratuitous animation showing a CCD “bucket brigade” readout
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P-substrate

\( \Phi_1 \)
\( +10V \)
\( \Phi_2 \)
\( +0V \)
\( \Phi_3 \)
\( +10V \)
\( \Phi_1 \)
\( -10V \)
\( \Phi_2 \)
\( +0V \)
\( \Phi_3 \)
\( +10V \)
Smearing

- side effect of bucket-brigade readout on CCD sensors
  - only happens if pixels saturate
  - doesn’t happen on CMOS sensors
Analog to digital conversion (ADC)

- **flash ADC**
  - voltage divider → comparators → decoder
  - for n bits requires $2^n$ comparators

- **pipelined ADC**
  - 3-bit ADC → 3-bit DAC → compute residual → $4\times$ → repeat
  - longer latency, but high throughput
  - some new sensors use an ADC per column
Fill factor

✦ fraction of sensor surface available to collect photons
  • can be improved using per-pixel microlenses

Q. An image sensor performs 2D sampling. What is the prefilter, with and without microlenses?
What per-pixel microlenses do

✧ integrating light over a pixel serves two functions
  • capturing more photons, to improve dynamic range
  • convolving the image with a prefilter, to avoid aliasing

✧ if the pixel is a rectangle, then this prefilter is a 2D rect

\[
rect(x) = \Pi(x) = \begin{cases} 
0 & \text{if } |x| > \frac{1}{2} \\
\frac{1}{2} & \text{if } |x| = \frac{1}{2} \\
1 & \text{if } |x| < \frac{1}{2} 
\end{cases}
\]

• if only a portion of each pixel site is photo-sensitive, this rect doesn’t span the spacing between pixels, so the prefilter is poor

✧ microlenses both gather more light and improve the prefilter
  • with microlenses, prefilter width roughly equals pixel spacing
Antialiasing filters

✦ improves on non-ideal prefilter, even with microlenses
✦ typically two layers of birefringent material
  • splits 1 ray into 4 rays
  • operates like a 4-tap discrete convolution filter kernel!
Removing the antialiasing filter

✦ “hot rodding” your digital camera
  • $450 + shipping

anti-aliasing filter removed

normal
Removing the antialiasing filter

- “hot rodding” your digital camera
  - $450 + shipping

anti-aliasing filter removed

normal

(maxmax.com)
Outline (2nd half of lecture)

- examples of camera sensor noise
  - don’t confuse it with JPEG compression artifacts
- probability, mean, variance, signal-to-noise ratio
- laundry list of noise sources
  - photon shot noise, dark current, hot pixels, fixed pattern noise, read noise
- SNR (again), quantization, dynamic range, bits per pixel
- ISO
- denoising
  - by aligning and averaging multiple shots
  - by image processing will be covered next week
Nokia N95 cell phone at dusk

- 8×8 blocks are JPEG compression
- unwanted sinusoidal patterns within each block are JPEG’s attempt to compress noisy pixels
Canon 5D II at noon

- ISO 200
- f/13.0
- 1/320 sec
- RAW w/o denoising
Canon post-processing

- ISO 200
- f/13.0
- 1/320 sec
- RAW w/o denoising
Canon 5D II at dusk

- ISO 6400
- f/4.0
- 1/13 sec
- RAW w/o denoising
Canon 5D II at dusk
Canon 5D II at dusk
Photon shot noise

- the number of photons arriving during an exposure varies from exposure to exposure and from pixel to pixel
- this number is governed by the Poisson distribution
Poisson distribution

- expresses the probability that a certain number of events will occur during an interval of time
- applicable to rare events that occur
  - with a known average rate, and
  - independently of the time since the last event
- if on average $\lambda$ events occur in an interval of time, the probability $p$ that $k$ events occur instead is

$$p(k; \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$
Mean and variance

- the mean of a probability density function is

$$\mu = \int x p(x) \, dx$$

- the variance of a probability density function is

$$\sigma^2 = \int (x - \mu)^2 p(x) \, dx$$

- the mean and variance of the Poisson distribution are

$$\mu = \lambda$$

$$\sigma^2 = \lambda$$

- the standard deviation is

$$\sigma = \sqrt{\lambda}$$

Deviation grows slower than the average.
Signal-to-noise ratio (SNR)

\[
SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma}
\]

\[
SNR \text{ (dB)} = 20 \log_{10} \left( \frac{\mu}{\sigma} \right)
\]

example

- if SNR improves from 100:1 to 200:1, it improves 20 \log_{10}(200) - 20 \log_{10}(100) = +6 \text{ dB}
Photon shot noise (again)

- photons arrive in a Poisson distribution
  \[ \mu = \lambda \]
  \[ \sigma = \sqrt{\lambda} \]

- so
  \[ SNR = \frac{\mu}{\sigma} = \sqrt{\lambda} \]

- shot noise scales as square root of number of photons

- examples
  - doubling the width and height of a pixel increases its area by \(4\times\), hence # of photons by \(4\times\), hence SNR by \(2\times\) or +6 dB
  - opening the aperture by 1 f/stop increases the # of photons by \(2\times\), hence SNR by \(\sqrt{2}\) or +3 dB
Empirical example

- Kodak Q14 test chart

- SNR improves with increasing signal

(http://www.imatest.com/docs/noise.html)
Dark current

- electrons dislodged by random thermal activity
- increases linearly with exposure time
- increases exponentially with temperature
- varies across sensor, and includes its own shot noise

[Image: Canon 20D, 612 sec exposure]

(http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/)
Time exposures in astronomy

• 30-minute exposure (on film)
• telescopes can rotate to avoid smearing stars
• What is the unmoving star in the middle?

