Digital cameras, CMOS and CCD sensors

Lecture 3:
Digital Imaging Systems
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Content of the lecture on:
Digital cameras, CMOS and CCD sensors

- Basic description of digital cameras
- Geometrical
  - Properties
  - Limitations
- Densitometric
  - Intensity resolution, S/N ratio
- Spectral
  - Wavelength range and properties
- Temporal
  - Exposure time, possible repetition rates
- Applications, history and future
Digital camera aspects

- Optical imaging
- Sensor properties
  - CCD
  - CMOS
- Image processing in camera
Camera optics

- The optical camera aspects are the same old ones for digital cameras as for film based ones
  - Lens quality
  - Aperture
  - Depth of focus
  - Focal length
Basic camera optical principles

- The depth of focus depends on the focal length and aperture
  - Smaller aperture = bigger depth of focus but less light = longer exposure
Focal length aspects

- The effective focal length relates to image sensor size,
- Many digital sensors are much smaller than standard 24x36 mm film
- Can thus easily get long telephoto, but may have wide angle problems
Digital camera lenses come in a wide range of sizes and qualities.

Generally speaking:
- Bigger is better
- Glass is better than plastic

But there are also exciting trends towards extremely small liquid based lenses for e.g. mobile phones.
Geometrical image distortions

- Pincushion Distortion
- No Distortion
- Barrel Distortion
Geometric "barrel" distortion
Geometric "barrel" distortion corrected
Two types of sensors CCD and CMOS

○ CCD - Charge Coupled Device
  ● A CCD has photosites, arranged in a matrix.
  ● Each comprises a photodiode which converts light into charge and a charge holding region
  ● The charges are shifted out of the sensor as a bucket brigade

○ The A/D conversion is done at the edge of the circuit
Two types of sensors CCD and CMOS

- CMOS – Complementary Metal Oxide Semiconductor
  - Each pixel contains a photodiode that converts light to electrons
  - A charge-to-voltage conversion section
  - A reset and select transistor
  - An amplifier section

- The A/D conversion is done at each pixel
Sensor architectures: Interline, full frame, frame transfer CCD and CMOS
Types of CCD Image Sensors: Full Frame

The pixels are both photosites and the VCCD. Charge is transported down the columns from pixel to pixel. Charge in the first VCCD row is transferred into the HCCD. The HCCD clocks out one row at a time.
CCD function – full frame

- In the full frame design the charge holding region is integrated with the light sensing region. Light is collected over the entire imager simultaneously.
- Then the light has to be shut off so that the charge can be transferred down the columns.
- Finally, each row of data is moved to a separate horizontal charge transfer register. Charge packets for each row are read out serially and sensed by a charge-to-voltage conversion and amplifier section.
- This design features a high, almost 100% fill factor but external shuttering is required and light can not be collected during readout.
A modern (2007) 12 megapixel full frame transfer sensor
Types of CCD Image Sensors: Interline

- An interline image sensor has a light shielded VCCD adjacent to each photodiode photosensor.

- Charge is transferred from the photosites to the vertical CCD in one cycle. Then charge is transferred into the horizontal CCD, one row at a time.

- The next image can be integrated while the previous image is safely transferred out of the imager.

- Interline imager sensors, unlike full-frame devices, do not require an external shutter.
In the interline transfer design the charge holding region is shielded from light. Light is collected over the entire imager simultaneously and then transferred to the next, adjacent charge transfer cells within the columns.

This implies a low fill factor, which on modern designs usually is compensated for by microlenses.

Next, the charge is read out: each row of data is moved to a separate horizontal charge transfer register. Charge packets for each row are read out serially and sensed by a charge-to-voltage conversion and amplifier section.
Frame transfer CCD operational principle

Parallel Clocks for Image Array

Parallel Clocks for Storage Array

Serial Clocks

Output Amplifier
CCD function – frame transfer

- Also the frame transfer CCD has photosites, arranged in an X-Y matrix. (Almost) the entire photosite is light sensitive, i.e. a good fill factor.

- When light has been collected over the entire imager simultaneously it is rapidly shifted into an equal size rectangular array of charge holding regions which is shielded from light.

- If this transfer goes very rapidly it can be done without shuttering the light, the resulting smear can be neglected.

- From the shielded frame the image can be read out while the next one is being integrated.

- A disadvantage is that an extra large chip area is needed for storing the image.
CCD advantages-disadvantages

**Pro:** CCD:s started developing in early 70-ies, optimized for optical properties and image quality, continues to improve

- The optimized architecture produces a low-noise, high-performance imager.
- More light sensitive than CMOS (1 lux vs 5-10 lux)

**Con:** The optimization makes integrating other electronics onto the silicon impractical. In addition, operating the CCD requires application of several clock signals, clock levels, and bias voltages, complicating system integration and increasing power consumption, overall system size, and cost.
CMOS - fill-factor limits in layout
The CMOS sensor’s architecture is arranged more like a memory cell or flat-panel display.

