The Fundamentals of Camera and Image Sensor Technology

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Digital Cameras: Basic Course

- Light Basics + CCD/CMOS Imager Fundamentals
- Digital Camera Principals
- Interfaces
- Camera Types and When to Use
Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
  - Light Basics
  - CCD and CMOS Sensors
- Digital Camera Principals
- Camera Interface Standards
- Camera Types and When to Use
Light is a very narrow band in the electromagnetic spectrum.
We are primarily interested in wavelengths from **200–1100 nm**

- **Visible Light**: 400 – 750 nm
- **NUV**: 200 – 400 nm
- **NIR**: 750 – 1100 nm
Light Basics

Light is represented as both a particle and an electromagnetic wave

- A light particle is called a photon.
- Photons have some energy. (UV -> IR)
- The amount of energy determines the wavelength.
- The wavelength corresponds to a color.
- Intensity of light = number of photons.

\[ E = \frac{hc}{\lambda} \]

- \( E \) = Energy of Photon
- \( h \) = Planck's constant
- \( c \) = Speed of light
- \( \lambda \) = Wavelength of Light
Light Basics

Photoelectric Effect: Photons to Electrons

- Light photons hitting a Silicon surface will dislodge electrons
- Number of electrons released depends on intensity and wavelength

![Diagram showing the photoelectric effect]
Quantum Efficiency (QE):
The ratio of light that the sensor converts into charge.

- **60% QE** = For every 10 photons hitting a pixel, 6 electrons are released.

- QE response is sensor specific. Camera design does not affect the QE curve.

- QE is given in either absolute or relative terms. Relative QE is not good for comparison.
The **Full Well Capacity** is the maximum number of electrons that register a signal in a pixel. *Larger pixels have higher well capacity which also leads to higher sensitivity*, better Signal to Noise Ratio (SNR), and increased dynamic range.

**Full Well Capacity:**
- 4,000 electrons – Small pixels
- 10,000 electrons – Medium pixels
- 50,000 electrons – Large pixels
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The main difference between CCD and CMOS is how they transfer the charge out of the pixel and into the camera’s electronics “Read Out”.

**CCD**

- **Pixel:** Current

**CMOS**

- **Voltage Sample**
- **Read Out Circuitry:**
CCD and CMOS Sensors

CCD Sensor
Think “Bucket Brigade!”
CCD and CMOS Sensors

CCD Sensor

- “Charge-Coupled Device”
- CCD imagers are **Current Driven Devices**
- Charge is collected in pixels
- The charge is then physically shifted on the imager surface to the output for sampling
- The CCD output is an *analog pulse* where the charge is proportional to the light intensity
Microlens

- Microlenses increase the photon collection area of the pixel and focus the photons into the photosensitive area (Good “Fill Factor”)
- Almost all modern CCD designs use microlenses (Color & Monochrome)
- **PRO** - Effectively increases the quantum efficiency of the pixel
- **CON** – Creates and angular sensitivity to the incident light ray
Microlenses decrease sensitivity to angular rays

CCD focal plane

Lens

Center rays

Peripheral rays

Angular QE data for Kodak KAI 0340 CCD

Varies due to the photosensitive area not being square!
CCD and CMOS Sensors

- Horizontal lines are shifted down the sensor. Pixels are read out from a horizontal shift register through a common circuit.

- **Main Advantage:**
  - Sensitivity, however CMOS is surpassing
  - Fidelity

- **Main Disadvantage**
  - Speed

*CCD: Charge-Coupled Device*
CCD Issues: Blooming

- Blooming is known as the spread of charges to adjacent pixels due to over saturation of pixels.
- This makes some very bright spots in the image.
CCD and CMOS Sensors

CCD Issues: Smearing

- Smear is similar to blooming. It’s caused by pixels becoming saturated, and light spilling over into the vertical shift register while clocking out.

![Image of vehicle with smattering effect]
CMOS Sensor

- “Complimentary Metal-Oxide Semiconductor”
- CMOS imagers are **Voltage Driven** Devices
- Light striking the pixel creates a voltage proportional to intensity
- The voltage is sampled directly at the pixel, digitized on the imager and cleared for the next frame (picture)
- The CMOS imager has a completely digital output
CMOS Issues: Pattern Noise + Sensitivity

- CMOS layer stack up prevents using microlens and has lower charge conversion than CCD, usually resulting in lower sensitivity in older CMOS sensors.
- Higher Image non uniformities (aka “Fixed Pattern Noise“) due to unevenness between the individual Pixel cells and multiple A/D circuits in column readout.
  - Newer CMOS sensors address this!
- CMOS is more resistant to Smearing or Blooming than a CCD!
CMOS Sensor

Voltage sampling is faster than rolling charge in CCD.

- This makes readout faster than CCD
- Less flow of charge = Less power

Main Advantages:
Speed + Power Consumption
Sensitivity in newer sensors

Main Disadvantages:
Pattern Noise
Sensitivity (older sensors)
CMOS Issues: Rolling Shutter

- An electronic shutter (CCD) or **global shutter** (CMOS) allow exposure of the whole frame at the same time.
- A **rolling shutter** will expose the frame line after line. The number of exposures equals the number of lines in the frame.

Image taken with global shutter

Image taken with rolling shutter
CCD and CMOS Sensors

CMOS Issues: Rolling Shutter

A strobe can be used to help freeze the motion and minimize rolling shutter effects.
CMOS Issues: Rolling Shutter

Image example with a moving object taken with global shutter.

