A Graduate Course on Image Sensors
and Digital Cameras

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Motivation

• Sales of digital cameras has surpassed film cameras

• Emergence of CMOS image sensors making *camera-on-chip* possible – enabling new applications:
  - PC camera
  - cell phones and PDAs
  - toys and games
  - biometrics
  - camera arrays and networks

• More EEs are attracted to the field, but
  - Little teaching material available
  - Study of digital camera system requires working knowledge in many areas (photometry, optics, device physics, circuits, signal processing, color science . . . )
Outline

- Digital cameras and image sensors
- The course
  - Objectives
  - Requirements
  - Topics
  - Course history
- Digital camera simulator (vCam)
- Demo
Digital Camera System

- Lens
- CFA
- Image sensor
- AGC
- Auto Exposure
- Auto Focus
- ADC
- Color Processing
- Image Enhancement & Compression
- Control & Interface
Architecture of Olympus Camera

- Lens
- CCD
- I/O Control
- Memory Manage
- JPEG Engine
- CCD Timing I/F
- RISC
- Video LCD I/F
- Co-pro
- Cache
- S-RAM
- PCMCIA I/F
- IRQ
- Clock
- D-RAM

LCD monitor
CCD Camera

Many chips — CCD, ADC, ASICs, memory, ...
Sub-micron CMOS Enables Camera-on-Chip

VLSI Vision Ltd. (ISSCC ’98)
CCD Image Sensors (Interline Transfer)
CCD image sensors

- **Advantage:** High quality
  - optimized photodetectors (high QE, low dark current)
  - low noise and nonuniformity (CCDs do not introduce noise or nonuniformity)

- **Disadvantages:**
  - inability to integrate other camera functions on same chip with image sensor
  - high power (due to high speed shifting clocks)
  - limited frame rate (due to analog serial readout)
Most popular type called Active Pixel Sensor (APS), pixel has photodiode and 3 transistors
CMOS Image Sensors

- **Advantages:**
  - unlimited ability to integrate other camera functions with image sensor on same chip
  - lower power consumption than CCDs (10X)
  - potential for very high frame rates

- **Disadvantages:** lower quality than CCDs
  - nonoptimized photodetectors (process often modified to optimize the photodetector)
  - high noise and nonuniformity due to multiple levels of amplification (pixel, column, and chip)
Color Imaging

- Color filter array (Bayer pattern)

- Color processing

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From ADC → Color Interpolation → White Balancing → Color Correction → Gamma Correction → Color Conversion → To DSP
Course Objectives

- Provide an introduction to design and analysis of image sensors (especially CMOS)
- Develop basic understanding of signal path through digital camera
- Develop understanding of the performance measures and tradeoffs involved in the design of image sensors and digital cameras
- Have fun using many basic EE (and some non EE) stuff to understand a “cool” system
Course Requirements

- Prerequisites: Undergrad device, circuit, system courses
- Reading: Lecture notes and research papers handed out
- Students: MS or PhD level (EE, CS, Applied Physics)
- Homeworks: Six weekly homeworks
- Exams: Take home midterm
- Project:
  - 1-2 project topics proposed
  - performed in 1-2 student groups
  - two weekly progress reports/ meetings and final report
  - Most projects used the camera simulator
Course Topics

- Imaging optics (1 lecture)
- Photodetector operation, QE, dark current (3 lectures)
- CCD and CMOS image sensor operation (3 lectures)
- Noise analysis, SNR, and dynamic range (3 lectures)
- Fixed pattern noise (FPN) (1 lecture)
- Spatial resolution, MTF (1 lecture)
- Color imaging and color processing (1 lecture)
- Camera simulator (1 lecture)
- Recent developments (1 lecture)
Course History

- Course offered four times (Spring 98-01)
- Class enrollment: 16 MS and PhD students (mostly EEs, some CS and Applied Physics)
- Example projects:
  - How large should pixel size be?
  - Honey-comb versus square pixel array
  - High dynamic range image sensor schemes
  - Auto-exposure algorithms
Optimal Pixel Size

![Graph showing the relationship between pixel size (µm) and Average ΔE. The x-axis represents pixel size in micrometers (µm), ranging from 5 to 15, and the y-axis represents Average ΔE, ranging from 0.8 to 2.6. The graph displays a trend line indicating the optimal pixel size for a specific ΔE value.](image-url)
Conclusion

- Graduate level course on image sensors and digital cameras
- Course only requires undergraduate EE level background
- Course uses a “system approach”: 
  - builds a model for the signal path through digital camera
  - discusses sensor architectures and operation
  - introduces important performance measures
- Example of how the study of a complex system can be made accessible to MS level EEs
- Example of the bidirectional flow of ideas between research and teaching
vCam: Digital Camera Simulator

Set of MATLAB routines modeling light source, object, optics, sensor, ADC characteristics, and for performing color and image processing

Developed for research on image sensors and digital cameras