Each photosite contains a photodiode that converts light to electrons, a charge-to-voltage conversion section, a reset and select transistor and an amplifier section. This additional electronics limits the fill factor.

Overlaying the entire sensor is a grid of metal interconnects to apply timing and readout signals, and an array of column output signal interconnects. The column lines connect to a set of decode and readout (multiplexing) electronics that are arranged by column outside of the pixel array.

This architecture allows the signals from the entire array, from subsections, or even from a single pixel to be readout by a simple X-Y addressing technique—something a CCD can’t do.
A typical CMOS chip design

Diagram showing the components of a CMOS chip, including:
- Photosensitive Area (640 x 480 pixels)
- Sensor Interface Block
- I²C Serial Interface
- CDS
- Column Offset
- White Balance Gain
- Global Gain
- Global Offset
- 10 Bit ADC
- Post ADC

Signals and connections include:
- MCLK
- INIT
- STBY
- SYNC
- SCLK
- SDATA
- ADC(9:0)
- HCLK
- VCLK
- SOF
CMOS advantages-disadvantages

**Pro:** Lower system cost
- A CMOS imager is made with standard silicon processes in high-volume foundries. Support electronics easier to integrate. Benefit from process and material improvements made in mainstream semiconductor technology.

- Lower power usage
- Easy integration of additional circuitry on-chip
- Can read out subsections for variable resolution/speed

**Con:** Image quality
- A longer development and more optimized designs
## Comparison table CCD vs CMOS

<table>
<thead>
<tr>
<th>Aspect</th>
<th>CCD</th>
<th>CMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>High</td>
<td>Moderate</td>
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<td>Uniformity</td>
<td>High</td>
<td>Low to medium</td>
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<tr>
<td>Speed</td>
<td>Moderate to high</td>
<td>Higher</td>
</tr>
<tr>
<td>Windowing</td>
<td>Limited</td>
<td>Extensive</td>
</tr>
<tr>
<td>Antiblooming</td>
<td>None to high</td>
<td>High</td>
</tr>
<tr>
<td>Energy need</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Clocks</td>
<td>Multiple</td>
<td>Single</td>
</tr>
<tr>
<td>Bias</td>
<td>Multiple, higher</td>
<td>Single, low voltage</td>
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<td>voltages</td>
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CMOS vs CCD conclusion

- CCD:s are still usually the choice in applications where image quality is the primary requirement.
- CMOS sensors are much cheaper, mass produced in mobile phones, toys, cheap cameras etc. More than 90% of all chips produced are CMOS.
- A typical CCDs consume 2 to 5W of power, a CMOS chips typically 20mW to 50mW.
- CMOS is developing rapidly also for high-end application:
  - 12 mpixel CMOS sensors are available
  - Improved designs closes the quality gap
  - Large pixel designs improve fill factor
- CCD:s are also improving:
  - 85% quantum efficiency and 16 bit dynamic range available
CMOS vs. CCD today

- Today there is no clear line dividing the types of applications each can serve. CMOS designers have devoted intense effort to achieving high image quality, while CCD designers have lowered their power requirements and pixel sizes.

- As a result, you can find CCDs in low-cost low-power cellphone cameras and CMOS sensors in high-performance professional and industrial cameras, directly contradicting the early stereotypes.

- Latest Nikon has CCD while Canon has CMOS both high end in the 10-20 megapixel range
Tubes, CCD:s and CMOS trends

Trends: Image Sensor Technical Migration

- Professional DSC
- Motion Analysis
- Medical
  - Radiology
  - Digital Endoscopy
- Low Power Space Apps
- Automotive
- Computer Video
- Consumer ESC
- Biometrics
- Optical Mice
- Imaging Phones
- Toys
- Bar Code
- Security
"As an independent test lab for digital cameras, we have observed a decrease in the image quality of digital cameras during the last 3 years," says Image Engineering. www.image-engineering.de

Newer cameras have an increasingly worse image quality and the reason for that is obvious:

"The more pixels a camera has, the better it is" was true in the beginning of digital photography when compact cameras had a VGA resolution (640 x 480)

When the pixel count exceeded 6 Megapixels in 2004, this was no longer the case but consumers still buy cameras with the highest pixel count.
The More Pixels, the Worse the Image!

- Customer preferences induces manufacturers to produce cameras with an increasing amount of pixels without increasing the sensor size,
- Which in turn leads to a decreasing sensitivity and an increase in the visibility of image noise
- It also rarely shows a better reproduction of details because the lenses do not have a high enough resolution.