Image example showing distortion caused by a rolling shutter

Distorting caused by a rolling shutter

Picture taken from a moving car. The railing in front has vertical bars. Note that the vertical bars are shown distorted caused by the rolling shutter. The actual shutter setting is short enough to freeze the movement.
Progressive and Interlaced Scanning

- Image from camera is formed by sequence of pixel lines scanned and displayed in one of two different ways.
  - Progressive scanning:
    - Scanning of first line, second line, third line, etc... until the entire frame is scanned.
  - Interlaced scanning:
    - Scanning of odd-numbered lines, then scanning of even-numbered lines. Both fields are then combined to form the entire frame.
    - Found in analog cameras
Interlaced scan is used in normal TV systems. Odd lines (1-3-5...) are scanned in first field. In second field, even lines (2-4-6...) are scanned. One full frame consist of 2 interlaced fields (2:1 interlacing).

The benefit is smoother motion when displayed on a monitor.

The drawback is that each field has a separate exposure. The 2 exposures in one frame cause fast moving objects to blur; interlace blurring.
CCD and CMOS Sensors

Interlace Blurring
Non-interlaced scan or progressive scan is used in machine vision. The lines are scanned progressive from top to bottom in one full frame.

The scanning system is a non-standard. The video **can not be shown on a standard CCTV monitor**.

The benefit is that a full frame is available as the result of a single shutter event.
Progressive and Interlaced scanning

Interlaced (odd lines)

Interlaced (even lines)

Progressive
Progressive and Interlaced scanning

- Interlaced scanning:
  - Spatial resolution is reduced but temporal resolution is improved. Twice as many ‘full’ images are presented per second.

- Progressive scanning:
  - Sharper images are formed
  - No interlaced blurring!

Note: With interlaced, you’ll see smoother motion with same frame rate, but will also notice the interlaced lines in the image.
The image size in inches relates back to the tube camera. The image format of a tube which could be placed in a 1” deflection coil was called 1” format. The active image size is 16 mm in diagonal. It is the same as for a 16 mm film format.

Below is the most common image formats shown.

<table>
<thead>
<tr>
<th>Format</th>
<th>Image Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1” format</td>
<td>16 mm</td>
</tr>
<tr>
<td>Type 1</td>
<td></td>
</tr>
<tr>
<td>2/3” format</td>
<td>11 mm</td>
</tr>
<tr>
<td>Type 2/3</td>
<td></td>
</tr>
<tr>
<td>1/2” format</td>
<td>8 mm</td>
</tr>
<tr>
<td>Type 1/2</td>
<td></td>
</tr>
<tr>
<td>1/3” format</td>
<td>6 mm</td>
</tr>
<tr>
<td>Type 1/3</td>
<td></td>
</tr>
</tbody>
</table>

### Image Size

- 16 mm diagonal
- 12.8 mm horizontal
- 9.3 mm vertical
- 11 mm diagonal
- 8.8 mm horizontal
- 6.6 mm vertical
- 8 mm diagonal
- 6.4 mm horizontal
- 4.8 mm vertical
- 6 mm diagonal
- 3.3 mm vertical
Lens specs must match image format.

- 1/3” Sensor Format ideally should be paired with 1/3” format lens
- Larger format lens can be used on smaller sensor
- Smaller format lens can NOT be used on larger sensor

**Image Format**

- **Bad**
- **Good**
- **OK**
The most common lens for CCTV cameras are of the C-mount or CS-mount type.

The lens thread and the distance from the lens reference flange to the image plane is standard.

The lens thread is 1-32 UN-2A. Diameter is 1 inch.

The flange back distance in air is 17.526 mm for C-mount. For CS-mount it is 12.526 mm.

Glass filters or prism between lens and focal plane will increase the distance.

TIP - With a 5 mm adapter ring, a C-mount lens can be used on a CS-mount camera.
Summary / Tips

- CCD: High image fidelity, lower speed.
- CMOS: High speed, lower image quality.
- Don’t use Rolling shutter for motion.

A number of photons ...  
... hitting a pixel during exposure time.  
... creates a number of electrons ...  
... forming a charge that is converted by a capacitor to a voltage ...  
... and then amplified ...  
... and digitized ...  
... resulting in a digital gray value.
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Charges from the pixels must be converted first to a voltage. This is done with a capacitor circuit.

Then the voltage levels must be measured and converted to a number. This is done with the analog to digital converter (A/D).

Along the way, Gain and Offset can be adjusted before the conversion.
Binary Counting vs. Decimal:

- A pixel is given a number value based on amount of light it receives
- Cameras use binary numbers to represent the amount of light
- Humans (and cameras) use decimal numbers which represents a grey scale

The more bits you use, the higher you can count!

### Analog and Digital Concepts

The A/D Converter will represent voltage levels as Binary Numbers and convert to digital!
So with more bits, you have more values to represent the light intensity from black to white. This is called “Bit Depth.” \(2^8=256\)

- **8 bit image**
  - 256 pixel values available

- **4 bit image**
  - 16 pixel values available

- **1 bit image**
  - 2 pixel values available
High Bit Depth Considerations

- With more bits, you get a more accurate measurement of the light. (8, 10, 12 bits = 256, 1024, 4096 grey scales)

- With more bits, you also have more data to transfer, process, store (12 bit = 50% more data more than 8 bit).
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Digital Camera Benefits

Goal of Digital Cameras: To Replace Analog Cameras

Digital cameras use the same sensors as analog cameras

→ So, there is no difference in image quality at the sensor level, **BUT**...
Digital Camera Benefits

No Frame Grabber required with Digital!