Lee Frost, star trails

(Palomar 200-inch)
Hot pixels

- electrons leaking into well due to manufacturing defects
- increases linearly with exposure time
- increases with temperature, but hard to model
- changes over time, and every camera has them

Canon 20D, 15 sec and 30 sec exposures
Fixing dark current and hot pixels

✦ example
  • Aptina MT9P031 (in Nokia N95 cell phone)
  • full well capacity = ~8500 electrons
  • dark current = 25 electrons/pix/sec at 55°C

✦ solution #1: chill the sensor
  • Retiga 4000R bioimaging camera
  • Peltier cooled 25°C below ambient
  • full well capacity = 40,000 electrons
  • dark current = 1.64 electrons/pix/sec

✦ solution #2: dark frame subtraction
  • available on high-end SLRs
Fixed pattern noise (FPN)

- manufacturing variations across pixels, columns, blocks
- mainly in CMOS sensors
- doesn’t change over time, so read once and subtract

Canon 20D, ISO 800, cropped
Read noise

- thermal noise in readout circuitry
- again, mainly in CMOS sensors
- not fixed pattern, so only solution is cooling

Canon 1Ds Mark III, cropped

(image tainted by JPEG artifacts?)
Signal-to-noise ratio (again)

\[
SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma}
\]

\[
= \frac{P Q_e t}{\sqrt{P Q_e t + D t + N_r^2}}
\]

✦ where

- \(P\) = incident photon flux (photons/pixel/sec)
- \(Q_e\) = quantum efficiency
- \(t\) = exposure time (sec)
- \(D\) = dark current (electrons/pixel/sec), including hot pixels
- \(N_r\) = read noise (rms electrons/pixel), including fixed pattern noise

(formula from http://learn.hamamatsu.com/articles/ccdsnr.html)
Signal-to-noise ratio (again)

\[ SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma} \]

\[ = \frac{P Q_e t}{\sqrt{P Q_e t + D t + N_r^2}} \]

Examples

- Retiga 4000R = \((1000 \times 55\%) / \sqrt{(1000 \times 55\% + 1.64 + 12^2)}\)  
  = 20.8:1 assuming 1000 photons/pixel/sec for 1 second

- Aptina MT9P031 = \((1000/11 \times 69\%) / \sqrt{(1000/11 \times 69\% + 25 + 2.6^2)}\)  
  = 6.5:1 assuming pixels are 1/11 as large as Retiga’s
Dynamic range

\[ DR = \frac{\text{max output swing}}{\text{noise in the dark}} = \frac{\text{saturation level} - D_t}{\sqrt{D_t + N_r^2}} \]

✦ examples

• Retiga 4000R = \((40,000 - 1.64) / \sqrt{1.64 + 12^2}\) electrons
  = 3,313:1 (11.7 bits) for a 1 second exposure, and
  = 3,333:1 (11.7 bits) for a 1/60 second exposure

• Aptina MT9P031 = \((8500 - 25) / \sqrt{25 + 2.6^2}\)
  = 1500:1 (10.5 bits) for a 1 second exposure, but
  = 3200:1 (11.6 bits) for a 1/60 second exposure

✦ determines useful ADC precision

✦ after gamma correction (for JPEG), you only see \(~8\) bits
ISO

- amplifies signal before analog-to-digital conversion
  - avoids losing low signal due to quantization and any noise introduced after quantization (yes, there is some)
  - doubling ISO doubles the signal, which is linear with light, so equivalent to doubling exposure time, or minus 1 f/stop

- maximum ISO on Canon 5D II is 6400
  - higher ISOs implemented using multiplication after ADC?

- raising ISO improves SNR relative to multiplication after ADC, or equivalently, brightening in Photoshop

- but raising exposure time improves SNR faster, so

- maximize exposure time to the limits imposed by object motion, camera shake, or sensor saturation, then maximize ISO to the limit imposed by ADC saturation
Averaging several short-exposure, high-ISO shots to avoid camera shake & reduce noise
Aligning a burst of short-exposure, high-ISO shots using the Casio EX-F1

1/3 sec

burst at 60fps
Jesse Levinson, Andromeda
(single exposure, 3 minutes)
Slide credits

✦ Brian Curless
✦ Eddy Talvala
✦ Abbas El Gamal


✦ Filippov, A., How many bits are really needed in the image pixels? (sic), http://www.linuxdevices.com/articles/AT9913651997.html