- This is true for compact cameras, not directly for high end cameras
Creating color

- One- or three-chip camera
  - three-chip is usually at least 3 times as expensive
- The color filter matrix for one-chip, usually "Bayer mosaic"
  - Reduces color resolution to about half
  - Also reduces light collection efficiency
  - Anisotropic in x and y
  - A new method invented by Foveon uses "vertical filters" with less resolution loss
2D Mosaic vs vertical filtering

傳統 CCD & COMS

SIGMA SD9

B25%  G50%  R25%

B100%  G100%  R100%
What is a digital camera?

1: A sensor chip with optics and some driving circuits and interfaces
2: A complete system for capturing, improving and storing digital images
3: A digital video camera which also compresses and stores image sequences, possibly also adding additional effects
Digital cameras (1)
Low end and high end examples
The components of a digital camera (2)
Digital camera operational steps: Exposure

- The lens assembly usually includes an infrared (IR) blocking filter and an optical anti-aliasing filter.
- The camera usually has an adjustable focal length taking lens, controlled by zoom and focus motors. The zoom motor also controls an optical viewfinder.
- When the user presses the shutter button halfway, the camera performs automatic exposure and automatic focus processing.
- The camera lens focuses light from the scene onto the CCD or CMOS sensor.
- The analog signal from the sensor is amplified and converted to digital form, normally using a 10 or 12-bit analog to digital (A/D) converter.
- When the user fully depresses the shutter button, an image is captured and stored in DRAM.
Digital camera operational steps: De-mosaicing

- In order to create the final high-resolution digital image, the digital data is processed by a camera ASIC digital image processor, or by a high-performance microprocessor, sometimes supported by a digital signal processor (DSP).

- The first step is de-mosaicing: Since most digital cameras use a single color image sensor that provides only one color value for each light sensitive cell, filtered through the color filter array (CFA), interpolation is used to "fill in" the "missing" color values for each pixel, this is also called "de-mosaicing."

- A sophisticated algorithm decides if the "missing" color values are in a smooth area of the image or along an edge, and adaptively determines the best digital code value to use for each missing color value.
Digital camera operational steps: White balancing

- De-mosaicing provides a full-color, but not yet perfect, image. To get a good color image, the camera must also provide white balancing to compensate for spectral variations in the illumination.
  - While both daylight and indoor lighting provide "white" light, daylight actually has more energy in the blue portion of the light spectrum and indoor lighting provides more energy in the red portion of the spectrum.
- An image processing algorithm is used to analyze the scene and adjust the red and blue signal strengths to match the green signal strength in white and neutral areas of the picture.
Even after white balancing, the color image is not yet perfect. This is because the RGB spectral sensitivities of the image sensor do not perfectly match the way your eyes see colors. As a result, the color image typically appears desaturated, muting bright colors like red and blue.

Color correction digitally compensates for this, improving the color reproduction, and also transforming the digital image into the output color space.

The output color space used for most digital cameras today is sRGB, which is a color space that is designed to be ready for display on a typical computer monitor.
Digital camera operational steps: Sharpening

- The next image processing step is sharpening. The anti-aliasing filter and other lens components slightly soften the image captured by the color image sensor. The picture may also be slightly blurred by the display monitor or printer.

- Therefore, digital cameras usually include digital image processing to sharpen the image applying adaptive spatial filters, which locate and emphasize fine edge details in the image.

- In some cases, a photographer may prefer different sharpness levels, for example, depending on whether the photo is a portrait or a nature shot. To provide this creative control, some digital cameras offer a variety of different sharpness settings such as "soft," "standard" and "sharp."
Digital camera operational steps: Compression

A raw digital image is very large, typically many MB. To increase the number of images stored on the card, image compression is usually used to reduce the file size, typically using the JPEG algorithm.

- JPEG works by dividing the image into small blocks, and converting the RGB data into a luminance and two chrominance signals. These signals are then transformed into spatial frequencies using the discrete cosine transform (DCT). Some of the information in the higher spatial frequency regions where the human eye is less sensitive can be discarded without any visible quality loss.

- However, if you are to analyze the image in a computer this information loss can be very problematic.