Analog problems:
- Pixel jitter
- Noise
- EMI Susceptibility
- Settings via dipswitch

Digital Solutions:
- Exact pixel readout
- No losses on the cable
- Settings via software

Overall Image Quality is Better with Digital!
Digital Camera Benefits

Analog

- CCIR / PAL → 624 lines, 25 fps
- EIA / NTSC → 525 lines, 30 fps
- Proprietary → more lines
- Interlaced / progressive scan

Digital

- 640x480 @ 30 -> 250 - > 800 fps
- 1392x1040 @ 20 -> 60 - > 200 fps
- Or Choose your own frame rate
- Or choose your own resolution, region of interest (ROI)
- Progressive Scan

Why Digital?

- Much more flexible
- Natural choice for high resolutions
Digital Camera Benefits

Analog

- Composite → 1 wire - cross talk
- S-VHS → 2 signal wires
- RGB → 3 or 4 signal wires

Digital

- RGB
- YUV 4:2:2
- Mono8 / Mono16
- Raw Bayer (Color) output
  - Use your own interpolation
Digital cameras can provide advanced features

- Test Image
- Time Stamp
- Frame Counter
- I/O Port Status
- Error Checking
- Partial Scan
- Image Flip
Digital cameras can do on-board processing

Example: High Dynamic Range Images (HDR)

Other examples: Blemish Compensation, Flat Field Correction (FFC), Multi-ROI
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Image Quality Basics

Temporal Noise:
- Anything besides light that causes a pixel’s value to change over time (temperature, ADC errors, etc.). This is measured by EMVA 1288

Spatial Noise:
- “Fixed Pattern Noise.” Constant non-uniformities in the image caused by bad sensor design, electrical noise, etc.
Some Sources of Temporal Noise:

- **Shot Noise / Photon Noise:** Due to random fluctuations in the light. [Brighter/Better Light = less shot noise]

- **Dark Current Noise:** The rate at which electrons are produced due to thermal effects. Every 8°C = Dark noise doubles. [cooler camera = less dark noise]

- **Quantization Noise:** Errors coming from the A/D conversion process. [Use a better ADC = less quantization noise]
Some Sources of Spatial Noise (Fixed Pattern):

- Bad sensor design
- EMI
Image Quality Basics

Signal To Noise Ratio (SNR):

- The ratio of good signal caused by light to unwanted noise. The most important measurement of image quality for digital cameras.

SNR Tips:

- High SNR achieved with large well depth (lots of signal to drown out the noise)
- Good camera design require less light to overcome

[Diagram showing signal electrons from light and noise electrons from heat, spatial, temporal, etc.]
Signal to Noise Ratio (SNR)

- **SNR Curve Characterization**: At-a-glance indicator of image quality and performance. Each camera has its own and is unique.

**Image Quality Basics**

![Signal-to-Noise Ratio (bits)]

- **Saturation**: well is full!
- **“Good” Image Quality**
- **“Acceptable” Image Quality**

- **Noise floor**: point where Signal = Noise
- **Dynamic Range**
- **MORE LIGHT!**
- **Higher SNR! (S/N)**
- Use the SNR Curves of various cameras to compare performance.

- A camera good in low light is not always the best in bright light!!

- Know before you buy!
Dynamic Range (DR): The measure of how well a camera can represent details when both bright and dark areas are present.

What effects DR?
- Sensor well depth
- Sensor algorithms with Knee points
- Multi-Exposure
- Higher bit depth
**EMVA1288**: Industry standard for measuring image quality of digital cameras.

- Testing uses known set of conditions (light, lens, targets, etc.).
- Manufacturers’ report data in agreed-upon format.
- Results for multiple cameras published to show level of consistency.
- Allows customer to compare apples to apples.
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Camera Controls

What are some camera controls can we use to affect image quality?

- Gain
- Exposure
- Brightness (black level)
- Image Format
- Resolution (Array Size)
**Camera Controls**

**Gain:** Amplifies analog signal from pixel before conversion.
- **Pro:** Higher Grey Scale level (Brighter)
- **Con:** Noise introduced (6db gain = 2X increase)

The camera’s gain setting is adjustable. As shown in Figure 59, increasing the gain increases the slope of the response curve for the camera. This results in a higher gray value output from the camera for a given amount of output from the imaging sensor. Decreasing the gain decreases the slope of the response curve and results in a lower gray value for a given amount of sensor output.

Increasing the gain is useful when at your brightest exposure, a gray value lower than 255 (in modes that output 8 bits per pixel) or 4095 (in modes that output 12 bits per pixels) is reached. For example, if you found that at your brightest exposure the gray values output by the camera were no higher than 127 (in an 8 bit mode), you could increase the gain to 6 dB (an amplification factor of 2) and thus reach gray values of 254.

![Figure 59: Gain in dB](image)
Gain Considerations:

- Increasing gain will increase visibility of both signal and noise!
- Does not increase image quality!
- Use only as a last resort to increase brightness.
- Gain may be limited at higher bit depths.
Example Images of Gain Effects:

High Gain used to compensate for low light. Bright image, but noise is apparent.

Low gain and good lighting is used. Light drowns out noise and makes clean image.
**Exposure Time:** The length of time that the sensor is open for collecting light. Also known as shutter speed and integration time.

