Intro to Cameras and Imagers

CPS 1/296

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Solid State Cameras

- Not a depth sensor – no direct measurement of depth
- Captures a projection of a 3D scene on a 2D plane
- Features of cameras:
  - Have become very inexpensive
  - Very fast
  - Very high resolution
  - Few or no moving parts
  - Can be made very small
  - Can be used entirely passively
- Example:
  - HDTV = 2M pixels/30th second
  - Assume 8bpp
  - HDTV sensor outputs 60 MB/s
  - Note: Recording media built on assumption of lower bandwidth due to compression

Crude History of Solid State Sensors

- TV images originally captured by tubes
  - Big
  - Expensive
  - Delicate
  - Hard to manufacture
- Silicon sensors proposed in late 60s, early 70s
- Two competing technologies
  - CCD
  - CMOS

Emergence of CCDs

- CCD technology takes an early lead
- Adopted by video camera manufacturers
- First CCD video cameras hit market in 70's
- Advantages:
  - Reliability
  - Accuracy
  - Size
  - Cost
  - (Though not all realized in initial efforts)
- Enthusiastically adopted by astronomers
- Fun link: http://www.digicamhistory.com/1970s.html

CCD Quick Facts

- Manufactured using photolithography techniques
- Involves some complications over (now) standard CMOS fabrication lines
- Typically more expensive than a logic chip of the same size (but this is a crude generalization)
- Fabs typically produce logic or CCDs, but not both
- Currently the most common sensor for:
  - Good quality digital still cameras
  - Digital video cameras
- Challenged by CMOS
- More on CMOS later…

How Does a CCD work???

- First, let's recall how semiconductors work
- A semiconductor's ability to conduct is influenced by "external" factors
  - Surrounding magnetic fields
  - Temperature
- Basic concept allows us to think of a chip as a network of pipes and valves

How Does a CCD work???

- See picture(s) on board
- A CCD is both:
  - An array of photodiodes
  - An array of capacitors
- During the exposure period, incident photons:
  - Liberate an electron from the valence level, after which
  - Liberated photon is sucked into a "potential well"
- After exposure:
  - Electrons are fed out of the CCD in bucket-brigade fashion (multiple stages per photodiode)
  - Bucket brigade works horizontally and vertically
  - Bucket brigade feeds in to an amplifier and A/D converter

So is a CCD an analog device?

YES!

Issues with CCDs

- Strongly influenced by temperature
- (Relatively) slow readout
- No random access
- Require a mechanical shutter (but there are some workarounds)
- Have some strange failure modes
  - Blooming
  - Smear

http://marsrovers.nasa.gov/gallery/press/opportunity/20040126a/MERB_Sol1_Postcard-B002R1_br2.jpg

More CCD Facts

- Linear response
- No way to sense color (but there are workarounds)
- Sensitivity adjusted by increasing amplifier gain
- Refined to have
  - Remarkably high quantum efficiency (QE)
  - Remarkably high charge transfer efficiency
- Embellishments:
  - Electronic shuttering
  - Blooming protecting
- Embellishments come at expense of QE

CMOS Sensors

- A CMOS sensor is like a DRAM that sees
  - Photons liberate charge
  - Charge collected in a capacitor
  - Capacitor is read with random access
- Not prone to blooming
- Lower power consumption than CCDs
- Can be made using (mostly) "commodity" chip equipment and techniques
  - Potential for reduced cost
  - Potential for integration with other functions

CMOS "camera on a chip"

- Timing
- Variable gain amplification
- A/D conversion
- Entire image processing pipeline
  - Contrast curve
  - Color correction, processing
  - Image enhancement
    - Sharpening
    - Noise reduction

Initial Problems with CMOS sensors

- Transistors on surface used for controlling reset and readout
- Metal Oxide on chip surface is opaque (contrast with polysilicon for CCDs)
- Substrate not well suited for charge collection
  - Diffusion
  - Dark Current
- Readout of tiny voltages prone to problems
- Prone to "fixed pattern" noise

Improvements in CMOS sensors

- Manufacturers adapt fabrication methods to reduce diffusion, dark current problems
- Active pixel technology:
  - Adds an amplifier to each each pixel
  - Reduces signal loss, but
  - Sacrifices more pixel area, and
  - Potentially makes fixed pattern noise worse
- Reduction in feature sizes reduces QE loss from transistors
- Transistor sharing between pixels (recent technique)
- Correlated double sampling (or similar techniques) compensate for fixed pattern noise

CMOS vs. CCD Today

- CCD proponents: CCDs are the best photon counters
- CMOS proponents: CMOS sensors give best bang for the buck
- CMOS eroding CCD market share
  - CMOS creating new markets (phones, keychain cameras, etc.)
  - Markets dominated by CMOS sensors
    - Webcams (even the better ones)
    - Mobile phone cams
    - Low quality still and fusion cameras
    - Very high speed cameras
  - Markets dominated by CCDs
    - Scientific instruments (many but not all areas)
    - Good to high quality compact still cameras
  - Battleground markets
    - Digital SLRs (large sensors)
    - High quality video cameras

Some General Sensor Issues

Electronic Shuttering

- Basic problem: Sensor is photosenstive (the nonstick pan problem)
- Need a way to "instantly" sample contents of the sensor
- CCD solution: Interline transfer mechanism
  - Shunt charge to shielded area
  - Block charge accumulation
  - Problems: Not 100% effective, costs area
- CMOS solution(s) similar in spirit

Dealing with Low Fill Factor

- Fill Factor = % of pixel area that is photosensitive
- Reasons for low fill factor:
  - Interline transfer area for CCDs
  - Anti-blooming gate for CCDs
  - Transistors in CMOS sensors
- Solution: "microlenses" or "lenslets"
- Microlenses focus light on photosensitive area

Dealing with Color

- Sensors (mostly) don't notice color
- Sensitivity to color is often an annoyance
  - Nonuniformity with wavelength
  - Exception: Foveon X3 sensor
- Sensing color typically requires filters
  - Trade spatial resolution for color, or
  - Duplicate sensors

Dealing with Noise

- Many sources of noise:
  - Fixed pattern
  - A/D conversion
  - Reality
  - Properties of substrate
  - Properties of charge transfer/readout mechanism
  - Amplification
  - Reset noise
- Modeling and dealing with noise are major challenges

More and more pixels?

- Trend towards increasing pixel density
- Driven by:
  - Marketing
  - Some genuine technological advances
- Issues with increasing pixel density
  - Noise (why?)
  - Diminishing returns?