- Some digital cameras provide the user with the ability to select different quality levels so that they can make the best trade-off between file size and image quality for their particular needs.
Digital camera operational steps: File format

- Finally the compressed image data is stored in a JPEG image file usually according to the Exif format (Exif stands for Exchangeable Image File).
- In addition to the compressed JPEG image the file contains metadata such as:
  - Camera manufacturer and model number
  - Exact date and time the picture was taken
  - Focal length, subject distance, lens fnr, and shutter speed used to take the picture
  - Ambient light level, flash setting
  - User-selected camera settings (sharpness level, quality level, etc.)
  - A "thumbnail image"
  - Some cameras even allow short "sound bites"
The Exif digital file format

- **JPEG Compressed Main Image**
- **Tags:**
  - Date/Time
  - Flash Fired
  - F/Number
  - Focal Length
  - Exposure Time
- **JPEG Compressed Thumbnail Image**
- **Image Metadata**
- **Metadata Within Image File**

Image File: DCP_0021.jpg
Digital camera considerations

- Make sure the camera has the right resolution for your needs. Maximum megapixels are usually not optimal.
- Make sure the camera has “enough” memory.
- Make sure the lens will handle the pictures you plan to take. Lens quality varies widely. Optical zoom, large aperture, macro setting are aspects to consider.
- Do not confuse digital zoom with optical zoom. Digital zoom is just image post-processing.
- Do not confuse actual resolution with interpolated resolution. Like digital zoom, interpolated resolution is an illusion.
- See how long the batteries will last. Many digital cameras eat batteries.
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Geometric properties

- The sensors are rigid structures
  - Always gives the same geometrical properties
  - Resolution is limited by the sampling, defined by the number of pixels
    - Watch out for aliasing
- Essential geometrical properties are determined by lens optics
  - Barrel or pincushion distortion
  - Spectral aberrations
  - Bad focus in image corners
A top-of-the-line camera sensor today (Kodak KAI-11000CM) features:

- 11M pixels
- 2672 x 4008
- Each 9 microns
- Image size of 24x36, i.e. The same as standard film

Uses interline transfer with special limited resolution fast read-out allowing 20 fps monitoring of image
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Densitometric aspects

○ What physical property is being imaged?
  ● The light being captured by the lens onto the sensor
    ○ Typically the light reflection of a surface
    ○ May also be light transmission e.g. in microscopy cameras

○ How well can this property be described?
  ● Typically with very good sensitivity, up to 85% of all photons can be captured
Densitometric aspects, 2

- What is the densitometric resolution? What is the signal to noise ratio? How many meaningful greylevels do we get?
  - Number of greylevels depends on system quality
  - Usually 10- or 12 bits even in cheap systems
  - Noise mainly depends on thermal effects
  - Cooled systems can have very good dynamic ranges, better than 16 bits
  - In astronomy sometimes exposures for hours and images with 32 bit digitization are used
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CCD/CMOS spectral range

- CCD and CMOS sensors are normally used for visible light.
- Have good natural sensitivity in near infrared, usually removes that by filters.
- Can be specially adapted for other parts of the spectrum e.g. X-rays.
IR cameras show emissive, heat images
Night vision through image intensifier
X-ray CMOS camera

- Radicon Imaging Corp. The Shad-o-Snap 1024 x-ray-sensitive camera.
- The camera retrieves images as 128 X 124-pixel thumbnails at up to 1 fps,
- Full-resolution 8-bit tiff or 16-bit raw files at 0.3 fps.
- It features a CMOS photodiode imager with a 5 X 5-cm active area, 48-µm-pixel spacing
- Suitable for biomedical applications in the 10- to 160-kV range.
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The temporal dimension
Image sequences, film and video

- CCD and CMOS technology are the dominating means of registering moving images.
- Were first used in analogue video cameras, where the sensor signal was stored on analogue video tapes.
- Have now been replaced by digital video cameras.
- Are now being replaced by disk based and solid state digital video cameras where digital video is stored on memory cards.
The temporal dimension
Image sequences, film and video

- The CCD and CMOS technologies can be pushed to very high speed performance
- Special designs can have exposures down to nanoseconds and repetition rates up to 240,000 frames per second
- This has replaced film also in high speed photography
Example of high speed film
High speed CMOS camera system

- The 1280 PCI 1,280 x 1,024 pixel images at frame rates to 500 frames per second, and at reduced resolutions up to 16,000 fps.
- Electronic global shutter to 7.8µs.
- PanelLink™ digital output for real-time image transfer to frame grabber.
- Large 12-micron pixels provide maximum sensitivity and color fidelity.
Photron FASTCAM Ultima APX

Features:
- Full, 1,024 by 1,024 pixel resolution, up to 2,000 frames per second (fps)
- 10-bit monochrome, 30-bit color **CMOS sensor** with large pixels for increased sensitivity
- Recording at frame rates up to 100,000 fps
- Global electronic shutter to 4µs
- Image memory can be expanded to 8 Gigabytes to facilitate 3 second record duration at maximum resolution and 2,000 fps or 6 seconds at 1,000 fps
Historical notes

- Photography about 150 years
- First electronic photography – the television camera tube 1940-ies
- First solid state sensors 1970-ies
- First digital camera for consumers 1994
- First year more digital cameras than film based cameras sold 2003
- First year with no film based cameras in major photo catalogues 2008
Camera from 1851