**Exposure Time Considerations:**
- Frame rate may be reduced with increase.
- Motion blur is greater with increase.
- SNR is greatly increased with more exposure (longer shutter time – filling pixel well)
Camera Controls

Example Images of Exposure Effects:

Underexposed image: Detail lost in shadows

Good image: Detail is visible

Better image: Good detail and good contrast

Overexposed Image: Detail lost in highlights

Note that “Good” and “Better” are always a matter of opinion and application. Contrast is King!
Camera Controls

Black Level (Brightness): Adds an offset to pixel values. Adjusting the camera’s black level will result in an offset to the pixel values output by the camera. Increasing the black level setting will result in a positive offset in the digital values output for the pixels. Decreasing the black level setting will result in a negative offset in the digital values output for the pixels.

• i.e. Black image emitting photons – adjust black level to capture or not

Black Level Considerations:

• Proper use is to ensure camera accurately measures light when scene is darker.

• Side effect is that it can make the image brighter or darker, but not by much.
Camera Controls

Example Images of Black Level Effects:

Low Black Level used. Good Contrast, but some detail is lost in the darker regions (reduced grey level count)

High Black Level used. Contrast suffers, but detail is seen in darker regions (increased grey level count)
Camera Controls

**Image Format:** The type of image sent from the camera. Usually specified by color or mono, and then by bit depth. (i.e. mono8)

**Image Format Considerations:**
- Higher bit depth = more data to transmit/process.
- Lower bit depth = loss of detail
- Be wary of anyone wishing to “view” a 12 bit image on a computer monitor. All monitors can *only* display 8 bits or less!
- Many people think they need 12 bits but don’t!
Camera Controls

- Example Images of Image Format Effects:

  - 8 bit: 88.2KB/image
  - 4 bit: 44.2 KB/image
  - 1 bit: 11.3KB/image
Color Format Considerations

- Color cameras can be as little as $50 more than mono cameras.
- But this is not always something you want.
- Color Images are nice, but usually not found in general machine vision.
- Color Interpolation does not work well when no colors are present (i.e. black text on white background).
- This will affect your image processing!
- More details later...
Camera Controls

**Resolution (array size):** The number of pixels in the sensor, i.e., 640x480

**Resolution Considerations:**
- More pixels can achieve higher detail.
- But more pixels is not necessarily better!
- More pixels = small pixels = low SNR.
- Small pixels are hard for lenses to resolve.
- Always choose the lowest resolution possible for the application.
- High resolution = high price too
What if we need to inspect the **whole label** but also need to read the **barcode**?
Camera Controls

Example Images of Resolution Effects:

The resolution we choose to read the barcode determines the resolution we need to inspect the whole label.
Summary / Tips

- Identify whether it is a low or high end application.
- Low end applications may only need frame rate, resolution, and a sample image to select a camera.
- High end applications will need deeper data. Get the EMVA1288 reports, manuals, sensor datasheets.
- Become familiar with the more common sensors: ICX285, ICX445, IMX174, KAI1020, etc.
- Digital cameras are packed with features. Many that customers would never think they need!
- Don’t let bad settings misrepresent image quality.
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  - DCAM (FireWire - IEEE 1394)
  - Camera Link (Framegrabber)
  - Camera Link HS (Framegrabber)
  - CoaXPress (Framegrabber)
  - USB3 Vision (USB 3.0 – SuperSpeed USB)
  - GenICam (Software common to many standards)
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## Digital Interface Standards

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<thead>
<tr>
<th>Host Org</th>
<th>Standard</th>
<th>Highlights</th>
</tr>
</thead>
</table>
| AIA      | Camera Link*      | • Version 2.0 released February 2012  
• Version 2.1 in development for maintenance & FPGA implementations  
• Industry leading standard for the past decade |
|          | Camera Link HS*   | • Version 1.0 released May 2012  
• Version 2.0 in development with increases in speed to 5 & 6 Gbits/s for Copper SFF-8470 connector, fiber connector, ROI support  
• Copper and Fiber interfaces with an available core for quick development  
• 3D Pixel format support and QSFP+ connector |
|          | GigE Vision*      | • Version 2.0 released in November 2011  
• Version 2.1 in development to be released mid 2016 including mechanical spec’s, improved testability, new pixel formats, support for 3D data |
|          | USB3 Vision*      | • Version 1.0 released January 2013 for Superspeed USB 3.0  
• Version 1.1 under research: high fps optimization, deterministic event transfers, multi-camera sync |
| EMVA     | GenICam**         | • Version 2.4 released in January 2014  
• Version 3.0 released in December 2015 with improved performance, reduced footprint, 3D pixel format support |
| JIIA     | CoaXPress*        | • Version 1.1 released in February 2013  
• Version 2.0 in development to be released Q3 2016 with increases in speed supporting 10 and 12.5 Gbits/s, forward error correction, multiple frame grabber support, 3D pixel format support |
| IIDC2 ** |                   | • Version 1.1.0 released June 2015  
• Version 1.2.0 released with improved image format, trigger control and peripheral support |

* Global standard available free for download (or will be upon release)  
** Software Standards
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GigE Vision

The Main Advantages of GigE Vision:
Cable Length and Cost Effective Components

- enhanced cable lengths up to 100 meters
- high bandwidth of up 1 Gb/s

COTS accessories are reliable because networks are worldwide!
GigE Vision

GigE Vision Standard Background:

- Created to mold Gigabit Ethernet to the needs of Machine Vision.
- Designed to increase stability and determinism, while reducing CPU load.
- Built-in error checking and packet resend features:
- Contains two protocols:
  - **GVCP**: GigE Vision Control Protocol for establishing a constant link to camera for settings, configuration, etc.
  - **GVSP**: GigE Vision Streaming Protocol for streaming images.
GigE Vision: What it is

Open framework for transferring imaging data and control signals between cameras and PCs over standard Network connections: GigE, 10 GigE, WiFi etc.

- **Device Discovery**
  Defines how compliant devices obtain IP addresses and are identified on the network

- **GigE Vision Control Protocol (GVCP)**
  Defines how to specify stream channels and control and configure compliant devices

- **GigE Vision Stream Protocol (GVSP)**
  Defines how images are packetized and provides mechanisms for cameras to send image data and other information to host computers

- **XML Camera Description File**
  Computer-readable datasheet of features in compliant devices
  Must be based on schema in EMVA’s GenICam standard
  Seven mandatory features

Four main elements
GigE Vision: What it is NOT

No performance guarantee.
Designed to allow vendors to differentiate products via features, performance levels

Does not automatically deliver:
- Reliability
- Line rate throughput at camera or PC
  Throughput is only guaranteed on the GigE link between them
- Deterministic real-time operation & low latency
- Recovery from packet loss
- Low CPU usage at the PC
- Real-time triggering and synchronization

Compliant products are still susceptible to native behavior of underlying GigE network and implementation

Good IMPLEMENTATIONS deliver ALL of this to a higher level
GigE Vision

GigE: Multi-Camera Applications by design

- GigE allows the usage of switches
- Multiple connections are possible
- Ideal setup for multiple cameras
- Save PCI-Slots

- Network cards can handle 4 cameras
- Multiple connections are possible
- No bus sharing like IEEE1394
- Ideal setup to replace analog cameras
GigE Vision

Filter Drivers

- A Filter Driver located above the NIC driver, but below the Windows IP Stack. It shows up as a network service.
- It detects any incoming GVSP (GigE Vision Streaming Protocol) packet and passes them directly to the GigE Vision library in the User Mode, thus reducing the CPU load significantly.
- GVCP take the normal way across the IP stack and the WinSock socket library.
**GigE Vision**

**Performance Drivers**

- A Performance Driver is a hardware driver for the NIC (*Intel chipset only*). It is basically the filter driver run on hardware.

- The main advantage of the performance driver is that it significantly lowers the CPU load needed to service the network traffic between the PC and the cameras.

- Compared to a Filter Driver, it also has a more robust packet resend mechanism.
Network Interface Cards (NIC)

- 1, 2 and 4 port NIC’s are available
- Multiple separate connections possible
- Cards are available for PCI/PCIe
- Inexpensive (BUT, buy quality with Jumbo Packs)
- Frame grabber companies may offer machine vision specific cards
- Prices for cards will continue to go down due to growing markets
- Most new PC’s ship with on-board GigE now
Ethernet Cable Categories

(Gigabit-) Ethernet uses CAT5, CAT6 and CAT7 cables. Most of these cables are well known from consumer electronics and PC networking.

Cat5e
- Cat5e is a more detailed version of CAT5 (nearly all new installations now Cat5e)
- Developed for longer cable lengths with 100 Base-T

Cat 6/7
- Developed for high speed multimedia, data and voice networks
- Special design for Gigabit Ethernet

Note on Shielding...
- U/UTP (Unscreened Unshielded Twisted Pair) - No shielding
- S/UTP (Screened Unshielded Twisted Pair) – Medium shielding
- S/STP (Screened Shielded Twisted Pair) – Best shielding
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DCAM (IEEE 1394 - FireWire)

- Invented by Apple (and TI) in the late 1980s
  - Apple’s original name: “FireWire®”

- Standardized by IEEE in 1995:
  - Standard name “IEEE 1394”

- FireWire® is a trademark of Apple:
  - Basler and many others call it “1394”
  - Sony calls it “i.Link®”

 ➤ BUT it’s all the same! – So don’t get confused 😊

*Note: 1394 has two flavors, 1394a and 1394b. The only differences are:*
- **Bandwidth**: 1394b has double the bandwidth of 1394a.
- **Cabling**: 1394b has a different connector.
DCAM (IEEE 1394 - FireWire)

IIDC 1394-based Digital Camera Specification

“DCAM”

- Industry standard for 1394a/b digital cameras created in 1996
- Specifies video formats, registers, features
- User can choose many combinations of camera and software vendors
- Most industrial 1394 camera makers are DCAM compliant
- Older interface, gradually dying out in the consumer market
DCAM (IEEE 1394 - FireWire)

**Laptop:**
- PCMCIA Card
- AC Power Adapter

**Desktop:**
- PCI or PCIe card
- Power is from PC

**Accessories:**
- Hubs
- Repeaters
- Analog Frame Grabber ~ $500
- IEEE 1394 Adapter Card ~ $40
Digital Cameras: Basic Course

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  - Camera Link (Framegrabber)
  - Camera Link HS (Framegrabber)
  - CoaXPress (Framegrabber)
  - USB3 Vision (USB 3.0 – SuperSpeed USB)
  - GenICam (Software common to many standards)
  - Interface Comparison
- Camera Types and When to Use
**Camera Link** was launched in 1999 *by key players in vision* and formally adopted in 2000 by the AIA. Camera Link establishes a point-to-point dedicated link between camera and frame grabber for high speed and easy cable concept.

Considerations:

- Ground-up designed for connection of cameras + frame grabbers
- High speed modified parallel LVDS interface.
- Standardized for 8 / 10 / 12 bit, single, multi-tap, RGB.
- Includes provisions for PoCL single cable solution with power over the interface cable.
- ~10m copper cable length with repeaters, active extenders, and fiber optic solutions available.
3 Levels of Camera Link:
- **Base Configuration:**
  - 2.0 Gbit / sec
  - One cable needed

- **Medium Configuration:**
  - 4.1 Gbit / sec
  - Two cables needed

- **Full Configuration:**
  - 6.8 Gbit / sec
  - Two cables needed
Camera Link

- The serial communication is routed through a separate channel than image capture.
- The frame grabber provides a special DLL file for software to access through.
Camera Link

Frame Grabbers:

- Usually supplied with processing software
- Can be PCI, PCIe, PCIx
- Some have additional IO
- Require a “Camera File” which tells the grabber what camera is attached and how to handle it
Cables are very robust and designed for industry

- Can be found in various lengths up to 10m
- Right angle and high flex available
- MiniCL reduces connector size
- PoCL Power over Camera Link offers one cable solution
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Camera Link HS (CLHS) is a good choice for:
Demanding machine vision applications…
with high bandwidth, (16.8Gbits/s)
real-time demands,
and error free data transmission needs.
Camera Link HS Design Goals

• Successor of Camera Link
• CLHS keeps Camera Link advantages:
  – High speed
  – Reliability
  – Real-time guarantee
  – Both Copper and Fiber options defined
• CLHS is far superior by:
  – Increased bandwidth
  – Much longer cables (10K meters)
  – Plug & Play capability
Camera Link HS Reliability

• High degree of transfer reliability

• Headers and real time signals ensured by 2 of 3 voting

• CRC-32 check and resend for video and communications

• Fiber optic offers immunity to electric and magnetic fields
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CoaXPress - A Brief History

Pan-European R&D Project:
2007 - Adimec and EqcoLogic research high speed interface options
2008 - Technology demonstrator at Vision 2008, Stuttgart, Germany

CoaXPress Consortium formed early 2009:

- Adimec (NL) ......................... Cameras
- Active Silicon (UK) ................. Frame Grabbers
- EqcoLogic (BE) ..................... Transceivers
- Components Express (USA) ....... Cable Solutions
- AVAL DATA (JP) .................... Frame Grabbers
- NED (JP) .............................. Line-scan Cameras

2010 – Version 1.0 released
2013 – Version 1.1 released
Further updates in development
CoaXPress Protocol Highlights

Essentials: Like most modern interface standards, CoaXPress is a packet based protocol using 8B/10B coding

Bitrate: 1.25, 2.5, 3.125, 5.0, or 6.25 Gbps
Through link aggregation: N x 6.25 Gbps (i.e CXP4)

Image formats: Arbitrary image size & speed
Multiple data streams in parallel

Data integrity: Redundant coding
CRC32
Link BER test

Control data: Uplink: Maximum 20.8 Mbps (shared with trigger)

Trigger: Uplink: Fixed latency of 3.4µs, +/- 4 ns accuracy

Plug & Play: GenICam including GenTL is mandatory. Also auto bitrate, link setup, device detection, data packing format, bit depth, etc.
CoaXPress Benefits

- Long cable length (130 ft./40m to over 330 ft./100m).
- High speed (6.25 Gbps per link).
- Good choice for data rates over 5 Gbps, and for 1 Gbps or greater when long cables are needed.
- Plug and Play (GenICam, GenTL).
- Digital video, control, GPIO, triggering and power over one cable.
- Coax ease of use, flexibility and reliability.
- Support of legacy coax cables (upgrade analog systems).
- Near real-time trigger accuracy.
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USB 3.0 Fact Sheet

**Specs**
- Up to 400MB/sec bandwidth
- 5/14/50m cables passive/active/optical
- 5V / 4.5W power to device
- Intel/AMD chipset support
- Win8 native support, Win7 SP expected

**Comparisons to USB 2.0**
- 10x Faster
- ~2x power for devices
- 1/3 the power usage for data transfer
- Host/Device optimizations
  - Removed need for CPU polling
  - Full-duplex
- Backwards compatible with 2.0
USB 3.0 Adoption

- “USB is the most successful interface in the history of the PC”
  - 3+ billion units/year
  - Near 100% adoption
- Likely 100+ million USB 3.0 controllers shipped to date
- Native USB 3.0 support integrated in latest Intel & AMD chipsets
- Windows 8 has out-of-the-box support

Source: 2011 USB DevCon Keynote
USB3 Vision Standard Details

- Hosted by AIA and has been deemed an international standard by the “G3” (EMVA, AIA, and JIIA)
- Based off existing, well-defined USB mechanisms for device discovery, control, and image streaming
- Builds off of experience with GigE Vision and other standards
- Uses GenICam to allow access to common and vendor-specific features
- Machine vision specific features:
  - Variable-sized image/data frames
  - Zero-copy transfers
  - Reliable recovery of error conditions
  - Standardizing a screw-lock USB 3 connector
What it Means

Plug & Play
- It just works, no configuration or multiple vendor software needed
- Windows P&P manager binds camera automatically

GenICam
- Standard and vendor-specific camera features automatically available

Zero-copy Image transfers
- Video data is copied to RAM by bus master DMA.
- The PC’s CPU is not involved. Typical CPU load < 1%

Low Latency and Jitter
- Uses bulk access with 5 GBit/s transfer speed
- Typical latency: Write = 45±5 µs, Read = 140±5 µs

Variable Image Size
- The camera can decide on-the-fly to send a smaller frame without the host knowing this in advance
- Applications
  - Line scan, e.g.; log inspection in a sawmill
  - Pick & Place
  - Live & Trigger
Digital Cameras: Basic Course

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- Interface Comparison
- Camera Types and When to Use
• The Goal of GeniCam is to unite the various machine vision interfaces
• Cooperatively developed by industry-leading vendors
• Hosted by European Machine Vision Association (EMVA)
  – www.genicam.org
• Unified API to seamlessly control many interfaces with one program
GenICam in a Nutshell

provides plug&play to machine vision cameras

Accessing Camera Features and Grabbing Images

- Camera Vendors
- Interface independent
- Driver
- Vision Library
- PC Software Vendors
- Customers
GenICam Modules

- **Client**
  - SFNC – camera features

- **Vision Library / SDK**
  - GenICam reference implementation
    - interpret XML file content
  - CLProtocol – Camera Link support
  - GenTL – transport layer API
  - GenCP – packet layout
  - GenApi – XML file format

- **Driver**
  - GenTL

- **Camera**
  - XML
GenICam is a core element of all modern interfaces

Latest newcomer: **USB3 Vision**
- Pure transport layer standard
- Fully relies on GenICam as mandatory front end
- Cameras are SFNC compliant

Mandatory
Optional
Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
- Concept of the Digital Camera

**Camera Interface Standards (Interface)**
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- USB3 Vision (USB 3.0 – SuperSpeed USB)
- GenICam (Software common to many standards)

**Interface Comparison**

- Camera Types and When to Use
## Interface Comparison

### Camera Interface Bandwidth
- IEEE1394a 400 Mbits/s
- USB 2 480 Mbits/s
- IEEE1394b 800 Mbits/s
- GigE Vision 1.0 Gbits/s
- USB3 Vision 3.5 Gbits/s
- CoaXPress 6.25 Gbits/s
- Camera Link 6.8 Gbits/s
- 10 GigE Vision 10 Gbits/s
- Camera Link HS 16.8 Gbits/s

### PC Bus Bandwidth
- PCI Bus 120 MBytes/s (~1Gbits/sec)
- PCIe Bus 1200 MBytes/s (~10 Gbits/sec)
Interface Comparison

Cable Length

- USB3 Vision 3-5m, greater with active and hybrid optical cables
- IEEE1394b 10m
- IEEE1394a 10m
- Camera Link 10m
- GigE Vision 100m
- CoaXPress 100m
- Camera Link HS 10,000m
There is no “perfect” interface. Always prioritize application requirements and compare.

Key Parameters For Vision Standard Selection:
- Cost
- Bandwidth requirements
- Current infrastructure
- Cable lengths required
- Triggering requirements
Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
- Concept of the Digital Camera
- Camera Interface Standards
- **Camera Types and When to Use**
  - Area scan
  - Line scan
Area Scan

- Main aspects
- Architecture
- AOI
- Binning
- Color
Area Scan

Main Aspects

- Like a Photo camera
- Fixed aspect ratio (4:3, 16:9)
- Easy design in
- Easy image processing
- Longer integration time possible
Area Scan

Architecture

- Micro lenses
- Color filters (opt.)
- Silicon
- Architecture Special Trend: Multi-Tap Sensors
  - Kodak manufactures high speed CCD’s with 2 or 4 output channels (“Taps”).

These sensors have great image quality, but must be handled very carefully in the camera.
Area Scan

- If the taps are not “balanced” properly, the user will see a line in their image.

Tap imbalance problem

Properly balanced Taps
Area Scan

- **Region Of Interest (ROI)**
- Sensor can be cropped at the hardware level.
- By only reading out selected pixels, we can increase the frame rate.
- We also save some bandwidth.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>max. fps continuously (Single GigE) (*1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2048 x 1080</td>
<td>53</td>
</tr>
<tr>
<td>1920 x 1080</td>
<td>56</td>
</tr>
<tr>
<td>1280 x 720</td>
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<td>1024 x 768</td>
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<td>736 x 576</td>
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<td>352 x 288</td>
<td>1144</td>
</tr>
<tr>
<td>176 x 144</td>
<td>2300</td>
</tr>
</tbody>
</table>
**Area Scan**

**Binining:** The physical combining of charges between pixels during readout

**Advantages:**
Brighter image, bandwidth saved due to smaller image size.

**Disadvantages:**
Reduces resolution, can change aspect ratio
COLOR

- 3- CCD
- 1- CCD (Bayer)
3-CCD Color

- **3-CCD Color**: Uses a separate CCD for each color
- Very good image quality
- More expensive

![Diagram of 3-CCD Color](image-url)
Area Scan

3-CCD Color

- No color interpolation (pixel to pixel)
- Controllable filter specifications
- Co-site sampling

RGB sensors are aligned pixel to pixel
Area Scan

Single imager Color – Bayer Filter Pattern

- The camera outputs a monochrome signal
- Color interpolation has to be done for every second pixel
- Color rendition is often done in the host - Bayer to RGB conversion
- The BAYER filter cannot be changed or modified
Area Scan

- 1-CCD Color: Bayer Pattern
- Lower Color spatial resolution
- Lower manufacturing cost

\[
\text{red part} + \text{green part} + \text{blue part} = \text{addition} \implies \text{interpolated}
\]
Area Scan

Bayer Pattern Considerations

- The frame grabber or software must know the orientation of the pattern on the sensor.
Area Scan

Single Chip vs. 3-CCD Color

**Single CCD Color Camera**
- Each pixel has just one color filter
- Color interpolation is needed
- Not true color
- Spectral response depends on the design of the color filter

**3CCD Color Camera**
- RGB each independent CCD
- Each pixel has full RGB data
- Spectral response can be flexible by the design of optical block

![Diagram of single and 3-CCD color cameras](image-url)
Area Scan

Additional Color Considerations – Filter Response

Typical Bayer CFA Response
Additional Color Considerations – Filter Response

3-CCD prism block transmittance

transmittance(%) vs. wavelength(nm)
Advantages of dichroic coatings

Filter coatings

- Soft polymer dye
  - Large overlap between colors
  - Batch-to-batch variation
  - Limited long term stability

- Hard dichroic coating
  - Steep edges, very little overlap between colors
  - Controllable specification, low variation
  - Very good long term stability
  - Used in 3CCD cameras
Digital Cameras: Basic Course

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Line Scan

- Main aspects
- How does that work?
- Architecture
- Trigger
- Color
Main Aspects

- Like a scanner or fax
- 2\textsuperscript{nd} dimensions comes by movement
- Very good price / pixel performance
- High pixel fill-factor - typically 100%
  - Typically big pixels
- Smear-free images
- Very short integration times
- Illumination intensity generally needs to be high
- Difficult design in / image processing
Line Scan

- 1d array of pixels (Line)
- Image produced line by line by scanning object
- **Main Advantage:** Excellent for scanning / web applications
- **Examples:** food sorting, wafer inspection, medical slide scanning.

![Pixels Image](image-url)
Line Scan

How Does that Work?

- Line Scan fits where constant object motion and high speeds are needed.
- Semiconductor wafer inspection
- Photovoltaic cells
- Food inspection/sorting
- Film scanning
- Postal applications
- Medical/microscopy
How Does that Work?
Architecture

- Single Tap Sensors
- Dual Tap
- Quad Tap
Line Scan

- **Single Tap**

- **Dual Tap**
Line Scan

- Quad Tap

Diagram showing the flow of signals from CCD-Out to CCD-Out through Shift-Register and Photodiode-Line.
Color

- Types of color Line Scan
- Tri-linear in more detail
- Summary
Line Scan

- Tri-Linear

CCD-Register
TG
Photodiode-Line
CCD-Out Red

CCD-Register
TG
Photodiode-Line
CCD-Out Green

CCD-Register
TG
Photodiode-Line
CCD-Out Blue
A tri-linear line scan camera takes three different scans, but the red, green, and blue line do not look onto the same position of the object.

Falling and rotating objects can only be inspected by the colors individually.

Visualization is difficult, but machine vision is possible.
Line Scan

Spatial Trigger Importance

- A trigger by time squeezes the object for different speeds (e.g., acceleration after a traffic light).
- Only a spatial trigger (Encoder) gives the right information.
Line Scan

- No rotation of the object for matching to a RGB trilinear image.
- The conveyer belt has to move straight.

NO!  YES!
The tri-linear camera must be aligned perpendicular to the conveyer.
Spatial Correction’s impact on Color with tri-linear

Raw Image

Corrected Image

Raw

Corrected
Prism-based Line Scan Camera Advantages

- One focal point for all channels
  - Reflected light is separated by wavelength through the optical beam splitter and sent to independent RGB CCD sensors simultaneously.
  - As a result, all CCDs capture the exact same point of the object at the same time.
Prism-based vs Tri-linear Technology Off-axis Position

**Drawback of tri-linear technology**
Camera positioned off-axis to the inspected object creates unwanted halo effects (distortion in color registration). Different magnification for all spectral bands.

**Advantages of prism technology**
Camera positioned off-axis to the object. No problem with spatial alignment – no halo effects. All CCDs capture the exact same point of the object at the same time. Same magnification for all spectral bands.

Source: Vision & Sensors, May 2010
Prism-based vs Tri-linear Technology Undulating Objects

**Drawbacks of tri-linear technology**
When inspecting undulating objects, the waviness causes constant timing and focus variations between the R, G and B lines.

**Advantages of prism-based technology**
Always one optical axis with precise pixel-to-pixel alignment.

Distorted color registration with tri-linear solution.

Exact color registration through co-site sampling with prism-based solution.
Prism-based versus Tri-linear Technology Cylindrical Objects

**Drawbacks of tri-linear technology**
When inspecting cylindrical objects, the R, G and B lines of the CCD are imaged as separate lines of the object.

**Advantages of prism-based technology**
Always one optical axis ensuring pixel to pixel accuracy and same magnification.

Distorted color registration with tri-linear solution.

Exact color registration through co-site sampling with prism-based solution.

R, G, B + NIR
Summary / Tips

- Area Scan cameras are fairly straightforward.
- Line Scan requires more attention to alignment and timing.
- Best color and spatial resolution come from 3-CCD cameras.
- Tip: 80% of Machine Vision applications are probably monochrome area scan.
- Area scan and Linescan applications rarely overlap. When in doubt, prototype with area scan.
Basic Course Summary

- Frame rate and resolution are usually not enough to pick a camera.
- Use sensor performance, camera design, feature set, and cost-effectiveness to narrow selection.
- Camera design can make or break image quality.
- No “one size fits all” interface. Remember to look at cabling, peripheral cost, and scalability requirements.
- Area scan and Line scan should be viewed as two separate disciplines. Skill-set, efficiency and cost vary greatly between the two.
Questions?
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